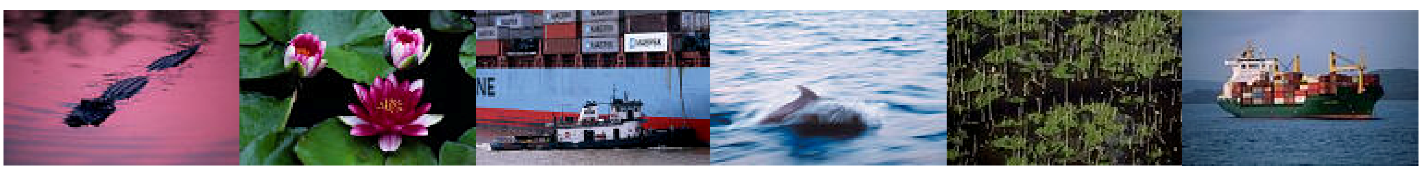
Final report

Strategies to reduce the maintenance dredging cost of the Mississippi River Gulf Outlet Channel



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January 2003

Preface

In times of an increasing environmental awareness and a continuous focus on economic interest a balance should be found between economic demands and environmental responsibility.

The main objective of my thesis (Masters of Science in Civil Engineering at the Delft University of Technology) is to create a strategy to reduce the current maintenance dredging costs of the Mississippi River Gulf Outlet Channel, while protecting and restoring the affected ecosystem surrounding the channel. This topic has my particular interest since it deals with Civil Engineering aspects, environmental topics as well as economic issues.

I would like to thank the Laminga Fund, the Corps of Engineers and Tulane University for their contribution to this thesis and making the internship at Tulane University possible. In addition I would like to express my gratitude to prof.M. Stive and M. Baptist for their recommendations and advise. Finally I would like to thank my supervisors, prof.H. Ligteringen, M.Geense, J.P. Noppen, prof. R.M. Bakeer and E.J. Russo for their valuable comments, recommendations and support.

Douwe Hoekstra

Delft, December 2002

General Project Information

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Period	June -December 2002
Location	U.S. Army Corps of Engineers & Tulane University, New Orleans
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Summary

Introduction
The Mississippi River Gulf Outlet Channel was constructed in the late 1960s to connect the Port of New Orleans with the Gulf of Mexico for vessels with a maximum draft of 11 m. The Port of New Orleans has a significant impact on the local and state-wide economy. About 80% of the cargo handled in the Port of New Orleans would be lost if the MRGO Channel would be closed. However the construction of the MRGO Channel has contributed directly and indirectly to the degradation of the wetlands surrounding the channel.

Objectives thesis
- To address the root causes of the existing maintenance dredging costs.
- To create a strategy to control and reduce the current maintenance dredging costs while limiting the negative environmental impact the MRGO Channel has on the surrounding wetlands for a period of 20 years.

Maintenance dredging costs
The maintenance dredging costs along the channel can be explained by variations in unit rate and amounts of materials to be dredged, Table i.

Section	Amounts of dredged materials (1970-2001)	Percentage	Total dredging costs (1970-2001)	Percentage	Unit rate ($/m^3)
Inland Reach	94.614.400 m^3	36.3 %	$ 127,544,550	33.7 %	$ 1.35
Breton Sound	101.034.000 m^3	38.8 %	$ 118,918,977	31.4 %	$ 1.18
Bar Channel	65.043.700 m^3	25.0 %	$ 131,886,862	34.9 %	$ 2.03
Total	260.693.000 m^3	100 %	$ 378,350,389	100 %	$ 1.46

Table i Maintenance dredging amounts and costs 1970-2001

The unit rate depends on the execution method, size and characteristics of the dredging operations. The amounts of materials to be dredged mainly depend on the sedimentation rate. The sedimentation in the MRGO Channel is a function of different and interacting sources of sediment and causes of sedimentation. The following possible sources of sediment have been analyzed:
- Mississippi River
- Wetland areas surrounding the MRGO Channel (Inland Reach)
- Open water section (Breton Sound and Bar Channel)
- Channel banks (Inland Reach)

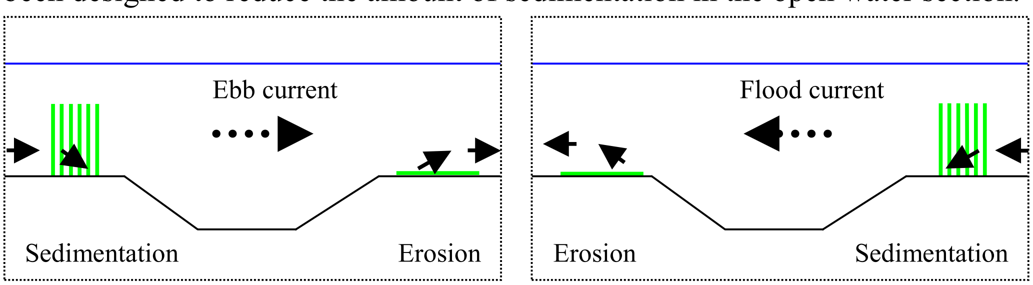
Subsequently the following possible causes of sedimentation in the channel have been analyzed:
- Currents (tidal, ship-induced, hurricane and storm conditions)
- Changes in local geometry
- Differences in salinity level (salt water wedge)
- Wave attack on the channel banks (wind-induced, ship-induced)

Data on the dredging operations over the period 1970-2001 has been analyzed in relation to the different sources and causes of sedimentation. The conclusion was drawn that bank erosion, by ship-induced waves, is the dominant cause of sedimentation in the Inland Reach. During a hurricane- or extreme storm-surge condition sediments from the surrounding wetlands and from the open water section enter the Inland Reach.
Sedimentation in the open water section is primarily caused by (tidal) cross currents.

Strategies
- Do nothing
A shipping forecast has been carried out to address the future navigational needs, the conclusion can be drawn that the number of ship-movements on the MRGO channel is not likely to increase or decrease significantly over the next 20 years.
The future maintenance dredging costs have been estimated at about $ 12 million a year, based on amounts of historic maintenance works.
Without implementation of measures a wetland area of about 70 hectares (165 acres) a year would be lost due to bank erosion.

- Inland Reach
The proposed strategy for the Inland Reach is a combination of a pile screen, a breakwater and a stepped bottom cross section. The breakwater alternative is especially promising in the creation of new wetland area, since a vegetation strip is constructed between the breakwater and the channel banks. The pile screen is promising in reducing the maintenance dredging costs.
The goal of maintenance dredging costs reduction is achieved under the proposed strategy. However the cost reduction of $ 1.8 million over a period of 20 years is marginal compared to the total amount of maintenance costs spent in the same period.
The proposed strategies would reduce the amount of wetland loss by 70% compared to no action.

- Open water section
A conventional alternative such as a (submerged) breakwater is not economical feasible compared to dredging for a period of 20 years. A new concept of artificial seaweed has been designed to reduce the amount of sedimentation in the open water section.



The designed construction is capable of bending in one direction only. The artificial seaweed enhances sedimentation in the vertical position and causes erosion in the horizontal position, resulting in a reduction of the sediment transport towards the trench. Economic construction and placement methods are required to make the bending finger variant economical feasible compared to dredging.

Structure thesis

The final report consists of five different sections which can be read independently and the appendices. The final report has been written for a non-technical target audience. Concepts that require specific knowledge on a certain topic are explained in the appendices. All costs are given in prices of 2002 unless specifically noted otherwise.

Section I Introduction	• General introduction • Problem analysis • Restrictions
Section II Analysis	• Shipping analysis • Channel dimensions • Wetland degradation analysis • Sedimentation rate analysis • Dredging costs analysis
Section III Strategies	• Criteria • Alternatives • Multi Criteria Evaluation • Proposed strategies
Section IV Artificial seaweed	• Theoretic background • Dimension optimization • Feasibility study
Section V Conclusions	• Conclusions • Recommendations • References
Section A Appendices	• Maps • Background information • Calculations

Figure i Structure thesis

Section I Table of contents

1 Introduction Mississippi River Gulf Outlet Channel

1.1 General

The Mississippi River Gulf Outlet (MRGO) channel serves as a deep draft waterway from the port of New Orleans to the Gulf of Mexico. The channel was designed to be an alternative shorter route to the Mississippi River. The Mississippi with its meandering bends, fierce currents and unpredictable shoaling causes significant navigation challenges for ships. However the construction of the MRGO channel in the late 1960s has a negative environmental impact on the surrounding wetlands.

1.2 Geography and dimensions

The MRGO channel connects the Port of New Orleans, Louisiana, USA to the Gulf of Mexico. The channel has a total length of 122 km (76 miles). The channel can be divided in the following three parts (Appendix 1):

1. Inland Reach
2. Breton Sound
3. Bar Channel

Figure 1-1 shows the location of the MRGO channel with the three different sections.

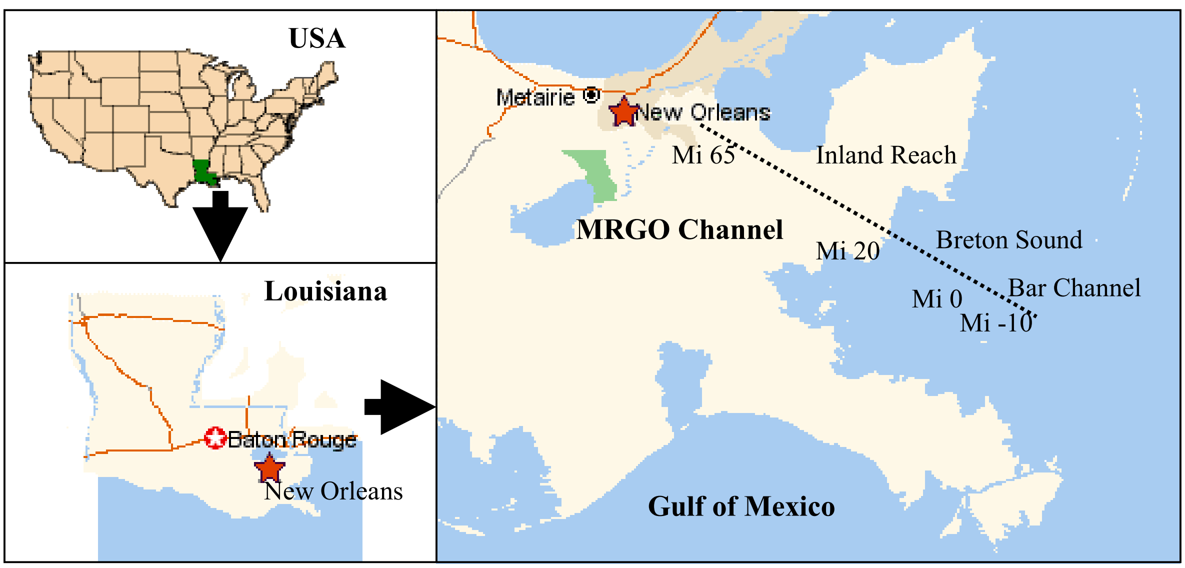


Figure 1-1 Map of the USA, Louisiana and the project area

The Inland Reach of the MRGO channel passes through a fragile wetland environment. From the coastal wetlands the channel emerges into a wide shallow bay, called the Breton Sound. From this point, the MRGO crosses a barrier island chain, the Chandeleur Islands, into the Bar Channel Reach, out in the deep waters of the Gulf of Mexico.

Table 1-1 gives the original[1] dimensions of the three different sections of the MRGO.

Section	Depth [2]	Bottom width	Surface width	Location [3]	Length
Inland Reach	11.0 m	152 m	229 m	Mile 65-20 [4]	74.0 km
Breton Sound	11.0 m	152 m	229 m	Mile 19 -0	32.2 km
Bar Channel	11.6 m	183 m	259 m	Mile 0 -(-10)	16.1 km

Table 1-1 Dimensions of the MRGO

The channel is located in the Mississippi Delta. The Mississippi Delta has a large impact on the boundary conditions of the MRGO channel (e.g. the morphological boundary conditions); appendix 6 gives more details on the Mississippi Delta.

1.3 Navigation

Most of the deep-draft ships sailing the channel are container ships. Besides the deep-draft vessels the channel is used by shallow draft barges, commercial fishing ships and recreational vessels. The large container ships generally range from 9 m to 11 m in draft. The channel plays a key role in the waterway system of Louisiana. Moreover the channel serves as the only alternative barge traffic corridor for the Gulf Intracoastal Waterway (GIWW) when the Inner Harbor Navigation Canal (IHNC) lock is out of service, Figure 1-2.

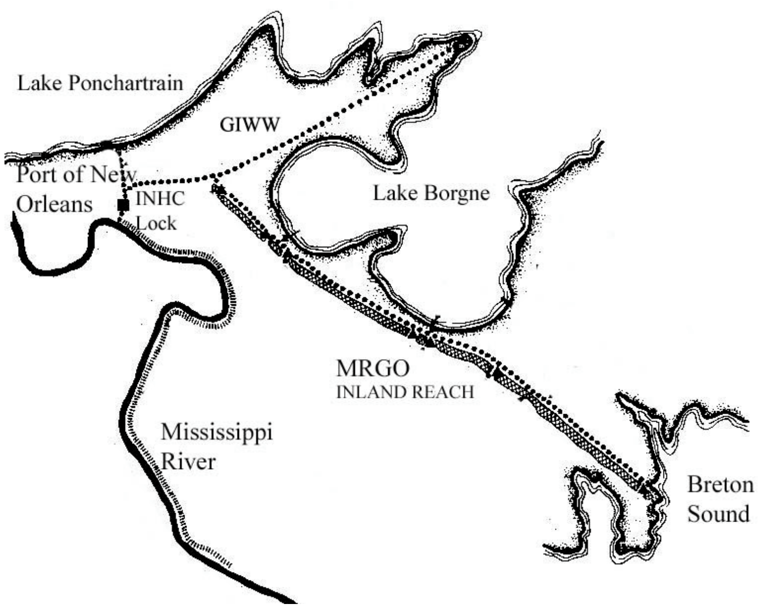


Figure 1-2 Waterways connected to the MRGO channel

[1] Channel dimensions directly after the construction of the MRGO in 1968.
[2] Depths are given in meters below Mean Low Gulf (MLG).
[3] Locations along the channel are referred to in miles. As on the map in appendix 1
[4] Mile demarcation of the channel in the direction of New Orleans to the Gulf of Mexico descends from mile 66 to mile -9.38.

1.4 Economic impact

Coastal Louisiana is important to the local and national economies through oil and gas production, the Port of New Orleans, and international seafood and recreation industries. Appendix 8 gives an impression of the economic impact the MRGO channel has on the city of New Orleans and the state of Louisiana, a summary of the appendix is given below.

The Port of New Orleans has a significant impact on the economy of New Orleans and the state of Louisiana. Maritime activity within the Port of New Orleans is responsible for more than 107,000 jobs, \$ 2 billion in earnings, \$ 13 billion in spending and \$ 231 million in taxes statewide. The economic impact of the Port depends to a large[5] extent on the presence of the MRGO Channel, since practically all deep draft vessels (except cruise ships) sail the MRGO to reach the Port of New Orleans from the Gulf of Mexico. Hence the MRGO Channel plays a dominant function in the maritime industry of New Orleans and the state of Louisiana.

1.5 Environmental impact

The Inland Reach of the MRGO channel passes through a fragile estuarine environment. This fragile ecosystem is part of the Mississippi Delta and the conditions in the area depend on the Delta Cycle. In appendix 6, the Delta Cycle is discussed in more details. The ecosystem surrounding the channel is in the “transgressive phase” which means land is subsiding and eroding in conversion to shallow open water. In natural conditions the transgressive process continues gradually and the degradation of the wetland area is small. However the construction of the MRGO channel has changed the morphological conditions in the wetlands surrounding the channel significantly. This has drastically accelerated the transformation from wetland area to sea. Chapter 6 gives an analysis of the degradation of the wetlands surrounding the MRGO.

1.6 Maintenance dredging operations

In order to meet the requirements of the channel, periodic and costly maintenance dredging is necessary. Chapter 7 gives an analysis of the maintenance dredging costs.

[5] A study carried out in 1993 by T.P. Ryan indicates that 80% of the cargo handled in the Port of New Orleans would be lost if the MRGO channel would be closed [REF 77].

1.7 Involved parties

As can be seen in appendix 10, different parties are related to the MRGO channel, which have their own sometimes conflicting interests. Although there are many conflicting interests the main conflict of interest is between the economic and environmental needs. The Port of New Orleans and the users of the channel (the shipping companies, and the fishing companies) have economic interests. The environmental community has mainly environmental interests. Other parties are either unambiguous, such as the contractors and advisors or have both economic and environmental interests, such as the USACE[6], local municipalities and elected officials, Figure 1-3.

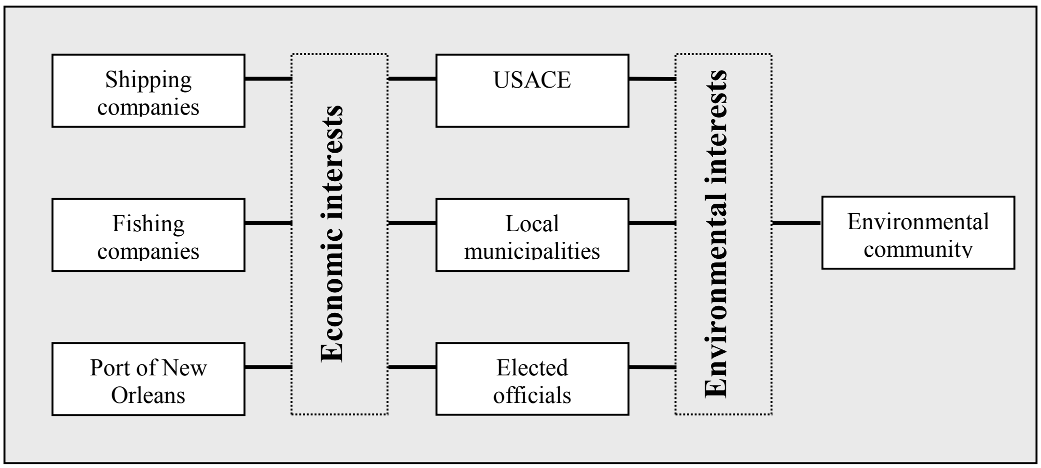


Figure 1-3 Parties and interests

Although the channel provides a more efficient waterway for container ships to the Port of New Orleans, the consensus of the surrounding municipalities is that the MRGO channel is in an undesirable alignment [REF 10].
There is a general perception that the local municipalities are subjected to increased hurricane and storm surge vulnerability. (Paragraph 6.7)

[6] USACE: United States Army Corps of Engineers.

2 Problem analysis

2.1 General

This chapter will start with the problem analysis. The entire scope of problems and issues will be summarized in the problem definition. Following this, the goals of the thesis are stated in paragraph 2.4.

2.2 Problem analysis

The MRGO channel plays a significant role in the local maritime economy of New Orleans and the regional economy of Louisiana. However the MRGO channel has a negative environmental impact on the wetlands surrounding the channel. The increased salinity level has deteriorated the environmental quality of the ecosystem. The loss of wetland area is persistent due to (bank-line) erosion and costly maintenance dredging is required. As part of a nation wide policy the U.S. Army Corps of Engineers wishes to reduce their Operation and Maintenance costs where possible.

2.3 Problem definition

Costly maintenance dredging is needed to meet the navigational requirements of the MRGO channel. The loss of wetland area and the degradation of the ecosystem surrounding the MRGO are persistent.

2.4 Project objectives

- To address the root causes of the existing maintenance dredging costs.
- To create a strategy to control and reduce the current maintenance dredging costs while limiting the negative environmental impact the MRGO channel has on the surrounding wetlands for a period of 20 years[7].

[7] Period of 20 years starting on October-01-2004 (the first day of the USACE fiscal year 2005)

2.5 Structure of the thesis

The structure of the thesis is outlined in paragraph 2.5.1 and 2.5.2. An overview of the structure is given in Figure 2-2 on page I-9.

2.5.1 The first objective

"To address the root causes of the existing maintenance dredging costs".

The maintenance dredging costs depend on the dredging-unit rate and the amounts of materials to be dredged. Both the costs per cubic meter and the amounts of dredged materials vary significantly along different locations of the channel.

First the sedimentation rate along the channel is analyzed approximately[8] to address the dominant causes of sedimentation along the different sections of the channel (chapter 7). Subsequently an analysis is made of the dredging costs per cubic meter along the channel using data from historic maintenance dredging operations at the MRGO channel (chapter 8).

Using the dominant cause of sedimentation and the unit rate analysis the root causes of the maintenance dredging costs can be addressed for each section of the channel.

2.5.2 The second objective

"To create a strategy to control and reduce the current maintenance dredging costs while limiting the negative environmental impact the MRGO channel has on the surrounding wetlands for a period of 20 years[9]".

The future amount of ship movements is estimated based on historic ship movements (chapter 4). The shipping analysis together with the analysis on the channel dimensions (chapter 5) and the analysis on the dredging costs (chapter 8) gives an estimate on the future maintenance dredging needs.

An analysis of the wetland degradation is made (chapter 6) to address possibilities to limit the negative environmental impact of the MRGO channel.

The actual process to create the strategies is roughly summarized in Figure 2-1. Different alternatives which reduce the maintenance dredging costs and/or restore the surrounding wetlands are presented (chapter 11). All generated alternatives meet the requirements and are suitable in the prevailing boundary conditions.
The alternatives will be evaluated in a Multi Criteria Evaluation (chapter 12). The added value[10] of an alternative will be weighted against the costs[11] of the alternative. The alternative that gives the desired[12] balance between value and the costs is chosen.

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[8] The sedimentation rate along the channel is analyzed with the use of data from historic maintenance dredging works at the MRGO channel (over the period 1970-2001).
[9] Period of 20 years starting on October-01-2004 (the first day of the USACE fiscal year 2005)

Certain locations are more suitable for wetland restoration or have more potential in reducing the maintenance dredging costs than others. Different alternatives are proposed for different locations (chapter 13). Consequently a preliminary design will be made for one of the chosen alternatives.

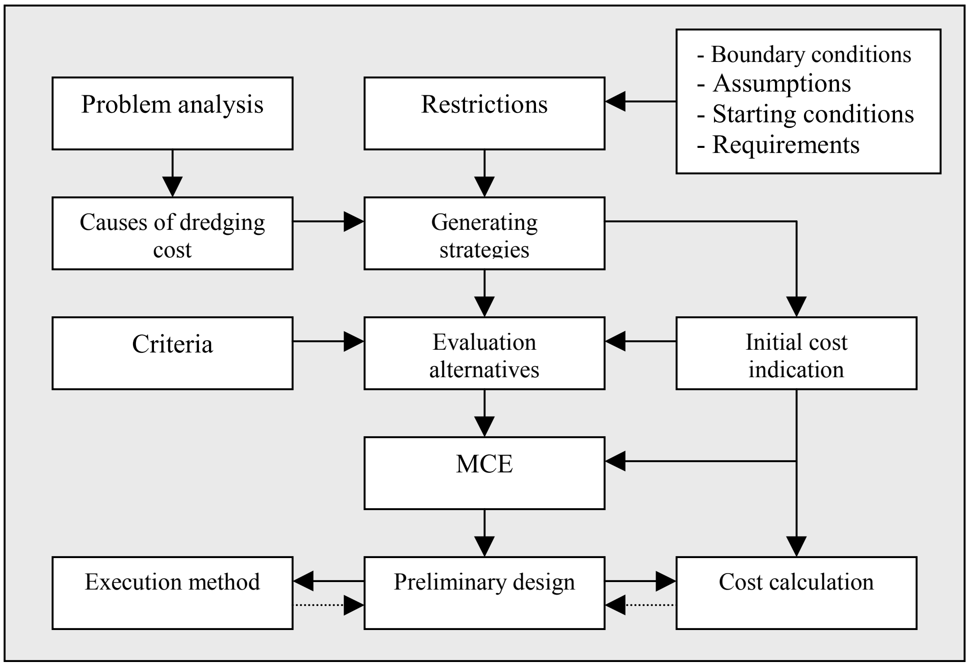

Figure 2-1 Design process

The final report is divided in five sections (page v). Figure 2-2 on page I-9 gives the structure of the thesis and the relation between the different sections and chapters.

[10] The added value consists of the amount of maintenance costs reduction and the intangible positive environmental impact.
[11] The costs per alternative consist of the construction costs and maintenance costs for a period of 20 years
[12] The assessment between value and costs is a subjective matter and depends on the views of the decision maker. (Chapter 12)

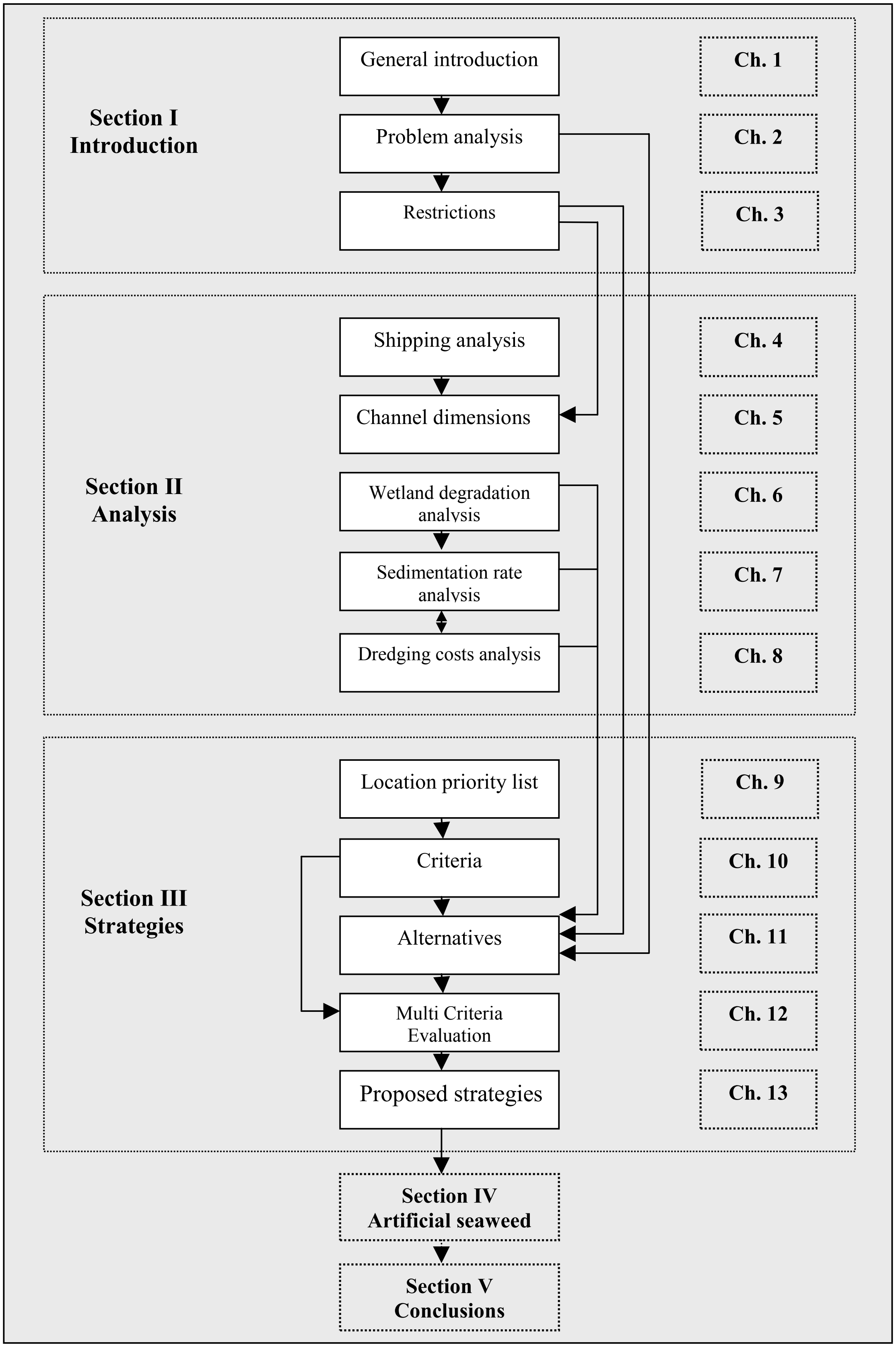

Figure 2-2 Structure final thesis

3 Restrictions

3.1 Introduction restrictions

In this chapter the restrictions are listed. A distinction is made between boundary conditions, assumptions, starting conditions and requirements.

- A boundary condition is an inevitable condition (set by the "outside world") that influences the design.
  (E.g. Mean higher high water = + 0.4 m Mean lower low water)
- An assumption is qualification or quantification of an uncertainty which should be verified afterwards [REF 13].
  (E.g. the inflation rate for the period 2005-2025 is 3%)
- A starting condition is a restriction set by the designer to limit the amount possible solutions.
  (E.g. The lifespan of the proposed solution is set at 20 years)
- Requirements are conditions which the final design has to meet.
  (E.g. The proposed solution should not exceed the present rate in wetland loss)

3.2 Boundary conditions

3.2.1 General boundary conditions

Fiscal year

The fiscal year of the US Army Corps of Engineers runs from 1-October to 30-September.

Channel dimensions

Table 3-1 gives the original[13] and present[14] channel dimensions. The surface width in the Inland reach has increased with 150 -450 m as a consequence of bank-erosion. Details on the bank line retreat are given in appendix 25.

Section	Depth[15]	Bottom width	Initial Surface width	Surface width	Location
Inland Reach	11.0 m	152 m	229 m	Variable	Mile 65-20
Breton Sound	11.0 m	152 m	229 m	229 m	Mile 19 -0
Bar Channel	11.6 m	183 m	259 m	259 m	Mile 0 -(-10)

Table 3-1 Original and present channel dimensions

[13] Channel dimensions directly after the construction of the MRGO in 1968.
[14] Channel dimensions based on a survey by the USACE in 1996.
[15] Depths are given in meter below Mean Low Gulf (MLG).

3.2.2 Legal boundary conditions

Federal laws and legislations closely related to the project are (appendix 14) ref EMRIS[16]:

- Archaeological resources protection act of 1979
- Coastal wetlands planning, protection and restoration act (CWPPRA)
- Clean water act
- Coastal barrier resources act
- Coastal zone management act
- Deepwater port act of 1974
- Food Security Act of 1985
- Oil pollution act of 1990
- Sustainable fisheries act
- Watershed protection and flood prevention act
- National environmental policy act
- Fish and wildlife coordination act
- Threatened and endangered species act
- Magnuson -Stevenson Fisheries Conservation and Management Act

3.2.3 Natural boundary conditions

The natural boundary conditions are listed in appendix 15. A brief summary of the most relevant boundary conditions is given below:

- The sea level rise is about 0.06 m (20 years).
- The subsidence is about 0.06 -0.12 m (20 years).
- The salinity ranges from 5.5 p.p.t. in the upper part of the inland reach to 18 p.p.t. in the open water section.
- A 3-m top layer of marsh and swamp deposits is present in the Inland Reach; layers below consist of silt and clay with a low bearing capacity.
- In the open water section the bottom layer (3 m to 5.2 m) consists of sand, shells and clay.
- The tidal amplitude in the open water section is 0.2 m (normal conditions).
- The (tidal) current velocity in the open water section is 0.1 -0.5 m/s (up to 1.4 m/s during hurricane conditions).
- The tidal current velocities in the Inland Reach are 0.18 m/s (flood) and 0.24 m/s (ebb) under normal conditions.
- The wind-induced wave height for a wind speed of 8.5 m/s is in the order of 0.15 -0.35 m.

[16] EMRIS Ecosystem Management Restoration Information System

3.3 Assumptions

Hurricane frequency

- Hurricanes have a significant impact on the wetland degradation (chapter 6) and on the sedimentation rate (chapter 7). Hurricanes that have a significant impact on the maintenance dredging operations have a frequency 0.1 per year.

Financial

- For the calculation of the construction costs the following exchange rate between the dollar and the euro is assumed: 1 US$ = 1 Euro for the (Exchange rate, August 2002).
- An annual inflation of rate 3% for the period 2005-2025.
- Historic inflation rates can be derived from the Consumer Price Indexes USA.

Functional

- All vessels with a draft of 6m (20ft) and up to 11 m (36 ft) sailing the MRGO make use of a pilot.
- Vessel dimensions:
  The dimensions of a second-generation container ship and a typical general cargo ship [REF 6] are assumed decisive in the calculation of the channel dimensions (carried out in chapter 5).

Decisive container ship		
Capacity	1500-1800 TEU	
Length	225-240 m	735-785 ft.
Width	30 m (one lane)	100 ft.
Draft	11 m	36 ft.

Table 3-2 Dimensions of container ship second generation

Decisive general cargo ship		
Length	140-160 m	460-525 ft.
Width	22 m (two lanes)	70 ft.
Draft	9 m	30 ft.

Table 3-3 Dimensions of general cargo ship

3.4 Starting conditions

- The lifespan of the proposed solution is set at 20 years; preferably the proposed solution should tackle the problem for a period exceeding the lifespan.
- Preferably the dredged materials should be used for wetland creation.
- Deep draft (container) ships sail midways through the channel.

3.5 Requirements

Some of the requirements are obvious and can be made at the beginning of the design process.
Other requirements become clear after initial studies and along the design process. This makes the design process truly cyclical.

Functional

- Safe and efficient navigation at the channel should be guaranteed for the next 20 years.
- The proposed alternative should withstand extreme weather conditions, such as extreme rainfall and drought. Frost does not occur in the region for any length of time to freeze the ground, and is therefore non-applicable. Hurricane resistance is not a requirement, since these forces are so great, and the chances for medium to high impact relatively infrequent, that it would be infeasible to design for this condition).

Financial

- The costs of the proposed solution (and its matching estimated maintenance costs) should be lower than the estimated future costs of the current maintenance method, for a period of 20 years. In other words, the net value of the costs (capital and maintenance) of the proposed solution should be smaller than that of the current maintenance activities. (For a period of 20 years)
- The proposed strategy should not have a negative effect on the competitiveness of the Port of New Orleans.

Environmental

- The proposed solution should not exceed the present rate in wetland loss; preferably the loss in wetland area should be reduced to a minimum.
- The proposed solution should not lead to a higher salinity level in the channel than the present salinity level.
- Special precautions have to be taken with the use of certain materials, such as for the prevention of leaching heavy metals or toxic substances.
- The disposal of dredged materials should not cause any serious harm to the environment.

Social acceptable

- The proposed solution should not exceed the present hurricane vulnerability; preferably the hurricane vulnerability to the surrounding parishes should be reduced.

Law

- The construction and operation of the proposed solution should not violate any law within the USA (appendix 14).

3.6 Recommendations

The causes of sedimentation are addressed in chapter 7 (section II), with the available data a fair estimation can be made of the relative dominance between the different possible causes of sedimentation. However for an accurate calculation of the sedimentation rate more data should be gathered on the following natural boundary conditions:

Soil conditions

General

- Grain size distribution of materials on the channel banks and on the channel bottom and of the dredged materials.
- Characteristics of materials on the channel banks and on the channel bottom and of the dredged materials. The following characteristics should be considered:
  - Cohesiveness
  - Grain form
  - Density
  - Angle of repose
  - Critical shear stress

Erosion vulnerability soil conditions

- The relation between the vulnerability to erosion for different prevailing soil types with a fixed current velocity.
- The relation between the vulnerability to erosion for a certain soil type with a variable current velocity.
- Relative compaction between materials on the channel bank and materials on the channel bottom.

Current velocities

Current velocities during extreme weather conditions

- Current velocity during storm surge, open water section and inland reach
- Current velocity during hurricanes, open water section and inland reach

Ship-induced wave height

- The ship-induced wave height of different vessel types.

Data salinity level

- Recent data on the salinity level in the MRGO channel. (Measurement should be carried out at different locations; moreover measurements should be carried out at different water-depths for each location).

Section II Table of contents

4 Shipping analysis

4.1 Introduction

The future amount of ship movements on the MRGO is estimated as one of the key factors in determining the future maintenance dredging costs. The future amount of ship movements is estimated based on historic ship movements.

4.2 Throughput MRGO Channel

Ideally located at the mouth of Mississippi River, the Port of New Orleans has been a center of international trade since 1718. The cargo throughput consists of 30% export versus 70% import [REF W1]. The trade is truly global and the counties of origin are equally represented; Europe 35%, Latin America 33%, Middle East and Asia 27% and a minor part to Africa and Australia (appendix 8).The top three types commodities being transported on the MRGO are farm products, metallic ores & products[1] and crude petroleum, in that order[2].

The peak tonnage year for the channel was in 1978, when 9.4 million tons were reported, along with almost 18,000[3] vessel trips. Annual tonnage throughput has decreased to 5.85 million tons in 2000. Vessel dimensions have increased over the past decades. Therefore the number of trips taking place since 1978 has decreased to a greater extent than the tonnage throughput.

Data[4] are available on the vessels that sail the channel with a pilot from 1998 -2001. The assumption is made that all vessels with a draft over 6 m (20 ft.) use a pilot. Consequently the number of trips[5] can be calculated for each draft, appendix 18. Ship movements during the period 1986-1994 are based on reference15. A summary of vessel trips and frequencies, categorized to draft class, is given in Table 4-1.

Draft class		Annual avg. 1986-1994		Annual avg. 1998-2001	
In meter	In foot	Trips (Per year)	Frequency (Trips/day)	Trips (Per year)	Frequency (Trips/day)
< 6	< 20	3965	10.86	N/A	N/A
6.1 -7.8	21- 25	416	1.14	283	0.77
7.9 -9.4	26-30	488	1.34	304	0.83
9.5 -10.9	31-35	202	0.55	266	0.73
11	36	25	0.07	15	0.04

Table 4-1 Ship movements and frequencies MRGO channel

[1] Steel is the largest handled commodity of the Port; however a significant part of the steel is transported over the Mississippi River.
[2] In the year 1999
[3] Including recreation-ships and fishing boats
[4] Data on the vessels, that sail the channel with a pilot (name, draft, date etc), is provided by Crescent pilots, New Orleans
[5] A vessel sailing from the Gulf of Mexico to the Port of New Orleans and back is counted as **two** trips.

4.3 Trends and forecasts

Appendix 8 shows the trends in the throughput of general cargo and containers. The two-years-average[6] number of ship movements is calculated (Figure 4-1[7]) based on the number of ship movements given in Table 4-1

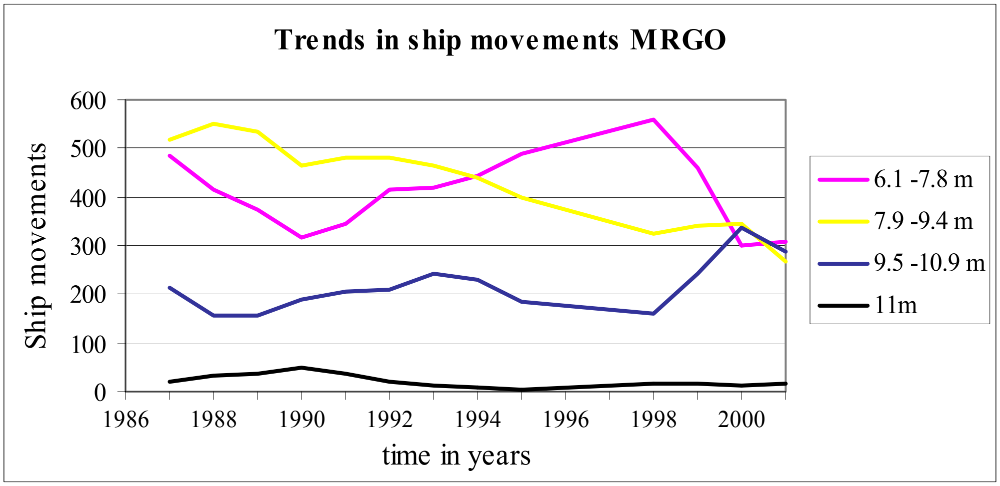

Figure 4-1 Trends in ship movements MRGO

Shipping forecasts require a comprehensive study, based on numerous interrelating factors. A very rough shipping forecast for the MRGO is made based on Figure 4-1 and the following considerations:

- The majority of the throughput on the MRGO channel is international trade. The future ship movements therefore depend heavily on the world economy. In a time of economic slow-down import will decrease and more products are produced domestically. Restrictions on international trade[8] will have a negative effect on the throughput. Throughput on the MRGO is therefore relative vulnerable to changes in the worldwide economy.
- The trend of scale enlargement in the shipping industry is assumed to continue. An increase in throughput (tonnage or TEU) will result in a lower percentage growth of the number of ships.
- The Port of New Orleans deals with competition of the Port of Galveston (Texas), Gulf-Port (Mississippi) and Jackson (Alabama). The assumption is made that the relative competitiveness of the Port of New Orleans remains constant over the next 20 years.

The number of ship-movements on the MRGO channel is not likely to increase or decrease significantly over the next 20 years. A shift from smaller draft-class to larger draft-class can be expected. . However, there is a niche market for the class of vessels using the MRGO, for north-south trade with South America. Many South American ports are unimproved to handle the larger container ships, and Gulf of Mexico trade with western ports of South America is draft limited by the Panama Canal. In addition, medium-class container vessels are economical for these trips.

[6] The two years average number of ship movements (S), for a year x can is calculated as followed; $S(x) = (S(x-1) + S(x))/2$
[7] No data was available for the years 1995 -1997. Figure 4-1 might misrepresent trends for those years.
[8] E.g. trade restrictions on imported steel implied in 2002.

Comparatively, the newer, larger vessels have economic advantage in making relatively longer trips in east-west trade in the world. The assumption is made that the number of ships sailing the MRGO remains relatively constant over the next 20 years.

5 Channel dimensions

5.1 Introduction

Assumptions concerning the dimensions of the channel are important in the design process. The dimensions of the channel have an impact on the maintenance dredging costs. The maintenance dredging costs would be reduced in case the required depth could be decreased.

Moreover the dimensions of the channel have an impact on the salinity level in the wetland area. Therefore a preliminary calculation of the channel dimensions will be made, to verify if the present channel dimensions meet the shipping requirements or could be modified. Table 5-1 gives the original[9] and present[10] channel dimensions.

Section	Depth[11]	Bottom width	Initial Surface width	Surface width	Location
Inland Reach	11.0 m	152 m	229 m	Variable	Mile 65-20
Breton Sound	11.0 m	152 m	229 m	229 m	Mile 19 -0
Bar Channel	11.6 m	183 m	259 m	259 m	Mile 0 -(-10)

Table 5-1 Dimensions of the MRGO

5.2 Assumptions

The required channel dimensions depend on the dimensions of the design vessel. The assumption is made that the draft of the design vessel is 11 m (The second-generation container ships). This assumption is made based on the following three grounds:

- At present the maximum vessel-draft in the channel is 11m (36 ft.). Only 0.5% of the ships that sail the channel have a draft of 11 m (appendix 18).
- The containerized cargo flows to the Port of New Orleans have shown a slowdown in the past years (appendix 8). An explosive growth of container throughput in the Port of New Orleans is not expected.
- No investments in container terminals on the MRGO, which can facilitate over 11 m (36 ft.) containerships, are proposed at the moment.
- The time horizon for this project 20 years, therefore it is not likely that ships with a draft exceeding 11 m will sail the channel.

5.3 Width calculation

[9] Channel dimensions directly after the construction of the MRGO in 1968.
[10] Channel dimensions based on a survey by the USACE in 1996.
[11] Depths are given in meter below Mean Low Gulf (MLG).

5.3.1 Factors

Using the PIANC guidelines the channel dimensions can be calculated. The bottom width of the channel, for straight sections, can be calculated with the following formula:

One way

$W = W_{BM} + \Sigma W_I + W_{Br} + W_{Bg}$

Two ways

$W = 2W_{BM} + 2\Sigma W_I + W_{Br} + W_{Bg} + \Sigma W_P$

W	The bottom width of the waterway
W_{BM}	Basic maneuvering lane
W_I	Additional width for straight sections
W_{Br}	Bank clearance on the “red” side of the channel
W_{Bg}	Bank clearance on the “green” side of the channel
W_P	Width for passing distance

Given the prevailing boundary conditions the channel dimensions can be calculated using the following:

W_{BM} The basic maneuvering lane is calculated by multiplying the vessels’ width by a factor depending on the manoeuvrability of the ship. In this case the manoeuvrability of the vessels is very poor, due to the large vessel dimensions, the shallowness of the MRGO channel and the low speed of the vessels in the channel. A factor of 1.6B will be used.

W_I The factor for the additional width depends on the following aspects:

Normative factors	Conditions	Additional width
Vessel speed	Slow 6 - 10 knots	0
Prevailing cross wind	15 - 33 knots (low)	0.4B
Prevailing cross current	N/A	0
Prevailing longitudinal current	Low < 1.5 knots	0.1B
Prevailing wave heights H_s	$H_s<1$	0
Aids to navigation	Good	0.1B
Seabed characteristics	Smooth and soft	0.1B
Depth of waterway	Depth <1.25T	0.2B
Cargo hazard level	Low	0.0
Total (ΣW_I)		**0.9B**

Table 5-2 W_I Additional width for straight sections

W_{Br} and W_{Bg} Conditions on the starboard (green) side and the larboard (red) side of the channel are equal. The channel has a sloping edge with wide banks and gentle slopes; a Bank Clearance of 0.3B is used for both sides.

W_P The separation distance depends on the vessel speed and the traffic density. A low vessel speed (6-10 knots) gives a factor of 1.2B, and the low density will add 0B; the total W_p is 1.2B.

5.3.2 One way vs. two ways

The choice between the one-way and the two-way channel depends on the frequency of the ship movements. As can be seen in appendix 18, only 15ships with a draft of 11 m (36 ft.) sail the channel per year, a frequency of 0.04 a day[12]. Taking into account only the decisive ship (container ship) a one-lane channel would be sufficient.

The vessel speed in the channel for deep-draft vessel is estimated to be about 6-10 knots (11-18 km/hr). Given the total channel-length of 76 miles (including the bar channel), the sailing time will be approximately 6 to 12 hours. However the sailing time on the Inland Reach is 4-7 hours (length of the Inland Reach is 46 miles).
A consideration should be made for which draft class a single lane would still provide sufficient capacity. The channel width depends on the width of the largest ship for which a double lane is required. The smaller the channel width the smaller the maintenance dredging costs. For the 9.5-10.9 m and 11 m-draft class a single lane would be sufficient with the use of passing points. Even for the classes 6.1-7.8 m and 7.9-9.4 m a single lane could provide sufficient capacity with the use of numerous passing points. However this would increase the sailing time through the channel and this would be unfavorable for the competitiveness of the Port of New Orleans. Therefore the division between one lane and two lanes is made for a draft of 9.5 m.

1. The width of a **one-lane** channel for the decisive container ship:

$W = W_{BM} + \Sigma W_I + W_{Br} + W_{Bg} = 1.6B + 0.9B + 0.3B + 0.3B = 3.1B$
B[13] = 30 m (100 ft.) → W = 93 m (310 ft.)

2. The width of a **two-lane** channel for the decisive general cargo ship:

$W = 2W_{BM} + 2\Sigma W_I + W_{Br} + W_{Bg} + \Sigma W_P = 3.2B + 1.8B + 0.3B + 0.3B + 1.2B = 6.8B$
B = 22 m (70 ft.) → W = 150 m (476 ft.)

3. The width of a **two-lane** channel for one decisive container ship and one decisive general cargo ship:

$W = 2W_{BM} + 2\Sigma W_I + W_{Br} + W_{Bg} + \Sigma W_P = 1.6B_c + 1.6B_g + 0.9B_c + 0.9B_g + 0.3B_c + 0.3B_g + 1.2B_c = 4B_c + 2.8B_g$
B_c (container) = 30 m (100 ft.) and B_g (general cargo) = 22 m (70 ft.)
W = 120 + 61.6 = 182 (596 ft.)

Channel dimensions

The two different decisive ships (the container ship and the general cargo ship) give different requirements for draft and width; three possible combinations are given in Table 5-3.

[12] Annual average over the period 1998 -2001, Table 4-1
[13] The decisive ship dimensions are given in chapter 3, paragraph "assumptions"

Vessels	Draft		Width	
Container ship	11 m	36 ft.	93 m	310 ft.
General cargo + general cargo	9 m	30 ft.	150 m	476 ft.
Container ship + general cargo	9 -11 m	30 -36 ft.	182 m	596 ft.

Table 5-3 Draft and width requirement

The present width of the MRGO (Inland Reach and Breton Sound = 152 m, Bar channel = 183 m) is according to the requirements of a two lane (general cargo ship) channel. However the present dimensions are not sufficient for the passage of two container vessels.

5.4 Depth calculation

The current depth of the MRGO channel maintained to at least 11m as stated on the nautical maps and is required by law (through the Rivers and Harbors Act 1956).
The actual draft is ranging from 11 m up to 12.5 m over a lane of 45 -150 m.
The deepest-draft ship sailing the channel has a draft of 11 m [REF 15]. The required channel depth for an 11m-ship is 11.8 m, given the prevailing boundary conditions at the MRGO, Table 5-4.

Depth factors[14]		Design vessel	
Draft of the design container ship	D	11 m	36 ft.
Tidal influence [I]	-	0 m	0 ft.
Maximum squat due to trim and sinkage [II]	S_{max}	0.5 m	1.5 ft.
Vertical motion due to wave response	R	0 m	0 ft.
Safety margin or net underkeel clearance [III]	m	0.3 m	0.9 ft.
Total		11.8 m	38.4 ft.

Table 5-4 Channel depth calculation

For the calculations of the total depth the following assumptions were used:

I No tidal window will be used therefore the tidal influence will be zero.
II In appendix 19, the squat has been calculated with both the formula of Huuska/Guliev and the formula of Barrass, both gave a squat of 0.5 m.
III m is 0.3 m for a soft muddy bottom [Lit. 6]

5.5 Conclusions

The present dimensions of the MRGO channel meet the requirements. The present width (bottom width) is sufficient for the passage of two general cargo vessels. The depth to which the MRGO channel is maintained meets the requirements.

[14] Depth is given relative to MLLW (- 0.01 ft Mean Low Gulf, MLG)

6 Wetland degradation analysis

6.1 Introduction

In order to create a strategy that is in line with wetland restoration it is vital to understand the processes and activities that are responsible for the wetland degradation.

The wetlands in the state of Louisiana are degrading at dramatic pace. The amount of wetland area that has been lost in the state of Louisiana in the period of 1932 -1990 has been estimated at a total of 2,760 km^2. (690,000 acres or 276,000 hectares, the size of the amount of wetland that has been lost between 1932 and 1990 is twice as big as the Province of Utrecht in the Netherlands)[REF CBS website].
The degradation of the wetland area in the state of Louisiana continues with a rate of 65 to 91 km^2 a year [REF W2] (about 16,000 to 22,400 acres a year).

The following processes and activities are direct or indirectly responsible for the degradation of the wetlands:

- The Delta Cycle
- Levee system
- Oil and gas exploitation
- Channels
- Sea level rise
- Storm surge
- Hurricanes
- Sediment reduction
- Subsidence
- Salt-water intrusion
- Nutria
- Ship-induced waves
- Increased tidal exchange

6.2 Delta cycle

The project area is part of the Mississippi Delta. Each delta is subjected to the complex process of the Delta cycle. In this natural process land is formed and returned to sea. The project area is currently subjected to the third phase of the Delta cycle, the “Transgressive barrier island arc”, in which erosion is taking place at the landward side of the barriers islands. Under natural conditions, the erosion is slow and mainly driven by large storms and subsidence. The construction of the MRGO channel has accelerated the Delta cycle significantly. More background on the Delta cycle can be found in appendix 6.

6.3 Levee system

After the great flood of 1927, serious measures were taken to protect people in the area against the forces of the Mississippi River. The construction of levees along the riverbanks of the Mississippi has ended the natural flooding process. Consequently preventing sediments, carried by the Mississippi River, to settle along the banks. The elevation of land through sedimentation, which is also part of the Delta cycle, was stopped and the area was subjected to subsidence.

Moreover the presence of levees prevents the supply of fresh water to the wetland area surrounding the Mississippi River. The equilibrium between the fresh water supply and the saltwater intrusion has been disturbed, resulting in a significant increase in salinity level.

6.4 Oil and gas exploitation

After the discovery of oil in the area, the exploitation of oil and gas has increased significantly. This had a negative impact on the environment through waste[15] and hindrance. Moreover have the exploitation of oil and gas contributed to the construction of numerous small oil and gas field access **channels** and direct **subsidence** of the area.
The excavated materials were cast on each side of these canals, resulting in the creation of spoil banks. A significant density of oil and gas canal webs appeared in many locations in coastal Louisiana. Besides direct removal of wetlands by canal dredging, the spoil banks effectively segmented and isolated many patches of wetlands. Within the wetland interiors completely closed in by spoil banks, the hydrology was significantly altered. These wetlands eventually died or are presently dying, in conversion to shallow open water. Another adverse impact of the oil and gas canals is that they effectively increased the edge surface area for erosion of the wetlands [REF USACE].

6.5 Channels

Before the construction of the MRGO channel in the late 1960's, numerous small channels had been dredged. These channels were constructed mainly for the exploitation of oil and gas activities, navigation, and drainage. To a lesser extent, waterways were improved to support recreational and commercial fishing activities. The construction of channels led to direct wetland loss, since excavated lands were replaced by water. Moreover, systematic development of these waterways caused higher salinity levels and increases in current velocities. Increases in current velocities in turn result in higher erosion rates. (However this effect is negligible compared to other causes of erosion).

6.6 Sea level rise

As a result of the global warming, influenced by the greenhouse effect, the total liquid water mass in the oceans has expanded. Moreover global warming causes the parts of the ice mass at the North Pole and Antarctica to melt. The combined effect of an increase in volume and expansion of the water mass causes the sea level to rise. This sea level rise can cause vegetation to become submerged for ever-greater time periods. The situation has become exacerbated in existing conditions, where river sediments no longer are able to nourish the wetlands and maintain a constant rate of vertical accretion. Marsh vegetation can only survive in a limited water depth, so sea level rise leads to wetland losses in the existing conditions.

[15] The assumption is made that the oil and gas exploitation has not influenced the water-quality significantly in the long term, relative to other causes of coastal losses. Consequently it is plausible that the wetland-vegetation has not deteriorated to a concerning extent as a result of pollution caused by the oil and gas exploitation.

6.7 Storm surge

During storm conditions the water level can increase significantly, especially in combination with high tide. The rise in water level often begins with a local atmospheric low-pressure area that lifts the water surface [REF 4]. The winds, which blow in the direction of the low pressure point, increase the water level even further. Depending on the wind direction the storm surge may move towards the coast (this is called positive storm surge) and flooding might occur [REF 4]. The forces exerted by these storm surges can cause the relatively fragile marsh to break up. When the water level decreases after the storm surge, the fragile marshes and floating vegetation can drift to sea along with the currents. When the storm surge reverses in seaward direction, it is termed negative storm surge As a result of this condition, water levels in the wetlands decrease and areas normally underwater become exposed to direct sunlight and air. In extended periods where drying of the substrate might occur, marine organisms have the potential to perish.

6.8 Hurricanes

Hurricanes can have an even more devastating effect on the wetlands. Most Atlantic hurricanes originate in the southern Atlantic Ocean, off the coast of Africa, in the months of June through November [REF W 24].
During this season, winds off the west coast of Africa sometimes converge, circulating counterclockwise. When water temperatures are warm enough and atmospheric conditions are correct; the wind speeds increase and begin to form around the eye. Hot, moist air from the ocean is pulled up into the eye of the storm and as the air rises and cools; moisture condenses and is released as heavy rain into the turbulent winds circling the eye. The released energy is pumped into the rotating cloud mass, making it rise and spin even faster. By the time the winds reach speeds of 119 km/h (74 mph), the storm has become a hurricane. During a hurricane the storm surge can reach a devastating height of 7.6 m (25 ft) above sea level [REF W 24]. The hurricanes cause marshes to break and areas of marsh are converted into open water. Although hurricanes have a direct devastating effect on the vegetation, they can bring a lot of sediments from the shallow fore shore to the wetland area [REF W 24]. These sediments may get distributed into the wetlands, which can mitigate the effects of subsidence in the short term. A significant amount of liberated sediments, being of relatively light and fine character, are carried out of the system to sea with the ebb tides.
The wetland areas are believed to dissipate the forces of a hurricane and can therefore lessen the impact of hurricanes on the municipalities in the state of Louisiana. Research has shown that for every 1.6 km (1 mile) of vegetative wetlands, storm surge height can be reduced by 0.3 m (1 ft.)[REF W5].

6.9 Sediment reduction

The construction of levees has reduced the amount of sediments that can migrate and settle into the wetlands. The subsidence could no longer be compensated by a natural increase of bed level driven by the sediment accumulation.

6.10 Subsidence

Subsidence occurs when the weight of topsoil-layers compresses the earth below. This process was always offset by new accumulations of sediments. When the increase in

bed level was stopped, as a consequence of the sediment reduction, the effects of subsidence became clear.
The combined effect of sea level rise, subsidence and sediment reduction has caused vegetation to drown, since the marsh vegetation can only survive in a limited water depth.

6.11 Salt-water intrusion

Before the construction of the MRGO channel the wetland area was filled with fresh to brackish water. A balance had been formed between the fresh water supply from the Mississippi River and the salt water intrusion from the Gulf of Mexico. As indicated above the supply of fresh water from the Mississippi was prevented by the construction of levees. Moreover the construction of the MRGO channel made a direct connection between the Gulf of Mexico and the wetlands. Salt water from the Gulf of Mexico could now enter the wetlands directly and rainfall was drained to the Gulf directly. Both effects resulted in a change from fresh/ brackish conditions into a brackish/salt water environment. The salinity level (chlorides, in parts per thousand, relative to water) increased from 2.4 -3.85 p.p.t to 5.5 -13.1 p.p.t [REF 15 & 46]. Much of the original wetland vegetation died because of this increased salinity level, resulting in bank-line erosion. Salinity changes also led to conversion of original wetlands to saline marshes.

6.12 Nutria

The nutria, a chisel-toothed creature with the size of small dog, was introduced in the wetlands in the 1930's. The nutria, originally from Argentina, were kept domestically, but they escaped or were intentionally released into the wetlands. Their numbers have been kept stable as they were hunted for their fur. After the fur prices dropped in the 1980's their numbers have increased dramatically, up to densities as high as 49 animals per hectare (20/acre) [REF 18]. The nutria forms a serious threat to the wetlands as they aggressively eat vegetation. The average weight of mature nutria is 5 -7 kg (12-16 pounds) and the nutria can consume 1-2 kg (3-4 pounds) a day of vegetation. The Louisiana Department of Wildlife and Fisheries has identified (through aerial surveys)[REF 18] thousands of hectares of marsh where nutria have removed all vegetation.

6.13 Ship-induced waves

The large container vessels that sail the MRGO channel cause very large quantities of water displacement. This water displacement results in a local water level rise in front of the ship. Large quantities of water are displaced over the channel banks into the surrounding marshes. As explained in appendix 20, a return current arises along the ship with the accompanying water level depression. This water level depression sucks the water from the surrounding marshes back into the channel. The forces exerted by these rapid and extreme water level fluctuations cause the marshes to deteriorate. Moreover the destroyed marshes are carried into the channel, where they cause sedimentation

6.14 Increased tidal exchange

The construction of the MRGO channel has created a direct link between the wetlands and the Gulf of Mexico. The currents of the diurnal tide penetrate the wetlands through the MRGO channel. The effect of a larger tidal exchange on the wetlands is two-fold; higher current velocities and a higher salinity level. Both effects directly and indirectly induce erosion.

Figure 6-1 gives the qualitative relations between the causes and effects of the wetland degradation.

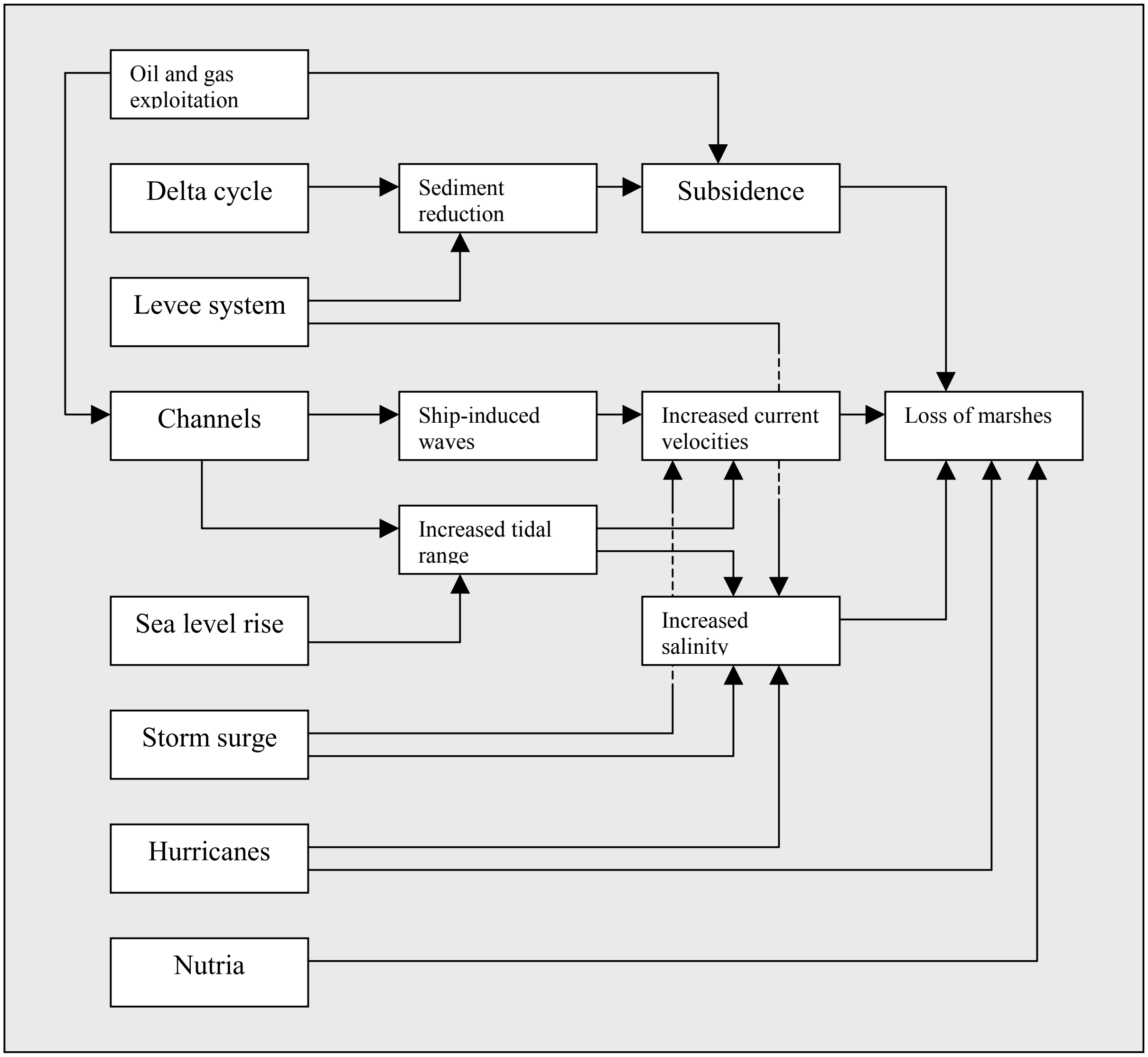

Figure 6-1 Causes of wetland degradation

6.15 Countermeasures

An overview of the different causes of the wetland degradation has been rendered in the preceding text. next step is to determine which of the causes are dominant and which of the causes can be dealt with in order to reduce the wetland degradation. Some of the causes have similar counter measures; a categorization is made according to:

6.15.1 Natural and inevitable events

Phenomena such as hurricanes and storm surges can have a devastating effect on the wetlands. A hurricane such as Hurricane Andrew (mid-August 1992) can result in a loss of wetland of 65.6 km^2 (25 square miles) [REF W24]. However hurricanes and storms simply occur and no measures can be taken to protect the wetlands against them. The sea level rise is part of a global problem and no local measures can be taken against it. Subsidence, which occurs as a consequence of the natural Delta Cycle, should be seen as inevitable.

6.15.2 Unfeasible countermeasures

The exploitation of oil and gas is vital for the local and national economy. The subsidence, caused by minerals extraction from the subsurface, can not be prevented. The levee system has been constructed to protect the residents in the surrounding area against flooding. Protection against flooding with an alternative system would be complex and expensive, and there is no interest in local inhabitants to relocate out of flood-prone areas.

6.15.3 Effective countermeasures

Closing some of the numerous channels in the project area can reduce the increased salinity level and increased tidal exchange. Some of the small channels have become useless or have low use, and can be closed with relatively low economical side effects. This may be a challenge in some cases, where from the social perspective; the few users of these waterways are very vocal to retain their usage. The canal system as a whole should be reviewed for efficient restructuring, considering societal desires, for reducing the amount of bank erosion. Bank protection works can be constructed to reduce the erosion caused by ship-induced waves. Some measures can be taken to limit the salt-water intrusion, such as sluices or air bubble curtains. The explosive growth of the Nutria population can be reduced by hunting.

The causes with matching impact, along with a judgment on the feasibility of respectively corresponding countermeasures, are given in Table 6-1:

Cause	Impact	Counter measures
The Delta Cycle	Large	Impossible
Oil and gas exploitation	Small	Complex and expensive
Levee system	Large	Complex and expensive
Sea level rise	Small	Unfeasible
Storm surges	Large	Impossible
Hurricanes	Large local impact	Impossible
Canals	Large	Feasible
Nutria	Large	Promising
Increased tidal exchange	Large	Complex / feasible
Ship induced waves	Large local impact	Feasible
Sediment reduction	Large	Complex / feasible
Subsidence	Large	Unfeasible
Salt water intrusion	Large	Complex / feasible

Table 6-1 Causes and impact of the wetland degradation

7 Sedimentation rate analysis

7.1 Introduction

The average annual amount of maintenance dredging gives an indication of the average sedimentation- or shoaling rate. In order to address the root causes of the maintenance cost it is vital to understand the causes of sedimentation along different locations of the channel.

Locations with a high frequency of maintenance dredging can indicate a high local shoaling rate. However the average annual amount of maintenance dredging and the average annual sedimentation rate are not necessarily equal. Two major effects have to be taken into account:

1. Certain sections of the channel are maintained more intensively and to greater dimensions than others. The frequency of dredging operations by reach is in relation to prevailing, observed sedimentation rates. The amount of overdredging that is conducted is related to the degree a given reach is exposed to periods of extreme sea conditions, where there is potential for events of greatly-accelerated channel shoaling. Here, overdredging provides storage for events of accelerated sediment deposition, without loss of navigable dimensions for shipping. In general, reaches of related character in channel maintenance are: mile 66 to 38 (low frequency and no over dredging); mile 38 to 27 (moderate frequency and some over dredging); mile 27 to 0 (high frequency and overdredging required); and mile 0 to –10 (very high frequency and overdredging required). Channel maintenance in the upper most reach has been significantly diminished for many years, due to overdredging conducted once many years ago for borrow to construct hurricane levees. It is highly unlikely that borrow in this manner would be acceptable in the future, due to the overall societal and environmental concerns of the region [REF USACE].
2. Differences in dredging execution methods and in sediment characteristics result in a different correlation between the shoaling-rate and the average maintenance-dredging rate, due to differences in water-content of the dredged materials.

Between miles 65- 46 the channel was dredged to an average depth of 17 m (55 ft.) below M.S.L. for the construction of a hurricane protection levee. The channel is maintained to a depth of around 12.2 m (40 ft.[16]) therefore maintenance dredging is not (yet) required for this part of the channel. However the fact that the section is dredged relatively infrequently does not mean that the shoaling rate is negligible small for this section. However at most locations the dredging frequency and degree of overdredging is small for reaches of related character and differences between average annual amount of maintenance dredging and the average sedimentation rate are leveled out in time.

Different dredging execution methods result in a different water-content in the dredged materials. For example when dredging is carried out with a dustpan dredger or a cutterhead dredger the dredged materials will have a higher water-content than

[16] Minimum draft of 36 ft. is required, at most locations the channel is dredged to 40 ft.

with a suction hopper dredger[17]. Sediment characteristics also play a role in the water-content of the dredged materials (appendix 24). A relative higher water-content results in higher volumes of dredged materials for an equal shoaling-rate.
In this chapter the average annual amount of maintenance dredging is used to give an **indication** of the average sedimentation- or shoaling rate. Differences in the amounts of dredged materials are used to explain possible differences in the shoaling rate. The following assumptions were made:

1. The amount of under/overdredging is negligible over a long time period.
   (This assumption does **NOT** hold for miles 65 -45, where the channel is over dredged to 17 m (55 ft.) for the construction of a levee).
2. The dredging execution method is constant within each different section.
   (Inland Reach; Cutterdredger, Breton Sound and Bar Channel; suction hopper dredger)
3. The sediment characteristics (water-content in the dredged materials) are constant within each different section.
   (This assumption does **NOT** hold for miles 45- 49) [18]

[17] Sediments in the dredged materials settle in the “Beun” of the ship resulting in a relative lower water content.
[18] Miles 45 - 49 have a significant higher clay percentage than the average over the channel length and the third assumption will **not** hold for this part of the channel.

Data are available on all maintenance dredging operations on the MRGO over the period 1970-2001. These data have been categorized to year and location, appendix 39. Figure 7-1, derived from the data listed in appendix 39, shows the maintenance dredging operations along different locations. The columns represent the accumulated amount of dredged materials at a certain location[19] over the period 1970-2001. Figure 7-1 will be used to address the root causes of the sedimentation and to explain possible differences in the shoaling rate.

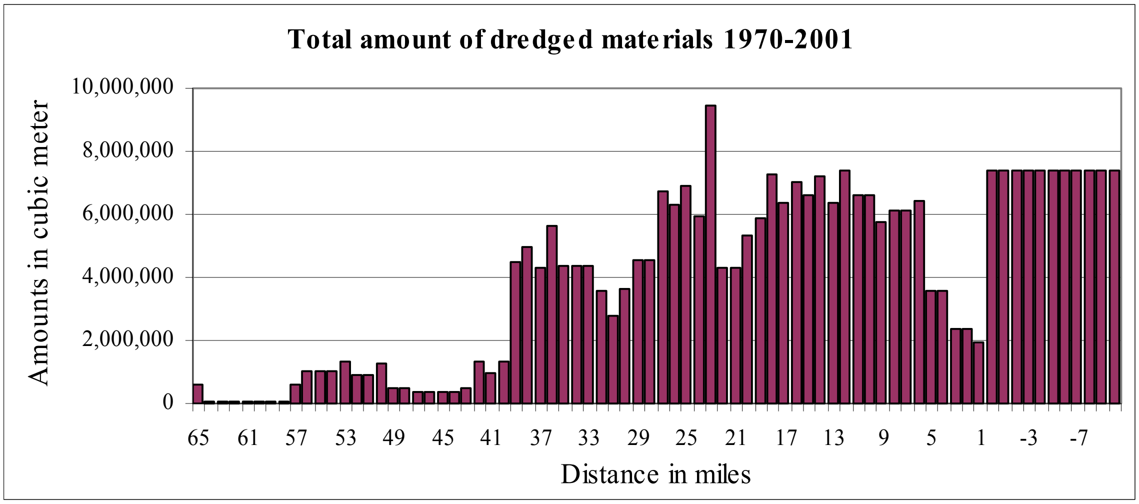

Figure 7-1 Total amount of dredged materials, maintenance dredging 1970-2001

Sections	Location	Conditions
Inland Reach	Mile 66-20	Inland
Breton Sound Reach	Mile 20-0	Open water
Bar Channel Reach	Mile 0- -10	Open water

Table 7-1 Sections of the MRGO channel

For the interpretation of Figure 7-1 the following should be considered:

- No further specification to location was made for the dredging operations in the Bar Channel, in the available data. Therefore the sedimentation rate in the Bar Channel appears to be constant. Most likely this is not the case. The depth of the surrounding shoals decreases drastically as the MRGO progresses from mile 0 to -10. Therefore the actual sedimentation rate will deviate from the constant rate shown in Figure 7-1.
- Between miles 65- 46 the channel was dredged to an average depth of 17m (55 ft.) below M.S.L. for the construction of a hurricane protection levee. The amounts dredged for this hurricane protection levee are **not** included in the amounts of maintenance dredging.

[19] The amount of dredged materials is per mile of channel length.

7.2 Causes of sedimentation

The sedimentation in the MRGO is a function of a complex system of different and interacting factors. First a division can be made according to the possible sources of the sediment. Possible sources of the sediments are:

- Mississippi River
- Wetland areas surrounding the MRGO
- Open water section (Breton Sound)
- Channel banks

Consequently a division can be made according to the causes of sedimentation. Some of the causes of the sedimentation are correlated to the causes of wetland degradation, as described in chapter 6.
Possible causes of the sedimentation are (Figure 7-2):

- Current velocities (tidal, ship-induced, hurricane and storm conditions)
- Changes in local geometry
- Changes in salinity level (salt water wedge)
- Wave attack on the channel banks (wind-induced, ship-induced)

Differences in local soil conditions can have a significant impact on the sedimentation rate. Although not solely a cause of sedimentation, localized soil conditions are included to explain differences in local sedimentation rate.

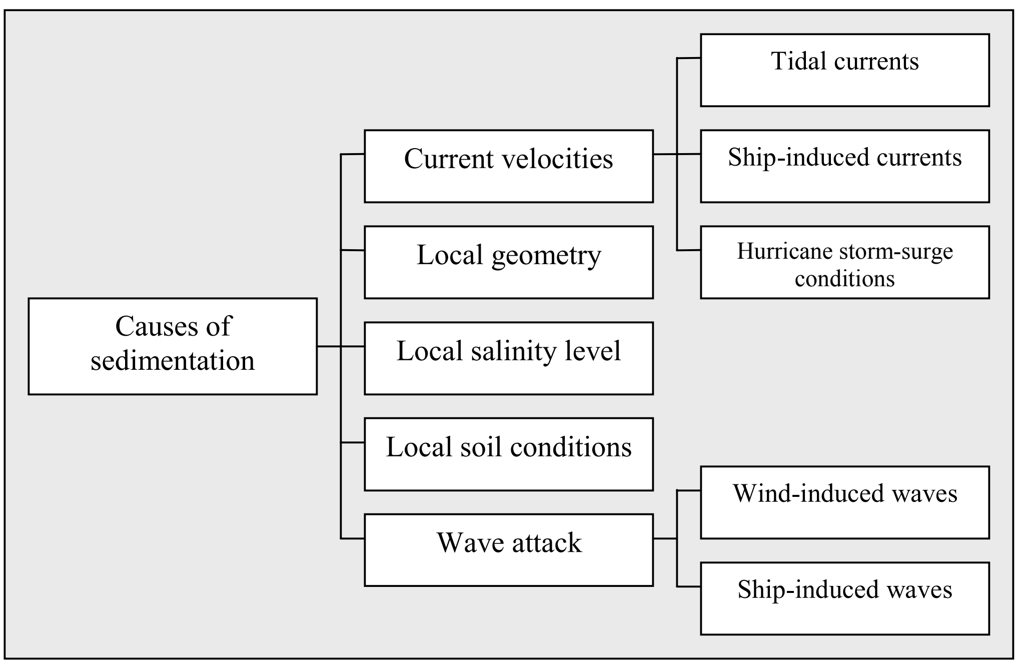

Figure 7-2 Causes of sedimentation

The different sources of sediment and causes of sedimentation can be matched according to Table 7-2.

Source Cause	Mississippi River	Wetland areas	Open water section	Channel banks
Tidal currents	X	X	X	X
Ship-induced currents		X		X
Hurricane /storm-surge		X	X	X
Local geometry	X	X	X	X
Local salinity level	X	X	X	X
Local soil conditions				X
Wind-induced waves				X
Ship-induced waves				X

Table 7-2 Matrix sources and causes sedimentation

Not all different possible combinations of source and cause are analyzed. To simplify the analysis certain combinations are analyzed as one.
To address the root causes of sedimentation the following causes, sources or combinations of cause and source are analyzed (marked with an “x” in Table 4-1):

- Bank erosion caused by ship-induced waves/currents (Paragraph 7.2.1)
- Bank erosion wind induced waves (Paragraph 7.2.2)
- Erosion caused by hurricanes (Appendix 24)
- Sediments carried by the Mississippi River (Appendix 24)
- Currents (Paragraph 7.2.4)
- Tidal intrusion (Appendix 24)
- Variations in salinity level (Appendix 24)
- Soil conditions (soft/firm marsh, swamp) (Appendix 24)
- Change in local geometry (Appendix 24)
- Miscellaneous effects (Appendix 24)

Some of these phenomena have an influence on the sedimentation rate only locally, while others have an influence over a larger section of the channel. This chapter and **appendix 24** give a general background on the different phenomena that could have an effect on the sedimentation rate. An indication is given which of the phenomena are dominant and which are negligible, in order to address the root causes of the sedimentation in the MRGO channel.

7.2.1 Bank erosion by ship induced waves/currents

The deep-draft container vessels that sail the MRGO channel cause large quantities of water displacement (appendix 20). This water level depression sucks the water from the surrounding marshes back into the channel. The forces exerted by these rapid and extreme water level fluctuations cause the marshes to break, resulting in sedimentation in the channel.

The ship-induced waves and the return currents are also responsible for direct erosion to the unprotected channel banks. Figure 7-3 indicates the impact on the channel bank by the ship-induced waves and the return currents. This bank erosion results in sedimentation in the channel.

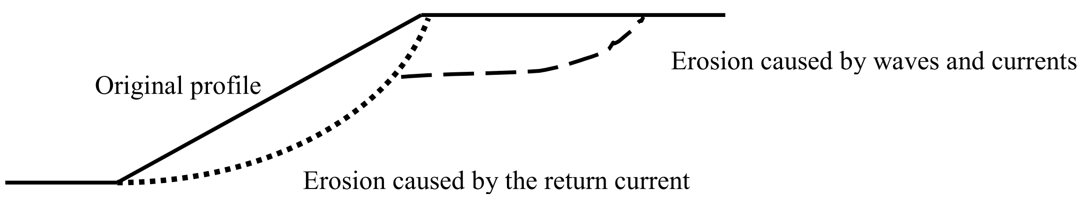

Figure 7-3 Bank erosion caused by wave and current action

In general either the waves or the return currents, induced by a particular ship, are responsible for the erosion; the influence of ship-induced waves will diminish as the return current and the water level depression increase. In other words, fast sailing ships are responsible for the biggest wave attacks along the channels' banks. The large, slower moving, container ships are responsible for a relative larger (return) current attack.

The relative dominance between the wave and current attack has been addressed using the model DIPRO (DImensioning PROtections), appendices 22 and 23. The required D_{50} of a bank protection was calculated both for the wave and the current attack, appendix 23. A larger grain size is required to protect the channel bank against the wave attack compared to the current attack. The conclusion can be drawn that the wave attack is **dominant** over the current attack.

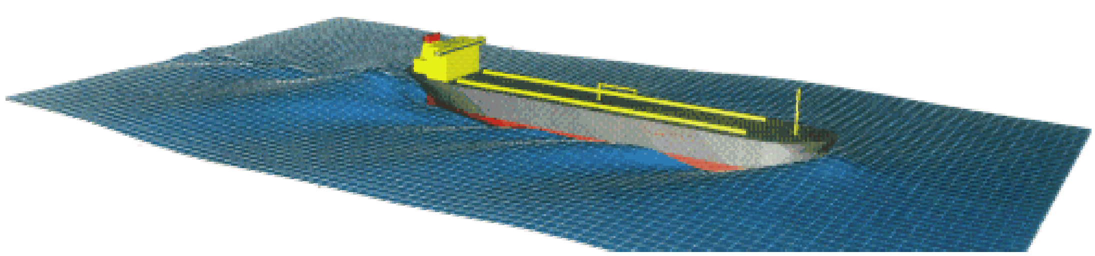

Figure 7-4 Impression of the ship-induced wave pattern (**PICTURE COPIED FROM** [ref W45])

7.2.2 Bank erosion by wind induced waves

In general bank erosion can occur when wind-induced-waves attack an unprotected channel bank. At the MRGO the wave height of wind-induced-waves is significant lower (in the order of 0.15 -0.35 m, paragraph 3.2.3.3.) than the wave height of the ship-induced-waves (in the order of 1.2 m [REF USACE]).
However the wind-induced-waves attack the channel bank with a higher frequency than the ship-induced-waves. Most likely the wind-induced-waves contribute to bank erosion at the MRGO, however their influence is unknown.

The load of the wind-induced-wave attack on the channel banks is determined by the fetch-length, the wind-duration, the wind-speed and the waterdepth. The decisive wind-duration, wind-speed and waterdepth are relative similar for all locations on the MRGO. For certain locations along the South Bank of the channel a significant higher fetch length should be considered.
If locations with a high fetch length would have endured more bank erosion[20] compared to locations with a low fetch length (over the period 1964-1996), the conclusion can be drawn that wind-induced waves are not negligible in the bank erosion process.

A survey was done by the USACE in 1996 to address the bank-line retreat. The amount of bank erosion (over the period 1964-1996) has been estimated based on aerographical pictures from this survey and data on the average water depth; the results are shown in appendix 25.

[20] Assuming all other aspects that have an effect on the bank erosion constant for this comparison

According to ref 41 (CUR manuals 200 and 201) the effective fetch (Fe)[21] length has been calculated for each location along the South Bank of the channel. Figure 7-5 shows the amount of bank erosion for each location along the South Bank and whether the effective-fetch length (Fe) is smaller or larger than 0.8 km.

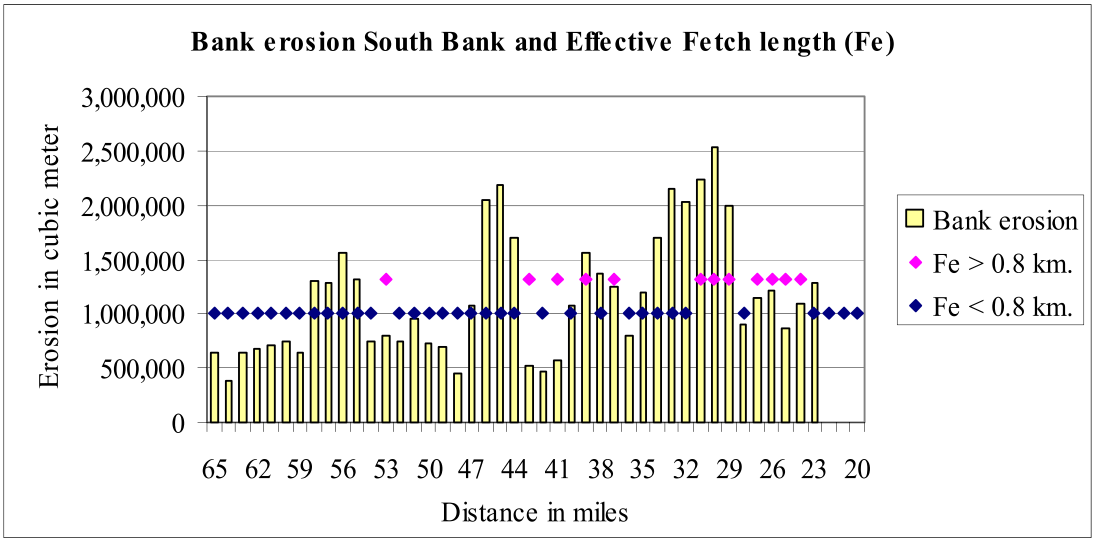

Figure 7-5 Bank erosion and effective fetch length

The average amount of bank erosion is 1.0 million m^3 (over the period 1964-1996) for locations with an effective fetch length (Fe) smaller than 0.8 km and 1.3 million m^3 for a fetch length larger than 0.8 km (represented by diamonds shown in Figure 7-5).

Locations with a significant higher wind-induced wave attack (locations with a high effective fetch length) have endured more bank erosion than other locations. This would lead to the conclusion that bank erosion is caused by ship-induced-waves and wind-induced waves. However the relation between the effective fetch length and the bank erosion is weak.

A rough estimation of the theoretical bank line retreat by ship-and wind-induced waves has been carried out to verify the relative dominance between the ship- and wind-induced wave attacks, appendix 37.
The theoretical bank-line retreat can **not** be calculated with accuracy due to limited data on the local soil characteristics and ship-induced wave height. However it gives an indication on the relative dominance between the ship- and wind-induced wave attacks.

Based on the estimations from appendix 37 it his highly plausible to conclude that the ship-induced wave attack is dominant over the wind-induced wave attack.

[21] The effective fetch length (F_e) for a certain location is equal to the weighted average of the projections $R(\alpha_w)$ of the wind-direction of all different fetch lengths in all directions α_w.
$F_e = (\Sigma\ R(\alpha_w)\cos^2\alpha_w) / (\cos\alpha_w)$.

7.2.3 Influence of bank erosion on the sedimentation rate

Based on the preceding analyses and interpretations, the impact of the bank erosion on the sedimentation rate is estimated. First the amount of materials eroded from the channel banks, over the period 1964-1996, is estimated. Secondly the total amount of sedimentation in the channel, over the same period, is derived. Consequently a rough indication can be given to what extent the sedimentation is caused by bank erosion.

Amounts of eroded materials

The initial surface width, of 228 m, has increased due to continuous erosion, while the bottom of the channel was maintained at a width of 152 m. The surface width after bank erosion ranges from 366 m to 533 m. Appendix 25 gives details on the bank-line retreat, caused by ship-induced waves and currents.

Given the bankline retreat and the average depth in the eroded foreshore the corresponding amount of bank erosion can be calculated. A calculation of the amount of bank erosion is made with the following assumptions:

1. The slope of the eroded foreshore is constant. This is not the case under normal conditions and this simplification is only made for a rough estimation.
2. The volume of eroded materials will increase with **100%** as the materials settle and form a fluid mud.
   (This assumption does **NOT** hold for miles 45- 49) [22]

The materials from the channel bank will settle at the channel bottom and consolidation will occur. However the consolidation process progresses slowly and settled materials remain in suspension. This fluid mud has a significant water-content; 30% - 70% of the dredged material is water, depending on the sediment characteristics [REF USACE]. In other words the amount of dredged materials will be larger than the amount of eroded materials, since a part of the dredged materials is water. The accompanying volume increase is assumed to range between 0% and 300%[23], depending on the sediment characteristics. To simplify the analysis the volume increase is assumed 100%[24]. Clay particles however take more time to settle, and remain in suspension for a long period of time[25]. Therefore a larger percentile volume increase can be expected between eroded and dredged materials for locations with a high clay percentage (more details in appendix 24).

The amount of bank erosion is calculated using a spreadsheet; the results are shown in appendix 25. The bank line retreat is higher at the North Bank than at the South Bank in general. The North Bank erodes with an average annual bank line retreat of 5.5 m a year. The South Bank erodes with an average rate of 3.6 m a year. However the average level above M.S.L of the South Bank is higher than that of the North Bank. Consequently every meter of bank line retreat will result in significant higher values of bank line erosion at the South Bank compared to the North Bank.

[22] Miles 45 - 49 have a significant higher clay percentage than the average over the channel length and the second assumption will **not** hold for this part of the channel.
[23] Assuming an original water-content of 5% - 45% for the materials in the channel banks.
[24] A water content 20% at the channel bank and a water content of 60% in the dredged materials
[25] Differences in fall velocity and chemical characteristics between clay, silt and peat particles result in a different consolidation rate.

Figure 7-6 gives the ratio between the amount of bank erosion at the South and North Bank. Materials eroded from the South Bank are 60% of the total bank erosion.

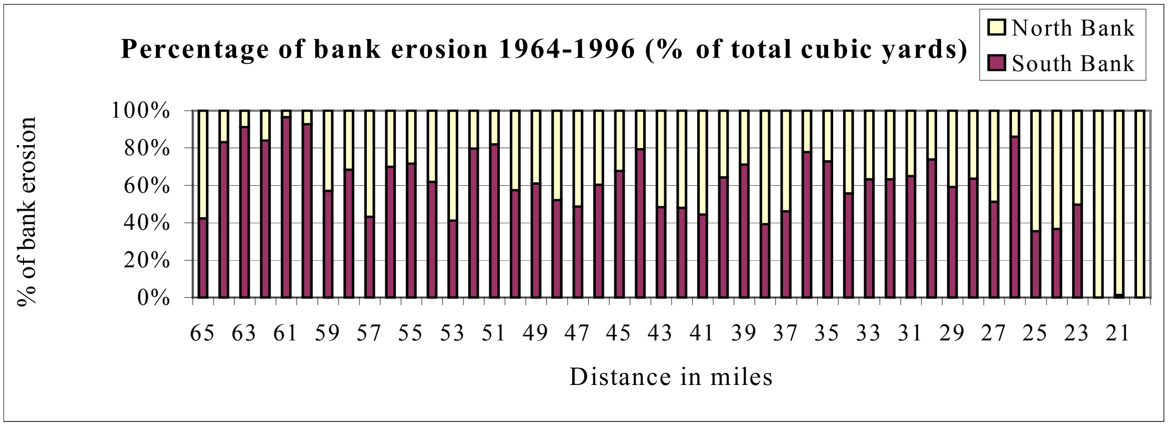

Figure 7-6 The distribution of bank erosion between the South and North bank 1964-1996

Amounts of dredged materials

The average annual amount of maintenance dredging gives a good indication on the average sedimentation rate. The average annual amount of maintenance dredging and the average annual sedimentation rate are not necessarily equal. Certain sections are usually maintenance dredged, while upper reaches were once overdredged (for borrow to construct levees). The borrow operation was conducted once many years ago, and effectively equated to an extreme level of advanced maintenance. Years of sedimentation has consumed all storage originally created by the borrow event. When the body of historical dredging data are viewed over a sufficiently long time period, any differences in dredging between borrow reaches and non-borrow reaches are leveled out.

Since the construction of the channel regular maintenance dredging has been carried out and data are available on the amounts and the corresponding locations.

Figure 7-7 shows the accumulated amount of dredged materials and the amount of bank erosion at a particular location.

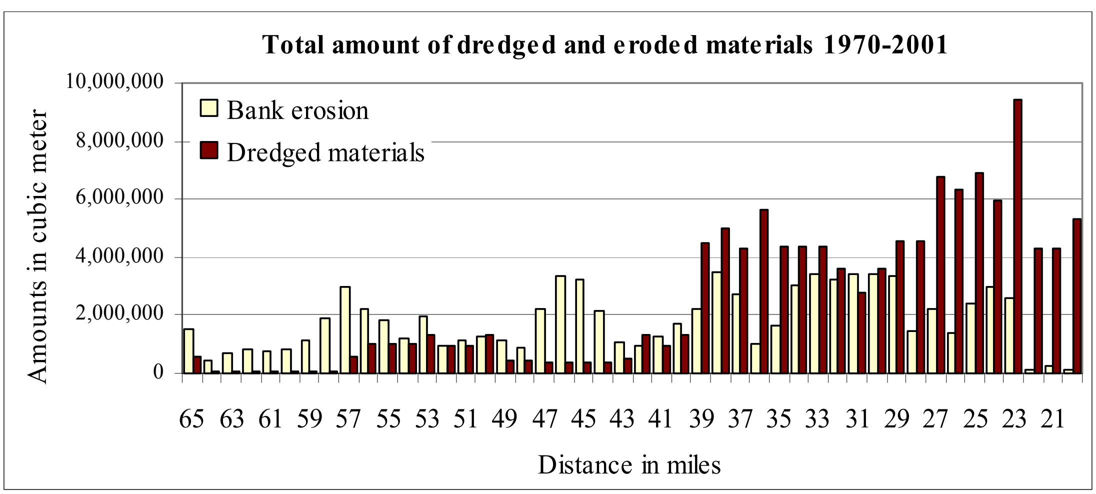

Figure 7-7 Total amount of dredged and eroded materials

Conclusion
The conclusion can be drawn that the bank erosion is responsible for a major part of the sedimentation in the channel. At some locations the channel bank erosion is clearly the dominant cause of sedimentation. However other phenomena play a role in the sedimentation-processes in the channel.

7.2.4 Cross currents
In the open water section the MRGO progresses through the flats surrounding the Breton Sound and the Bar Channel. The sedimentation rate in this part of the section depends mainly on the prevailing currents. The currents can be categorized into:

- Tidal currents
- Wind induced currents
- Longshore currents
- Density currents
- Ship induced currents

Tidal currents
The tidal wave progresses from the Gulf of Mexico into the Breton Sound through the tidal inlets between the barrier islands. The velocities of these tidal currents depend on the water volume that passes these inlets each tidal cycle. This water volume (tidal volume) depends on the tidal range and the magnitude of the tidal basin.

The tidal range in the Breton Sound section is 0.4 m. This small tidal range combined with the large tidal basin results in significant tidal currents. In Figure 7-8 a sketch[26] of the flood current pattern is given.

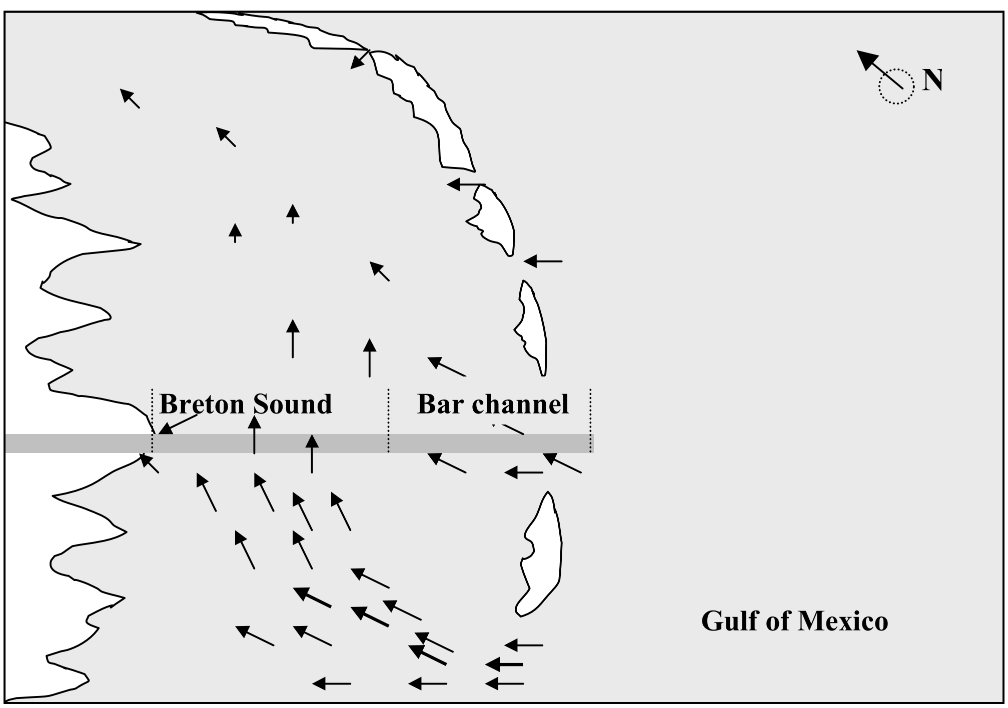

Figure 7-8 Expected **flood** current pattern open water section

[26] This sketch is made based on common hydraulic engineering sense, since insufficient data was available on the currents in the Breton Sound section. This sketch might therefore misrepresent the actual flood pattern.

The tidal currents progress in the same direction as the MRGO alignment between the Chandeleur Islands. At this location the amount of sedimentation caused by tidal currents is expected to be relatively low[27].

Wave induced currents
The Chandeleur Island chain protects Breton Sound against waves formed in the deep waters of the Gulf of Mexico. The prevailing wind-induced-wave-heights are small. The form of the coastline, consisting of numerous small estuaries and islands, indicates that the tidal currents are dominant over the wave-induced currents. The longest possible fetch-length within the Breton Sound is 40 miles.
The combination of this fetch-length and the shallow waterdepth in the Breton Sound (ranging from 1.5 -7 m) results in a significant storm surge during storm conditions. In turn this storm surge induces currents, with accompanying sedimentation in the channel.

Longshore currents
In general longshore currents are driven by wave activity and tidal currents. A longshore current is most likely present at the seaward side of the Breton and Chandeleur Islands. This longshore current has effect on morphological processes affecting the Breton and Chandeleur Islands. At the location where the MRGO channel and the longshore currents intersect the shoaling rate is significantly higher.

Ship induced currents
Ship induced currents cause erosion to unprotected channel banks (paragraph 7.2.1). Screw induced currents can cause erosion to the under-water parts of the channel slope. However the part of the channel bank below the topsoil layer has been stable over the period 1970- 2001 [REF 46] and sedimentation caused by ship screw induced currents is negligible.

[27] However the sedimentation rate around the barrier islands rim is high due to the presence of a longshore current.

7.2.4.1 Sedimentation and waterdepth

Sedimentation in a trench, as is the case for the open water section of the MRGO, mainly depends on the abrupt change in waterdepth between the trench and the surrounding flats.

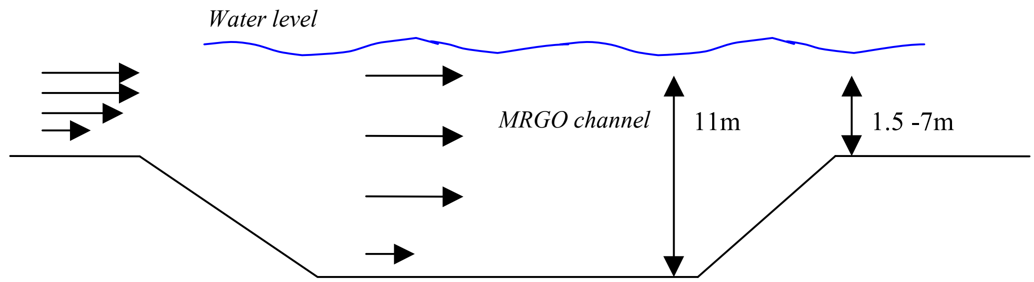

Figure 7-9 Cross current open water section MRGO

When a current (tidal, longshore or wind-induced) crosses a channel perpendicular the water velocity will decrease as the waterdepth increases[28], Figure 7-9. This rapid decrease in current velocity has significant impact on the bed load sediment transport[29]. The theoretical sedimentation rate increases as the depth difference between the channel and the surrounding flats increases. Figure 7-10 shows the difference in waterdepth between the MRGO and the surrounding flats (left) and the amount of dredged materials per mile.

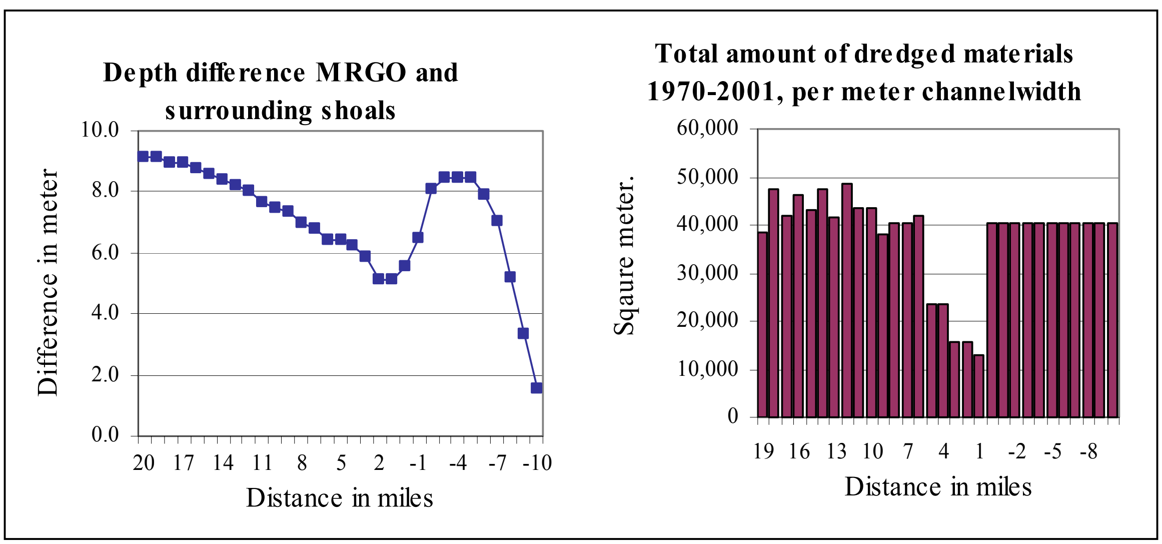

Figure 7-10 Depth differences and sedimentation rate

The actual sedimentation rate (derived from the amount of materials dredged) in the Breton Sound and the Bar Channel shows the same pattern[30] as the depth difference, which is in conformity with the theoretical expectations.

[28] The same amount of water through a larger cross-section results in a lower current velocity.
[29] The bed load sediment transport is determined almost exclusively by the local velocity and the bed shear stress conditions.
[30] No further specification to location was made for the dredging operations in the Bar Channel, in the available data. Therefore the sedimentation rate in the Bar Channel appears to be relatively constant. The actual sedimentation rate will deviate from the quasi-constant rate shown in Figure 7-10.

7.3 Conclusions

Sedimentation in the MRGO channel is a function of different and interacting sources of sediment and causes of sedimentation.

Bank erosion, by ship-induced waves, is the dominant cause of sedimentation in the Inland Reach. However sediments from the surrounding wetlands and from the open water section could enter the Inland Reach in hurricane- or extreme storm-surge conditions.

Sedimentation in the open water section is mainly caused by cross currents (tidal, longshore or wind induced). Other aspects have an impact on the sedimentation in the Inland Reach and the open water section. Figure 7-11 gives the dominant causes of sedimentation in the MRGO channel. Consequently a conclusion is drawn on other sources of sediment and causes of sedimentation.

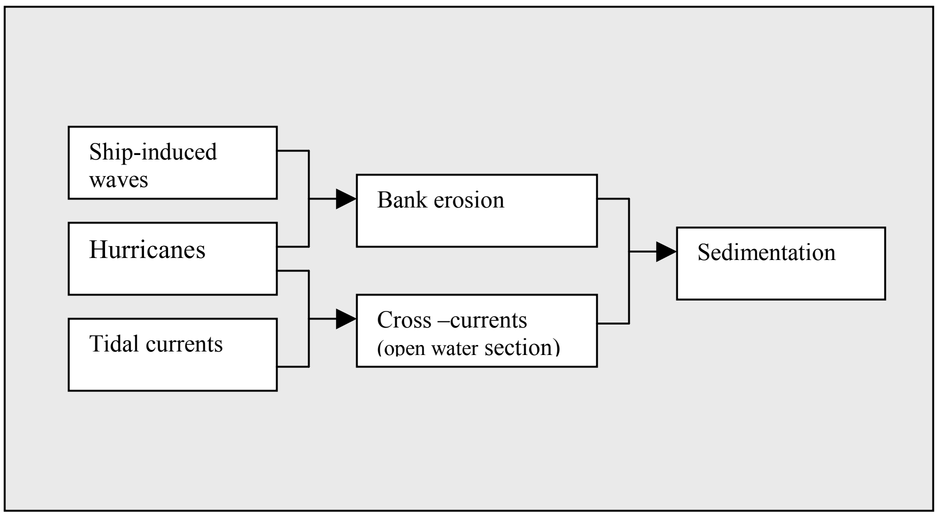

Figure 7-11 Causes of sedimentation

7.3.1 Sources of sediments

Possible sources of the sediments have been analyzed:

- Mississippi River
- Wetland areas surrounding the MRGO
- Open water section (Breton Sound)
- Channel banks

Sediments carried by the Mississippi River (Appendix 24)
The MRGO channel is only connected directly to the Mississippi River through the lock at Inner Harbor Navigation Channel. The lock location on the river, as well as its configuration, substantially prohibits sedimentation from entering the lock from the river. It’s highly plausible that the sediments carried by the Mississippi River play a negligible role in sedimentation in the Inland Reach.

Sediments from the surrounding wetlands (Appendix 24)
The tidal-current stretches relatively far into the MRGO channel. Consequently the tidal-current penetrates into the surrounding wetlands, through Bayous connected to the MRGO channel, and carry sediments into the channel. Under normal conditions the current velocities are too low to transport sediments from the surrounding wetlands into the channel, however during a hurricane or storm surge sediments could be transported into the MRGO. Most likely, this is not the dominant cause of sedimentation in the channel.

Sediments from the open water section
The amounts of sediment that enter the Inland Reach from the open water section are negligible under normal conditions (current velocities under normal conditions are around 0.2 m/s (appendix 15)). However during storm-surge/hurricane conditions the current velocities can increase significantly and sediments from the open water section could enter the Inland Reach.

Most likely sedimentation in the open water section is exclusively driven by sediments from the surrounding flats.

Sediments from the channel banks
When the amounts of eroded materials (bank erosion) are compared to the amount of dredged materials (in nearly the same time period[31]) it is plausible to conclude that bank erosion is the dominant source of sediments in the Inland Reach.

7.3.2 Causes of sedimentation

Some of the causes of sedimentation are clearly linked to a specific sediment source (e.g. ship-induced bank erosion). Other causes of sediment are not related to a source of sediment (e.g. sedimentation caused by changes in local geometry).

Possible causes of the sedimentation have been analyzed:

- Current velocities (tidal, ship-induced, hurricane and storm conditions)
- Changes in local geometry
- Changes in salinity level (salt water wedge)
- Wave attack on the channel banks (wind-induced, ship-induced)

Current velocities
Sedimentation in the open water section of the MRGO is mainly caused by cross currents (tidal, longshore or wind-induced).
The effect of current velocities on the sedimentation rate in the Inland Reach is negligible under normal conditions.

The average annual amount of dredged materials is significant higher for hurricane years than non-hurricane years. The conclusion can be drawn that hurricanes are a significant cause of sedimentation in the MRGO Channel, by moving sediments and intensifying bank erosion. Especially the Inland Reach is vulnerable to hurricanes, depending on the soil conditions.

[31] Amount of dredged materials over the period 1970-2001; Bank erosion over the period 1964-1996

Local geometry (Appendix 24)
The geometry of the channel has a large influence on the current velocity and consequently the sedimentation rate. Local changes of sedimentation rate can be ascribed to this cause.

Salinity level (Appendix 24)
The fresh water gradient is insufficient to create a clear salt-water wedge. However other phenomena involving salinity differences can occur. At certain locations industrial wastewater and drainage water is pumped into the channel. This fresh water results in a local area of low salinity. Flocculation might occur around these locations resulting in an increase local sedimentation rate.

Bank erosion (current and wave attack)
Bank erosion is either caused by wave attack (ship-induced waves or wind-induced waves) or current attack (ship-induced currents or tidal currents).
Locations with a significant higher wind-induced wave attack (locations with a high effective fetch length) show an increased bank erosion. This leads to the conclusion that bank erosion is caused both by ship-induced-waves and wind-induced waves, however the ship-induced wave attack is dominant over the wind-induced wave attack. Ship-induced currents can also result in a hydraulic attack on the channel banks. However appendix 23 makes is plausible that the ship-induced-wave attack on the channel banks is dominant over ship-induced-current attack.

7.4 Recommendations

The relations between the sedimentation rate and the possible causes have been addressed qualitatively in general and quantitatively to a reasonable extent where possible.

7.4.1 Critical assumptions

Conclusions have been drawn based on critical assumptions. All assumptions should be checked by further studies; in particular the following assumptions:

- In paragraph 4.3 the assumption was made that the number of ships sailing the MRGO remains relatively constant over the next 20 years.
  This assumption was crucial in the calculation of the channel dimensions.
- The volume of eroded materials has increased with **100%** as the materials settled and formed a fluid mud[32].
  This assumption was crucial in drawing the conclusion that the channel banks are the dominant source of sediment.

7.4.2 Further research

As noted in section I (paragraph 3.6) more information should be gathered on several aspects like current velocities and soil conditions to address the causes of sedimentation quantitatively. Research is recommended in the following fields:

Sources of sediment

In paragraph 7.3.1 the conclusion was drawn that the bank erosion is the dominant source of sediments under normal conditions. However sediments from the surrounding wetlands or from the open water section could enter the Inland Reach during a hurricane or extreme storm-surge.
To address the causes of sedimentation with more accuracy the amount of materials that enters the Inland Reach during a hurricane or storm-surge should be estimated. The following data are required for this study:

- Current velocities during hurricanes and storm-surge at the entrance of the Inland Reach and in the Breton Sound.
- Current velocities during hurricanes and storm-surge in the wetland and the bayous.

The amounts of sediments that pass the IHNC lock should be relatively insignificant. To address the (small) amounts of sediments that enter the MRGO through the IHNC lock the sediment concentration in the lock should be measured.

Sediment characteristics

As stated above a volume increase of 100% has been assumed, between soils on the channel bank and sediments on the channel bottom. Clearly this volume increase depends on the local soil conditions. Therefore a study is required to determine the characteristics of materials on the channel banks and on the channel bottom and of the dredged materials.

[32] This assumption does **NOT** hold for miles 45- 49

Causes of sedimentation
The conclusion can be drawn from appendix 23 that the ship-induced-wave attack on the channel banks is dominant over ship-induced-current attack.
Further research should address the hydraulic loads quantitatively.

A clear salt-water wedge cannot be observed at the MRGO channel[33]. However it remains possible that under certain conditions, e.g. extremely intense rainfall, a salt-water wedge is formed. Flocculation might occur around these locations resulting in an increase local sedimentation rate.
Further research should give clarity on sedimentation caused by differences in salinity.

[33] Measurements carried out in 1971, appendix 4, indicate a vertical mixed salinity level. Consequently the presence of a salt-water wedge is less likely.

8 Maintenance dredging costs analysis

8.1 Introduction

Since the construction of the MRGO channel, in the late 1960s, regular maintenance dredging has been carried out, to keep the channel at the required depth. Data on the maintenance dredging (amounts, costs and locations, appendix 41) are available over the period 1970-2001. This section gives an analysis and interpretation of this data. The maintenance dredging costs vary significantly along the channel.
Figure 8-1 shows the cumulative indexed maintenance dredging costs per mile over the period of 1970 to 2001.

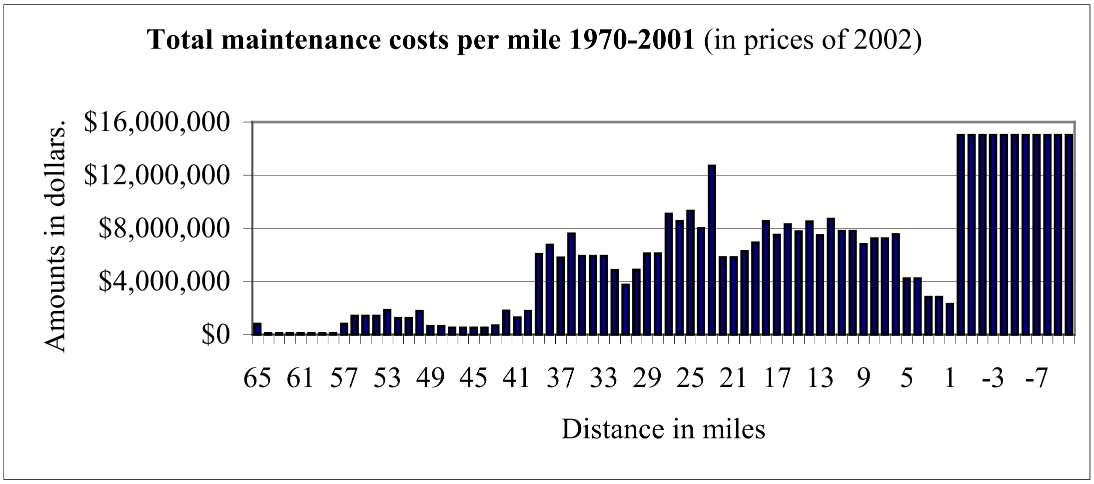

Figure 8-1 Accumulated indexed (prices of 2002) maintenance costs per mile 1970-2001

First a summary is given of the historic maintenance dredging at the MRGO to give an impression of the amounts of materials and the costs. In order to come to a strategy to reduce the dredging costs an analysis is made to identify the factors that determine the maintenance dredging costs, at different locations along the channel. Consequently the dominant causes of the maintenance dredging costs are addressed.

8.1.1 Summary of historic maintenance dredging

An average amount of about 8.1 million m^3 (10.6 million cubic yards) per year has been dredged over the period 1970-2001. A slight downward trend can be identified in average annual **amounts** of dredged materials over time, Figure 8-2.

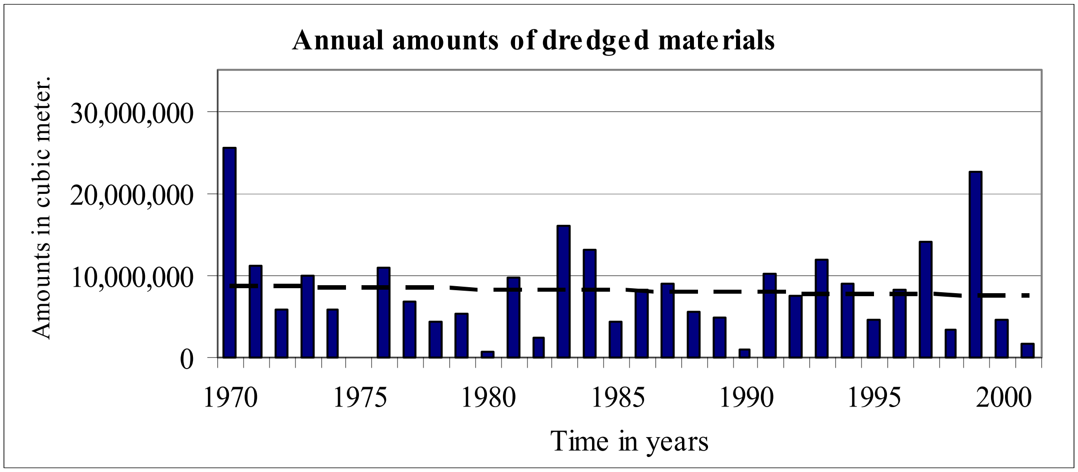

Figure 8-2 Annual amounts of dredged materials

The average annual dredging **costs** show a steady pattern, Figure 8-3, with an average of $ 12 million a year over the period 1970-2001.

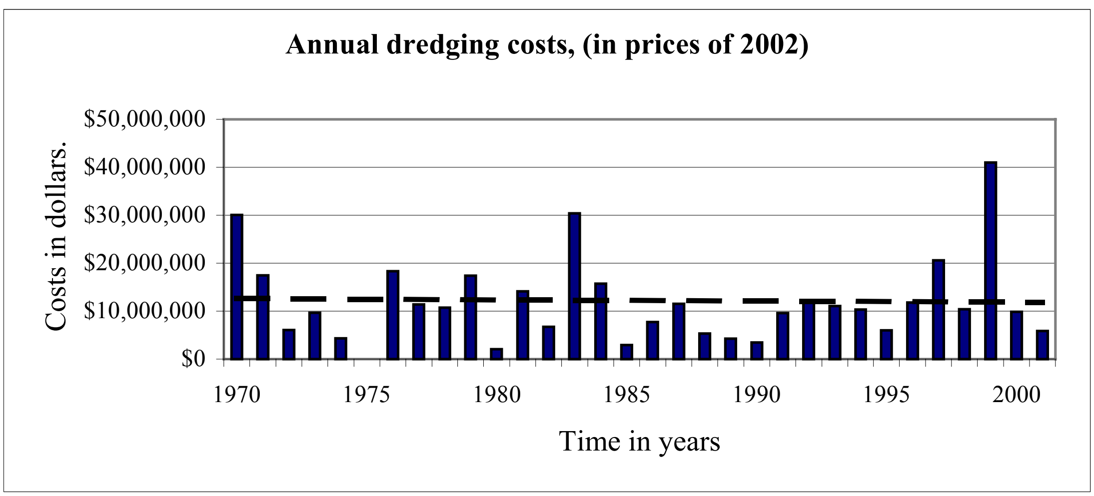

Figure 8-3 Annual dredging costs

The amounts of dredged materials and the accompanying maintenance dredging costs vary along the three different sections of the channel. Table 8-1 gives a summary of and the amounts and costs of each section.

Section	Amount of dredged materials (m^3)	Percentage	Total Dredging costs (in $ 2002)	Percentage
Inland Reach	94.614.400	36.3%	$ 127,544,550	33.7 %
Breton Sound	101.034.000	38.8%	$ 118,918,977	31.4 %
Bar Channel	65.043.700	25.0%	$ 131,886,862	34.9 %
Total	260.693.000	100.0%	$ 378,350,389	100 %

Table 8-1 Maintenance dredging amounts and costs 1970-2001

8.1.2 Factors influencing the dredging costs

The maintenance dredging costs in the MRGO channel are influenced by different factors, along different locations in the channel.
The maintenance dredging costs are the product of the amounts of materials to be dredged and the dredging unit rates. The amounts of dredged materials depend on the sedimentation rate and the dredging policy. The depth to which the channel is maintained is the dominant factor determining the amounts of materials to be dredged. Depending on the budget and the navigation requirements the channel can be overdredged or maintenance works can be postponed temporarily. The dredging policy is assumed consistent for all sections of the channel and can therefore not explain the significant differences in dredging costs per location.

However the unit rates of the maintenance dredging operations and the sedimentation rate vary along different locations of the channel. Chapter 8 analyzes differences in unit rates along the channel and chapter 7 explains local differences in sedimentation rate.

Figure 8-4 shows the factors that influence the maintenance costs specific for the MRGO channel.

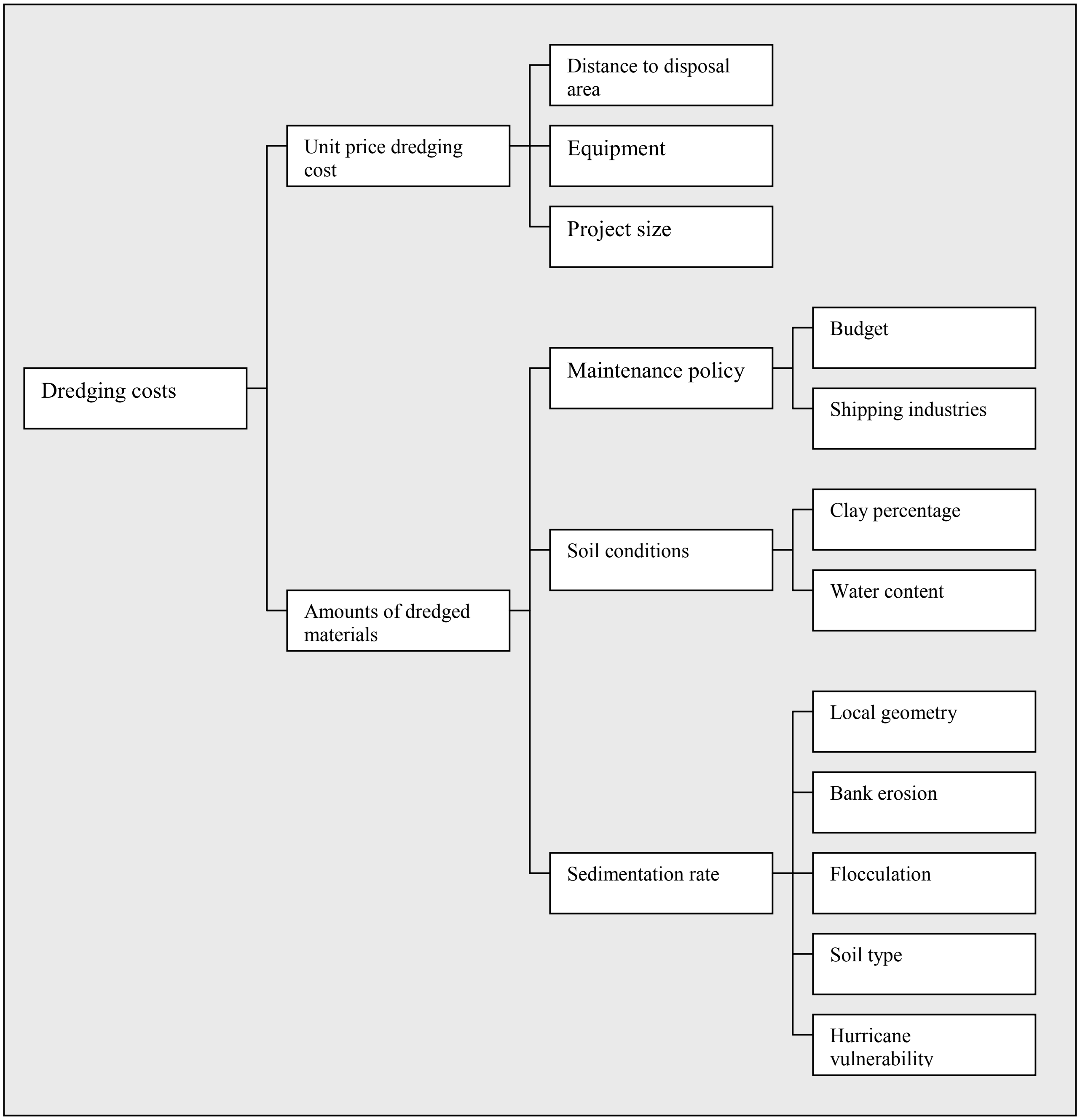

Figure 8-4 Factors influencing the maintenance costs

The dredging policy is assumed consistent for all sections of the channel and can therefore not explain the significant differences in dredging costs per location. However the unit rates of the maintenance dredging operations and the sedimentation rate vary along different locations of the channel. Chapter 8 analyzes differences in unit rates along the channel and chapter 7 explains local differences in sedimentation rate.

8.2 Unit rates

A comprehensive analysis of the unit rates is addressed in appendix 26; a summary of appendix 26 is given below:

The average unit rate for maintenance dredging operations at the MRGO is $ 1.46 per cubic meter over the period 1970-2001. The unit rate has changed over time, however a clear trend in unit rate over the period 1970-2001 can not be observed.

The dredging costs per cubic meter decrease for increasing project sizes at the MRGO. This is in line with the theoretical expectations.

The average costs per cubic meter vary along the different sections of the MRGO. The characteristics of the dredging operations are summarized in Table 8-2.
A characteristic that leads to a relatively high unit rate is marked with the (+) sign.

Characteristic	Inland Reach	Breton Sound	Bar Channel
Execution method	Cutter dredger	Cutter dredger	Hopper dredger **(+)**
Distance to disposal area	0.8 -10 miles [34] **(+)**	± 0.8 km	± 0.8 km
Sediment characteristics	High % of clay	Low % clay **(+)**	Low % clay **(+)**
Project size	Large	Large	Small **(+)**
	(+)	**(+)**	**(+)(+)(+)**
Costs per cubic meter	$ 1.35	$ 1.18	$ 2.03

Table 8-2 Characteristics of dredging operations

Conditions at the location of the Bar Channel make it necessary to use a relatively expensive hopper dredger. The average costs per cubic meter are significant higher for this section compared to the Inland Reach and the Breton Sound. The differences in unit rate between different sections are in line with the theoretical expectations.

[34] Prior to and including the fiscal year 1988 dredged materials were placed on the South Bank of the channel.

8.3 Sedimentation rate

The sedimentation in the MRGO is a function of a complex system of different and interacting factors (chapter 7). Bank erosion, by ship-and wave induced waves, is the dominant cause of sedimentation in the Inland Reach. Sedimentation in the open water section of the MRGO is mainly caused by cross currents (tidal, longshore or wind-induced).

8.4 Trends in maintenance costs

Amount of dredged materials

A slightly downward trend can be identified for the annual **amount** of dredged materials at the Inland Reach over the period 1970-2001 (Figure 8-5, blue line). This might indicate that the channel-banks have become more stable and bank erosion is decreasing in time[35]. A trend in the annual amounts of dredged materials for other sections can not be identified.

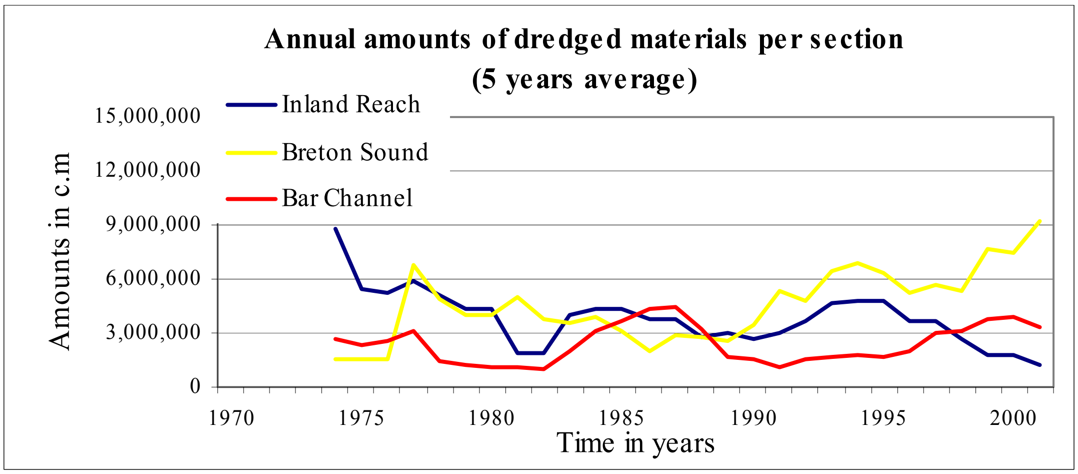

Figure 8-5 Annual amounts of dredged materials per section

[35] Data are only available on the location of the channel banks for the years 1964 and 1996. No data are available to prove a possible decrease in bank erosion.

Annual maintenance dredging costs

The average (indexed) annual maintenance costs are $ 12.2 million (over the period 1970- 2001). Figure 8-6 shows how the yearly maintenance costs have deviated above or below this average of $ 12.2 million. The hurricane years have been marked with a red bar. However a clear trend in annual costs over the period 1970-2001 can not be observed

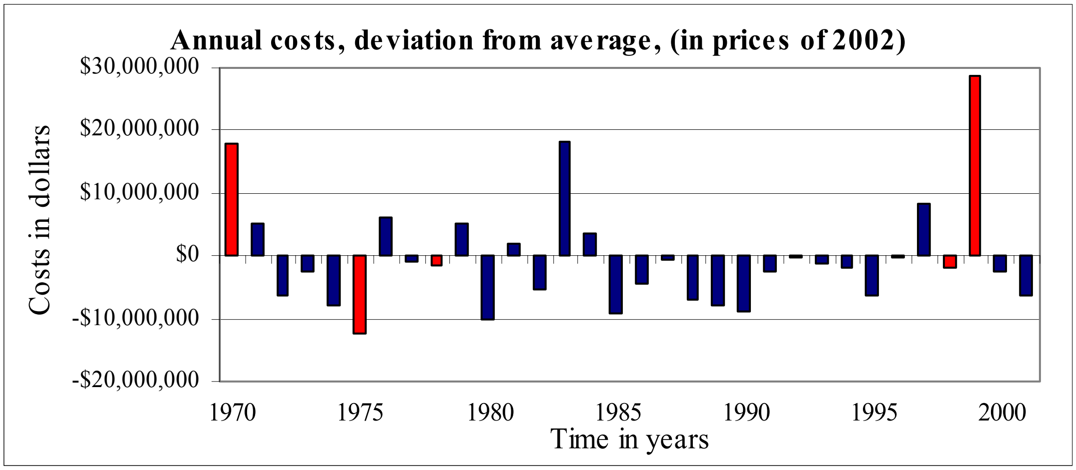

Figure 8-6 Deviation from average annual costs

8.5 Estimated future maintenance costs

Although it's difficult to estimate the future annual dredging costs, Figure 8-3 (on page II-37) can be used to give a rough estimate. The assumption is made that the linear trend of the average annual dredging costs over the period 1970-2001 is persistent over the period 2005-2025. Consequently the average annual maintenance dredging operations over the period 2005-2025, is estimated to be $ 12 million (in prices of 2002).

Total costs per section

Based on the downward trend in the amount of dredged materials (per mile) in the Inland Reach a downward trend in the total annual maintenance dredging costs can be expected for the Inland Reach. However more frequent maintenance works on mile 65-46 will result in higher dredging costs[36].The assumption is made that both effects are in the same order of magnitude and that the total future maintenance costs on the Inland Reach are in the same order of the average over the period 1970-2001.
The total amount of maintenance costs for the Breton Sound and the Bar Channel is assumed in the same order of the average over the period 1970-2001.

Costs per mile

Based on the downward trend in the amount of dredged materials (per mile) in the Inland Reach a downward trend in the annual maintenance dredging costs (per mile) can be expected for the Inland Reach.

[36] Between miles 65- 46 the channel was overdredged for the construction of a hurricane protection levee. The dredging operations for the levee construction clearly resulted in a reduction of the maintenance dredging costs (paragraph 7.2.10.1). Most likely maintenance dredging operations on mile 65-46 are required in future resulting in higher maintenance costs for the Inland Reach.

The annual maintenance dredging costs per mile for the Breton Sound and the Bar Channel are assumed in the same order of the average over the period 1970-2001. Appendix 26 gives the average annual maintenance costs per mile, over the period 1970-2001, and the estimated future annual costs per mile.

Section	Length miles	Average annual costs per mile (in $ 2002) [37]	Estimated future annual costs per mile
Inland Reach	19 [38]	$ 210,000	$ 100,000 -300,000
Breton Sound	20	$ 185,000	$ 100,000 -300,000
Bar Channel	10	$ 415,000	$ 300,000 -550,000

Table 8-3 Estimated future annual costs per mile

8.6 Conclusions

The average annual dredging costs show a steady pattern with an average of $ 12 million a year for the period 1970-2001.
Based on paragraphs 8.1 and 8.3 the conclusion can be drawn that the root causes of the maintenance costs along the MRGO can be explained by variations in sedimentation rate and differences in unit rate along the channel. Other factors as dredging policy are fairly constant over the channel and can not explain differences in maintenance costs.
Based on appendix 26 and paragraph 8.3 the conclusion can be drawn that the actual differences in maintenance dredging costs are in line with the theoretical expectations.

Inland Reach

The annual maintenance dredging costs in the Inland Reach are responsible for 34% of the total annual costs (on average). Bank erosion is the dominant cause of sedimentation. The unit rate of $ 1.35 per cubic meter is relatively low due to favorable characteristics of the dredging operations (large dredging operations, high clay percentages and the use of cutter-dredgers). The average annual costs per mile are expected to decrease in time (stabilization of the channel banks leads to a decrease in bank erosion).

Breton Sound

The annual maintenance dredging costs in the Breton Sound are responsible for 31% of the total annual costs (on average). Cross-currents (tidal, longshore or wind-induced) are the dominant cause of sedimentation. The unit rate of $ 1.18 per cubic meter is relatively low due to favorable characteristics of the dredging operations (large dredging operations, small distances to the disposal areas and the use of cutter-dredgers). The average annual costs per mile are expected to remain fairly constant in time.

Bar channel

The annual maintenance dredging costs in the Bar Channel are responsible for 35% of the total annual costs (on average). Cross-currents (tidal, longshore or wind-induced)

[37] Over the period 1970-2001
[38] The length of the Inland Reach is **46** miles. However over 90% of the dredged materials have been dredged over mile 38-20 (19 miles) (Figure 8-1 on page II-37). Therefore the average costs are calculated over the area where the costs have been incurred.

are the dominant cause of sedimentation. The unit rate of $ 2.03 per cubic meter is relatively high due to unfavorable characteristics of the dredging operations (small dredging operations, low clay percentages and the use of hopper dredgers). The average annual costs per mile are expected to remain fairly constant in time.

Table 8-4 and Table 8-5 give a summary of the amounts of dredged materials and costs for different sections.

Section	Amount of dredged materials (m^3) 1970-2001	Percentage	Total Dredging costs[39] (in $ 2002)	Percentage
Inland Reach	95 million	36 %	$ 128 million	34 %
Breton Sound	101 million	39 %	$ 119 million	31 %
Bar Channel	65 million	25 %	$ 132 million	35 %
Total	261 million	100 %	$ 379 million	100.0 %

Table 8-4 Amounts and costs dredged materials

Section	Length miles	Total dredging costs per mile (in $ 2002)[39]	Average annual costs per mile (in $ 2002)[39]
Inland Reach	19 **[1]**	$ 6,400,000	$ 210,000[40]
Breton Sound	20	$ 5,920,000	$ 185,000
Bar Channel	10	$ 13,280,000	$ 415,000

Table 8-5 Amounts and costs dredged materials

[1] The length of the Inland Reach is **46** miles. However over 90% of the dredged materials have been dredged over mile 38-20 (19 miles) (Figure 7-1). Therefore the average costs are calculated over the area where the costs have been incurred.

8.7 Recommendations

Differences in maintenance dredging costs along the MRGO channel are in line with the theoretical expectations. No further research is recommended on the dredging costs or the unit rates.

However two remarkable periods, with higher than average unit rates, can be observed in 1978-1981 and 2000-2001. Further studies could be carried out to explain this.

[39] Costs over the period 1970-2001
[40] $128 million divided by 32 years and 19 miles

Section III Table of contents

9 Location priority list

The maintenance dredging costs and the loss of wetland area vary along the channel. An alternative that could reduce the dredging costs or restore the wetlands will be more effective and economically feasible at certain locations than other locations.
At certain locations in the Inland Reach the construction of a bank protection is already completed[1] or scheduled[2] (appendix 27). For all other locations of the channel measurements are proposed in the order of priority shown in Table 9-1 and Table 9-2.
Locations on the priority list have been selected based on the following criteria[3]:

- Locations with high average annual maintenance costs over the period 1970-2001 (chapter 8).
- Locations with a high rate of direct wetland loss (appendix 25).
- Locations where further bank erosion could endanger the hinter (interior)-laying wetlands[4].
- Locations which are promising in the creation of new wetland area.[5]

Table 9-1 and Table 9-2 give the priority list for different locations and at which side of the channel the alternative should be implemented.

Inland Reach (Mile 66.0 -20.0)

Priority	Location	Criteria	Channel bank
2	24.2 -23.2	High maintenance costs	North and south bank
5	38.9 -38.0	Direct wetland loss	North bank
6	27.9 -25.0	High maintenance costs	South bank
7	31.8 -28.0	Wetland creation	North bank
8	28.6 -28.3	Wetland creation	South bank
9	48.3 -45.2	Indirect wetland loss	North bank
10	58.9 -57.3	Indirect wetland loss	North bank
11	42.8 -42.4	Wetland creation	North bank
12	42.8 -42.4	High maintenance costs	South bank
13	53.6 -53.2	High maintenance costs	North bank
14	34.4 -33.9	Indirect wetland loss	North bank
15	59.9 -54.4	Wetland creation	North bank

Table 9-1 Priority list Inland Reach

Breton Sound (Mile 19.9 -0.0) & **Bar channel** (Mile 0.0- -10.0)

Priority	Location	Criteria	Channel bank
1	0.0- -10.0	High maintenance costs	North and south bank
3	18.9-16.0	High maintenance costs	North and south bank
4	14.9-12.0	High maintenance costs	North and south bank

Table 9-2 Priority list open water section

[1] Existing bank protection: North Bank: 37.2-36.5, 36.2-35.6, 33.9-32.6 and 23.2-20
South Bank: 23.2-15
[2] Scheduled bank protection: North Bank: 49 -48.5, 40.9-38.9, 45.0 -43.1
South Bank: 38.9-38.5
[3] The priority itself is based on the average dredging costs per mile.
[4] In some locations the channel bank serves as a natural protection to the hinter-laying marsh-wetland areas. If bankline retreat would be persistent large areas of wetland could be lost.
[5] Locations such as abandoned oil and gas channels are promising in the creation of new wetland area

10 Introduction Multi Criteria Evaluation

10.1 General

A Multi Criteria Evaluation is used to select the most promising alternative. Different alternatives will be described qualitatively according to criteria listed in paragraph 10.2. Afterwards the intangible value of an alternative is addressed, according to the different criteria.
Consequently the value of an alternative is weighted against its costs (capital & maintenance). Finally an alternative can be chosen according to different principles of: the highest value, value for money or the most costs effective alternative.
Appendix 28 gives more details on the Multi Criteria Evaluation.

10.2 Criteria

Paragraphs 10.2.1 - 10.2.9 explain the different criteria that are used to measure the intangible value of an alternative. Table 10-1 gives a summary of the criteria and how the criteria are measured.

Criteria	Measured in
Navigability & safety	Relative to other alternatives
Sailing time (Gulf -New Orleans)	In hours
Wetland creation[6]	Hectares of created (lost) wetland
Ecological impact	Relative to other alternatives
Durability	Expected functional life-span
Predictability of the alternative	Relative to other alternatives
Hurricane resistance	Relative to other alternatives
Recreation & fisheries	Relative to other alternatives
Storm surge protection	Relative to other alternatives

Table 10-1 Criteria Multi Criteria Evaluation

[6] Wetland creation is negative when wetland loss is persistent.

10.2.1 Navigability & Safety

The navigability of a waterway depends on different aspects. The following aspects give an improvement of the navigability:

- A small number of bends
- A small number of shoals
- A clear overview
- Aids to navigation; buoys, pilot and guidance
- Channel dimensions; a large width and a deep draft
- Protection against winds, (cross)-currents and waves

Types of accidents that may occur are: Collision, grounding, sinking, fire and explosion. Appendix 32 gives an impression of the probability of collision. The safety of the channel can be expressed in the probability of ship-collision.

10.2.2 Sailing time

The operational costs of large container vessel are high. The competitiveness of a port in general depends heavily on the time it takes to reach that port. For this criterion the sailing time is defined as: The time is takes for the decisive container vessel to sail from the Gulf of Mexico to the Port of New Orleans. If the sailing time would be increased the Port of New Orleans will be less competitive. In that case compensating measures would be required to maintain the current level of competitiveness. The sailing time depends on the vessels' speed (and the channel length) as well as the capacity of the MRGO. In case the required capacity would exceed the present capacity vessel would have to wait resulting in a significant higher sailing time.

10.2.3 Wetland creation

The channel-banks will most likely continue to erode unless measures are taken. No action will result in the loss of valuable wetland area in the long term. The average bankline retreat was 9.1 m per mile per year (3.6 m/yr South and 5.5 m/yr North bank) over the last 32 years; (appendix 25). The bankline retreat is assumed constant over the last 32 years and future bank erosion is assumed constant as well[7]. An area of roughly 1350 hectares (3,300 acres[8]), surrounding the MRGO-channel, would be lost in 20 years if no measures were taken[9].

The execution time of an alternative has impact on the amount of created wetlands. The longer the execution time the more valuable wetland will be lost during the execution phase. However the criterion of "wetland creation" gives a score depending on the estimated area of created wetland over a period of 20 years[10]. In others words only the amount of wetland area created after 20 years is taken into account, not when the wetland area will be created.

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[7] This is a conservative assumption on the amount of bank-erosion. The actual bank-erosion will most likely be less since a slightly downward trend can be identified in the amounts of dredged materials in the Inland Reach.

[8] 45 miles, 30 foot, 20 years 45·5,280 ·30·20 = 142,560,000 square feet or 3272 acres

[9] In comparison; the total loss of the wetland area in Louisiana continues with a rate of 25 to 35 square miles a year [REF W2] (16,000 to 22,400 acres a year).

[10] Water areas with high levels of floating vegetation or subquatic vegetation are counted as wetland area.

10.2.4 Ecological impact

The implementation of alternatives and the use of construction materials can have a positive or negative impact on the fragile ecological system. In general the quality of the ecosystem would increase if the wetland-characteristics resemble the conditions of the original ecosystem (before construction of the MRGO-channel).
The ecological impact would be improved by application of the following features:

- Diversity of vegetation
- The use of indigenous vegetation
- Crossing possibilities for animals
- Reduction of salinity level (to the original level)
- Presence of spawning areas
- High water quality (absence of heavy metals and other micro- or macro pollutants)
- Environmentally friendly construction methods (water-based instead of land-based).
- Use of environmental and durable construction materials

10.2.5 Durability

The time period that a constructed, operated, and maintained project is able to serve its purpose, without serious maintenance, is called the lifespan. In general the lifespan itself is not a criterion since the maintenance costs are derived from the lifespan[11].
However the criterion durability is included as follows:

- Maintenance works can cause hindrance to navigation.
- Maintenance works can have a negative environmental impact.
- During the maintenance works the wetland area might be unprotected, which can result in high erosion rates or degradation of the surrounding wetlands.
- Frequent maintenance influences the public opinion. In some opinions, frequent maintenance resembles a waste of tax money.
- If the required lifespan of the project would be extended[12], a high durability is desirable.

A score on the durability is given according to the expected lifespan and the resistance of the alternative against; chemicals, ultra violet light and ship-collision.

10.2.6 Predictability of the implementation

Some processes (e.g. shoaling and morphological processes) are hard to estimate. It is difficult to give a precise estimation of the sedimentation-rate reduction enhanced by an alternative. Some alternatives have been used successfully at numerous locations world-wide and their behavior can be estimated with relative accuracy. Innovative, new alternatives might look promising in theory but prove unsuccessful after construction. The chance of successful implementation is therefore an important criterion.

[11] Therefore double counting would occur if the lifespan was taken as a criterion for economical reasons.
[12] The required lifespan could be increased to political decisions

10.2.7 Hurricane resistance

Hurricanes occur frequently along the coastline of Louisiana. However the frequency of a hurricane traveling through the project area is low, about 1 in 10 years. With a semi-probabilistic approach[13] the chance of a hurricane traveling through the project area for a certain period can be calculated [REF 2 and 73].

$$P = 1 - (1 - f)^{T}$$

P = probability of occurrence of the event within period T
T = considered period in years
f = average frequency of the event per year
The considered lifespan is 20 years, with an average frequency of 1/10 per year this results in a P of:

$$P = 1 - \left(1 - \frac{1}{10}\right)^{20} = 0.88$$

The probability that a hurricane will occur during the required lifespan, of 20 years, is 88%. Therefore the hurricane resistance is taken into consideration[14].
Moreover it will be both favorable for the wetland preservation and the maintenance costs if an alternative is capable of withstanding a hurricane.

(Other extreme weather conditions as extreme rainfall are included in the requirements[15], chapter 3).

10.2.8 Recreation & fisheries

Most likely people will not use the channel banks of the MRGO as a place for recreation. However numerous small recreational vessels and fishing boats use the MRGO channel. Recreational needs and the needs of the fishing companies have to be taken into consideration.

10.2.9 Storm surge protection

There is a perception that the construction of the MRGO-channel and the corresponding loss in wetland has made the surrounding municipalities (Plaquemines and St. Bernard) more vulnerable to flooding and hurricanes. A detailed analysis is currently ongoing by the Corps of Engineers to render such a determination. The vegetation of the original wetland provided resistance to storm surges, resulting in a relative reduction in the height that the water level could rise into the basin during a storm. Moreover the strength of a hurricane is reduced when traveling over land (wetland).
This criterion measures whether an alternative reduces the risk of flooding (caused by storms or hurricanes).

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[13] This approach is not valid for small values of T
[14] It is not economical to design an alternative that could fully withstand a severe hurricane. The additional measurements to make the alternative hurricane-resistant will be expensive and might even double the initial construction costs. Therefore hurricane-resistance is not set as a requirement
[15] In case an alternative does not meet the requirements it will not be presented

10.3 Costs

Costs are a major factor (in most cases the dominant factor) in the selection of an alternative. However the costs should not be taken as a criterion[16]. The costs will be weighted against the intangible value of an alternative. The total costs of an alternative are calculated by adding the:

- Capital costs.
- The sum of the estimated future maintenance costs over a period of 20 years (2005-2025).

Both the capital costs and the estimated future maintenance costs will be converted to prices of 2002[17], to make a cost comparison between different alternatives possible.

10.3.1 Capital costs

The capital costs are the costs to construct the proposed alternative.

10.3.2 Maintenance costs

The maintenance costs are the costs of periodical maintenance works required to maintain the desired functionality of the construction.
The maintenance costs can vary in time due to a change in weather conditions or due to a change in regulations[18]. However the maintenance costs is assumed constant over the period 2005-2025.

[16] The costs are measured in dollars whereas the value of an alternative is intangible. Therefore the value and the costs can not be added (which would happen if costs would be taken as a criterion).
[17] Maintenance costs assumed constant and converted to prices of 2002 using an annual average inflation rate of 3% (over the period 2005 -2025). Net present value factor [REF 41]:
$NCWf = ((1+i)^n-1)/(i(1+i)^n)$ with i= interest, n= number of years
[18] E.g. the dumping of contaminated dredged materials can be a factor 10 higher than uncontaminated materials depending on regulations.

11 Alternatives

11.1 Introduction

Different alternatives have been generated. The alternatives are described in appendix 30. This chapter gives a brief summary of the different alternatives. The alternatives can be divided in two main categories:

- Cost reduction
- Wetland restoration

Costs reduction

Alternatives in appendices 30.2 -30.11 have a focus on the reduction of the maintenance dredging costs and enhance the wetland restoration where possible, Figure 11-1. Alternatives discussed in appendices 30.1 -30.3 are strategies to reduce the maintenance dredging costs in general. The maintenance dredging costs can be reduced by strategies which decrease the amount of materials to be dredged (appendices 30.4 -30.11) or by lowering the unit rate (appendix 30.12). The alternatives that reduce the amount of materials have been generated based on the root causes of sedimentation, addressed in chapter 7.

Wetland restoration

Appendices 30.13 -30.14 discuss alternatives that have a focus on the restoration of the wetland area; less emphasis is put on the reduction of the maintenance dredging costs, Figure 11-1.

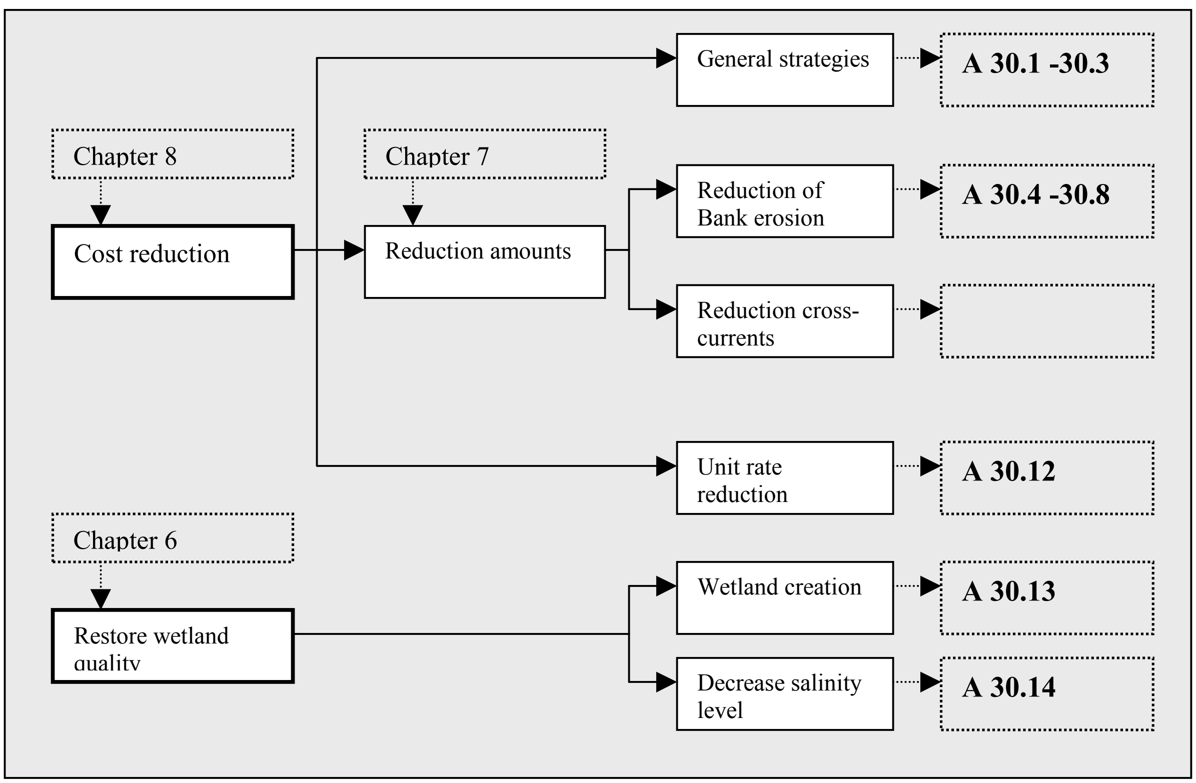


Figure 11-1 Structure appendix 30 and related chapters

11.2 Summary

A summary of the different alternatives, discussed in appendix 30, is given in Table 11-1. The objective of the alternatives is to reduce the maintenance dredging costs and/or to limit the degradation of the wetlands. A brief comment is given whether an alternative is feasible for the MRGO.

Function	Alternative	Feasibility
(Comparison other alternatives)	Do Nothing	-
Avoid maintenance operations	Discontinue MRGO use	Not applicable [19]
One time reduction in amounts	Stepped bottom	Promising
Prevention of sediment transport from wetlands	Closure connected channels	Further research
Reduction amounts by increasing strength of the channel banks	Sheet pile bank revetment	Promising
1. Reduction amounts by increasing strength of the channel banks 2. Allowing crossing possibilities animals	Rip-rap bank revetment	Promising
Reduction amounts by reducing loads and wetland creation	Breakwater	Promising
1. Reduction amounts by reducing loads 2. Water exchange vegetation strip and channel	Floating breakwater	Promising
Reduction amounts by reducing loads	Pile screen	Promising
1. Reduction amounts by reducing loads 2. Prevent structural measures on the channel banks	Speed limit	Compensation measures[20]
Reduction amounts of dredged materials	a. Jetty extension	High capital costs
	b. Submerged breakwater	High capital costs
	c. Artificial seaweed	Section IV
Unit rate reduction	a. Optimization dredging operations	Further research
	b. Sediment traps	Less feasible
Wetland restoration through direct creation of new wetlands	Wetland creation (dredged materials)	Promising
Wetland restoration through increasing quality	Salinity level reduction	Relative unfeasible

Table 11-1 Alternatives, function and feasibility

The functions of certain alternatives in Table 11-1 are similar (e.g. the function of the breakwater and the floating breakwater). From a methodological standpoint it is more correct to combine these alternatives in one alternative[21] with more variants[22]. However for practical reasons the emphasis was put on the differences in function between the alternatives in order to avoid a division in variants.

[19] The time scope of the project (20 years) makes the closure of the MRGO highly unlikely, since no alternative route from the Gulf of Mexico to the Port of New Orleans is available for deep draft vessels.
[20] Compensating measures for the shipping companies are required to maintain the current level of competitiveness of the Port of New Orleans.
[21] Alternative : serves the same **objective** achieved through a different **function.**
[22] Variant : serves the same **function** achieved through a different **form**.

12 Multi criteria evaluation

12.1 Introduction

Different alternatives have been presented in chapter 11. Alternatives to reduce the maintenance dredging and to restore the wetland quality have been generated. In this chapter a judgment is made between alternatives.

To reduce the amount of materials the stepped bottom alternative has been proposed. This alternative can be implied in combination with other alternatives and should therefore not be compared with other alternatives. The stepped bottom alternative should be judged against the do-nothing alternative in order to give a recommendation if the alternative should be implied in the first place. In paragraph 12.2 a judgment is made if this alternative should be implied, next to other alternatives

To reduce the sedimentation rate, and consequently the maintenance dredging costs, different alternatives have been presented. The boundary conditions make it necessary to divide the channel in the Inland Reach and the open water section (Bar Channel & Breton Sound). In paragraph 12.3 an alternative for the Inland Reach is selected and in paragraph 12.4 an alternative is chosen for the Open water Section.

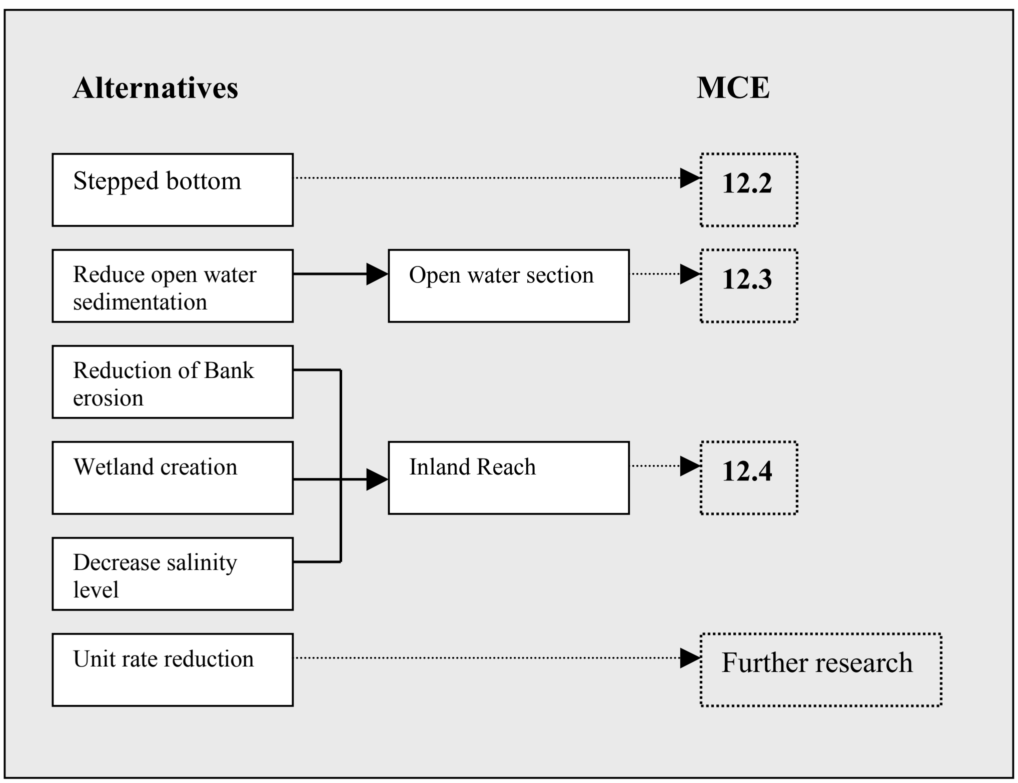


Figure 12-1 Structure chapter 12

The maintenance dredging costs can be reduced by reducing the amounts of materials and/or by reducing the unit rate. It is recommended to reduce the unit rate by making the amount of materials per maintenance work as large as possible. Maintenance dredging unit costs can be minimized if the dredging work can be bid during times when it is expected that there will be relatively good competition.

It is also an advantage in possibly lowering costs by bidding work when there are dredges know to be residing in the Gulf coast region. Further research should be done to find more reduction of the unit rate.

12.2 Stepped bottom

The stepped bottom alternative has a small negative impact on the safety, the navigability and the capacity of the channel. However the safety, the navigability and the capacity of the stepped bottom alternative meet the present requirements[23].

A one time maintenance cost reduction of about $ 14 million (appendix 30) on the total MRGO could be achieved when implying the stepped bottom alternative. Most likely the annual maintenance dredging costs in the Bar Channel and the Breton Sound would be reduced structurally when the stepped bottom alternative is implied[24]. The implementation of the stepped bottom alternative is recommended, however further research should address the impact on the safety, navigability and capacity on the MRGO channel.

[23] In case the amount of ship-movements would increase drastically passing points could be constructed. This would however increase the sailing time on the MRGO.
[24] Further research should be carried out to estimate this cost reduction.

12.3 Inland Reach

12.3.1 Multi criteria evaluation

Different alternatives have been generated to reduce the amount of bank erosion in the Inland Reach (appendix 30). The alternatives have been described qualitatively according to the criteria from paragraph 10.2 and quantitatively with an initial costs-estimation. The intangible value of an alternative is calculated first and compared to the costs of the alternative. The ratio costs/score is used to choose an alternative.

Intangible value

A score is given to each alternative for each criterion to address the relative value each alternative per criterion. The scores range from $1_{\text{very poor}}$ to $5_{\text{very good}}$[25]. Consequently the score is multiplied with a weight factor. Not all criteria are equally important therefore a weight factor has been given to each criterion. Finally the total intangible value per alternative is calculated, Table 12-3. (Details on the MCE are given in appendix 28).

First the weight factors are determined (with the method of Reference 13); the criteria have been arranged in a matrix. Consequently two criteria are compared (one of the left column and one of the top row). When the column criterion is more important than the row criterion a "1" is placed in the matching box. The horizontal sum gives the relative importance of each criterion.

		A	B	C	D	E	F	G	H	I	total
Navigability & safety	A		1	0	0	1	1	1	1	1	6
Sailing time	B	0		0	0	1	1	1	1	1	5
Wetland creation	C	1	1		1	1	1	1	1	1	8
Ecological impact	D	1	1	0		1	1	1	1	1	7
Durability	E	0	0	0	0		0	0	0	1	1
Predictability impl.	F	0	0	0	0	1		1	1	1	4
Hurricane resistance	G	0	0	0	0	1	0		1	0	2
Recreation & fisheries	H	0	0	0	0	1	0	0		1	1
Storm surge protection	I	0	0	0	0	0	0	1	0		1

Table 12-1 Relative importance criteria

[25] Scores: 1: very poor, 2: poor, 3: average, 4: good, 5: very good.

Criterion		Relative weight	In percentages
Navigability & safety	6	6/35 = 0.17	17 %
Sailing time	5	5/35 = 0.14	14 %
Wetland creation	8	8/35 = 0.23	23 %
Ecological impact	7	7/35 = 0.20	20 %
Durability	1	1/35 = 0.03	3 %
Predictability impl.	4	4/35 = 0.11	11 %
Hurricane resistance	2	2/35 = 0.06	6 %
Recreation & fisheries	1	1/35 = 0.03	3 %
Storm surge protection	1	1/35 = 0.03	3 %
	Σ = 35		Σ = 100 %

Table 12-2 Calculation weight factors

Value		**Do-nothing**	**Sheet piles**	**Rip-rap revetment**	**Breakwater**	**Floating breakwater**	**Pile screen**	**Speed limit**
Criteria	**Weight**							
Navigability & safety	17	5	2	5	5	1	5	4
Sailing time	14	5	5	5	5	5	5	1
Wetland creation	23	1	3	3	5	5	4	2
Ecological impact	20	2	1	3	4	5	5	3
Durability	3	5	3	4	4	1	2	5
Predictability impl.	11	5	4	4	5	1	1	3
Hurricane resistance	6	5	4	3	3	1	4	5
Recreation & fisheries	3	5	1	5	5	5	3	1
Storm surge protection	3	1	1	5	1	1	1	1
Total score	**100**	**336**	**276**	**388**	**453**	**340**	**411**	**272**

Table 12-3 Intangible value of the alternatives

The alternative with the highest score is the alternative with the highest intangible value.

Costs
The estimated annual maintenance dredging costs for the period 2005-2025 are given in prices of 2002. Consequently the total amount of maintenance costs in the period 2005-2025 is calculated in prices of 2002[26]. The per-mile total maintenance costs are added to the capital costs per mile to calculate the total costs per mile of each alternative over the period 2005-2025, Table 12-4.

Costs per mile	**Estimated annual maintenance costs**	**Maintenance costs (2005 -2025)**	**Capital costs [27]**	**Total costs [27]**
Do-nothing	$ 100,000-300,000	$ 1.4 -4.4 mln.	$ 0	$ 1.4 -4.4 mln.
Sheet piles	$ 30,000-210,000	$ 0.5 -3.1 mln.	$ 2-3 mln.	$ 1.5-6.1 mln.
Rip-rap revetment	$ 30,000-210,000	$ 0.5 -3.1 mln.	$ 1-2 mln.	$ 1.5-5.1 mln.
Breakwater	$ 5,000-75,000	$ 0.1 -1.1 mln.	$ 4-6 mln.	$ 4.1-7.1 mln.
Floating breakwater	$ 30,000-240,000	$ 0.5 -3.5 mln.	$ 2 mln.	$ 2.5-5.5 mln.
Pile screen	$ 30,000-180,000	$ 0.5 -2.6 mln.	$ 1.0-1.5 mln.	$ 1.5-4.1 mln.
Speed limit	$ 30,000-240,000	$ 0.5 -3.5 mln.	$ 0.1 mln.	**$ 0.6 -3.6 mln.**

Table 12-4 Costs per mile

[26] Maintenance costs assumed constant and converted to prices of 2002 using an annual average inflation rate of 3% (over the period 2005 -2025).
[27] Costs are in prices of 2002.

Costs/value ratio

The ratio between the total costs and the intangible value can be used to choose the proposed alternative, Table 12-5. The alternative that gives the desired[28] balance between value and the costs is chosen.

Costs/value ratio	Value	Total costs (2005-2025)	Costs per value point (in thousands dollars)
Do-nothing	336	$ 1.4 -4.4 mln.	$ 4- 13
Sheet piles	276	$ 1.5-6.1 mln.	$ 5- 22
Rip-rap revetment	388	$ 1.5-5.1 mln.	$ 4- 13
Breakwater	453	$ 4.1-7.1 mln.	$ 9- 16
Floating breakwater	340	$ 2.5-5.5 mln.	$ 7- 16
Pile screen	411	$ 1.5-4.1 mln.	**$ 4- 10**
Speed limit	272	$ 0.6 -3.6 mln.	$ 2- 13

Table 12-5 Costs/value ratio

Figure 12-2 gives the costs/value ratio for each alternative.

1 Do-nothing
2 Sheet piles
3 Rip-rap revetment
4 Breakwater
5 Floating breakwater
6 Pile screen
7 Speed limit

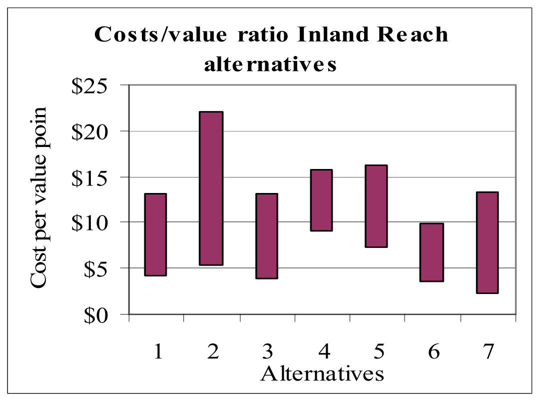


Figure 12-2 Costs/value ratio Inland Reach alternatives

Overview

The breakwater alternative has the highest intangible value compared to other alternatives (Table 12-3) however the alternative comes with significant higher costs (Table 12-4). The speed limit alternative gives the lowest total costs, but has a relative low value. The pile screen has the lowest costs/value ratio (Table 12-5). In other words the pile screen alternative gives the best value for money.

Interest		Proposed alternative
Highest intangible value	(Table 12-3)	Breakwater alternative
Lowest costs alternative	(Table 12-4)	Speed limit alternative
Best value for money	(Table 12-5)	Pile screen alternative

Table 12-6 Proposed alternatives

Depending on the interest of the decision maker a choice between the alternatives can be made.

[28] The assessment between value and costs is a subjective matter and depends on the views of the decision maker.

12.3.2 Sensitivity analysis

The weight factors of the criteria are subjective. According to different views and different interests other values can be given to the weight factors. To reduce the subjectivity of the weight factors, different scenarios according to different interest are proposed in a sensitivity analysis with different weight factors. The following points of view are considered (based on the interest of stakeholder groups):

- Environmental aspects
- Deep draft navigation
- Local residents
- Functionality
- Compromise between different interest

Appendix 33 gives the value of the alternatives for each perspective. Table 12-7 gives a summary of appendix 33. The three-highest scoring alternatives for each interest are marked.

Inland Reach

Interests	**Do-nothing**	**Sheet piles**	**Rip-rap revetment**	**Breakwater**	**Floating breakwater**	**Pile screen**	**Speed limit**
Environmental aspects				# 1	# 2	# 2	
Deep draft navigation	# 3		# 1	# 1			
Local residents	# 3		# 1	# 2			
Functionality	# 1		# 2	# 3			
Compromise				**# 1**	**# 2**	**# 2**	

Table 12-7 Summary sensitivity analysis

The breakwater alternative scores high for all different interests. The rip-rap revetment scores are high on certain interests, such as deep "draft navigation", "local residents" and "functionality" but scores lower on the "compromise".

12.3.3 Recommended strategy

A combination between the pile screen and the breakwater alternatives is recommended for the Inland Reach. At locations where new wetland area is created the breakwater alternative is recommended at other locations the pile screen alternative is proposed. The breakwater alternative is especially promising in the creation of new wetland area, since a vegetation strip is constructed between the breakwater and the channel banks. The pile screen is promising in reducing the maintenance dredging costs.

(The speed limit alternative could reduce the maintenance dredging costs however the shipping industry should be compensated. An optimum of the most economical speed limit could be addressed, based on the cost reduction and the compensation to the shipping companies.)

Moreover the stepped bottom alternative is recommended next to the breakwater and screen pile alternatives.

12.4 Open water section

12.4.1 Multi criteria evaluation

Intangible value

A score is given to each variant for each criterion to address the relative value each variant per criterion. The scores range from 1$_{\text{very poor}}$ to 5 $_{\text{very good}}$[29]. Consequently the score is multiplied with a weight factor. Not all criteria are equally important therefore a weight factor has been given to each criterion. Finally the total intangible value per variant is calculated, Table 12-8. (Details on the MCE are given in appendix 28).

Value	Weight	Do-nothing	Jetty extension	Subm. breakwater	Artificial seaweed
Navigability & safety	15	4	5	3	1
Ecological impact	30	5	2	3	1
Durability	15	5	4	1	3
Predictability impl.	15	4	5	2	1
Hurricane resistance	10	5	4	3	1
Recreation & fisheries	15	5	1	3	4
Total score	**100**	**470**	**325**	**255**	**175**

Table 12-8 Value of the open water section variants

The with the highest score is the variant with the highest intangible value.

Costs

The estimated annual maintenance dredging costs for the period 2005-2025 are given in prices of 2002. Consequently the total amount of maintenance costs in the period 2005-2025 is calculated in prices of 2002[30]. The total maintenance costs are added to the capital costs to calculate the total costs of each variant over the period 2005-2025, Table 12-9.

Costs per mile	Estimated annual maintenance costs	Maintenance costs (2005 -2025) [31]	Capital costs [32]	Total costs
Do-nothing Breton Sound	$ 100,000-300,000	$ 1.4 -4.4 mln.	$ 0	$1.4 -4.4 mln
Do-nothing Bar channel	$ 300,000-550,000	$ 4.4 -8.0 mln.	$ 0	$4.4 -8.0 mln
Jetty extension	$ 5,000-75,000	$ 0.1 -1.1 mln.	$ 6- 10 mln.	$6.-11.1 mln
Subm. breakwater	$ 60,000-270,000	$ 0.9 -3.9 mln.	$ 2- 5 mln.	$2.9 -8.9 mln
Artificial seaweed	$ 20,000-210,000	$ 0.3 -3.0 mln.	N/A	N/A

Table 12-9 Costs per mile open water section variants

[29] Scores: 1: very poor, 2: poor, 3: average, 4: good, 5: very good.
[30] Maintenance costs assumed constant and converted to prices of 2002 using an annual average inflation rate of 3% (over the period 2005 -2025).
[31] Costs are in prices of 2002.

Costs/value ratio
The ratio between the total costs and the intangible value can be used to choose the proposed variant, Table 12-10. The variant that gives the desired[33] balance between value and the costs is chosen.

Costs/value ratio	Value	Total costs (2005-2025)	Costs per value point (in thousands dollars)
Do-nothing Breton Sound	470	$ 1.4 -4.4 mln	3 -9
Do-nothing Bar channel	470	$ 4.4 -8.0 mln	9 -17
Jetty extension	325	$ 6.-11.1 mln	18 -34
Subm. breakwater	255	$ 2.9 -8.9 mln	11 -35
Artificial seaweed	175	N/A	N/A

Table 12-10 Costs/value ratio open water section variants

Figure 12-3gives the costs/value ratio for each variant.

1 Do-nothing Breton Sound
2 Do-nothing Bar channel
3 Jetty extension
4 Subm. breakwater

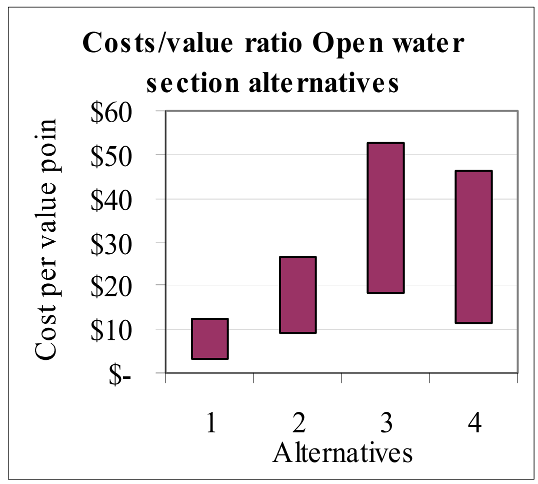


Figure 12-3 Costs/value ratio open water section variants

12.4.2 Recommended strategy

The construction of a rubble-mound breakwater is economically unfeasible. The capital costs of a breakwater are by far higher than the maintenance costs reduction. Therefore the construction of a rubble mound breakwater is not recommended.

A submerged geotube breakwater and artificial seaweed could reduce the maintenance costs. However the effects on the sedimentation rate should be studied first (e.g. with a numerical model as SUTRENCH) before a recommendation can be made.

A feasibility study on the artificial seaweed variant for the Bar Channel and the Breton Sound will be carried out in section IV.

[33] The assessment between value and costs is a subjective matter and depends on the views of the decision maker.

13 Proposed strategies

According to the priority list chapter 9 and the Multi criteria evaluation chapter 12 the proposed strategies are presented in Table 13-1 and Table 13-2.

Costs reduction Inland Reach

Priority	Location	Length[34]	Bank[35]	Alternative	Costs reduction[36] appendix 34
1	66.0- -10.0	76	N/A	Stepped bottom	$ 14.0 million
2	24.2-23.2	1.0	N + S	Pile screen	$ 0.2 million
3	38.9-38.0	0.9	N	Pile screen	$ 0.1 million
4	27.9-25.0	2.9	S	Pile screen	$ 0.3 million
5	31.8-28.0	3.8	N	Breakwater	$ -(5.3) million
6	28.6-28.3	0.3	S	Breakwater	$ -(0.4) million
7	48.3-45.2	3.1	N	Pile screen	$ 0.3 million
8	58.9-57.3	1.6	N	Pile screen	$ 0.2 million
9	42.8-42.4	0.4	N	Breakwater	$ -(0.6) million
10	42.8-42.4	0.4	S	Pile screen	$ 0 million
11	53.6-53.2	0.4	N	Pile screen	$ 0 million
12	34.4-33.9	0.5	N	Pile screen	$ 0.1 million
13	59.9-54.4	5.5	N	Breakwater	$ -(7.7) million
Total maintenance costs reduction[37]					**$ 1.8 million**

Table 13-1 Costs reduction Inland Reach

[34] Length in miles
[35] N: North side of the channel, S: South side of the channel
[36] Compared to the do-nothing alternative over the period 2005-2025
[37] The total reduction of maintenance dredging costs for the fiscal years 2005-2025, total reduction of maintenance costs is reduction minus the construction costs of the alternative.

Wetland creation Inland Reach

Priority	Location	Length[38]	Bank[39]	Alternative	Created wetland
1	66.0- -10.0	76	N/A	Stepped bottom	0
2	24.2-23.2	1.0	N + S	Pile screen	14.6 hectare
3	38.9-38.0	0.9	N	Pile screen	8.1 hectare
4	27.9-25.0	2.9	S	Pile screen	16.6 hectare
5	31.8-28.0	3.8	N	Breakwater	55.4 hectare
6	28.6-28.3	0.3	S	Breakwater	4.5 hectare
7	48.3-45.2	3.1	N	Pile screen	27.5 hectare
8	58.9-57.3	1.6	N	Pile screen	14.2 hectare
9	42.8-42.4	0.4	N	Breakwater	5.7 hectare
10	42.8-42.4	0.4	S	Pile screen	2.4 hectare
11	53.6-53.2	0.4	N	Pile screen	3.6 hectare
12	34.4-33.9	0.5	N	Pile screen	4.5 hectare
13	1056 acre	5.5	N	Breakwater	80.1 hectare
created wetland area					584 hectare
Wetland loss at other locations MRGO					969 hectare
Total increase in wetland area					**-(385) hectare**

Table 13-2 Wetland creation Inland Reach

14 Conclusions

Inland Reach

The proposed strategy for the Inland Reach is a combination of stepped bottom alternative, the pile screen alternative and the breakwater alternative.
The breakwater alternative is especially promising in the creation of new wetland area, since a vegetation strip is constructed between the breakwater and the channel banks. The pile screen is promising in reducing the maintenance dredging costs.

The goal of maintenance dredging costs reduction is achieved under the proposed strategy. However the cost reduction of $ 1.8 million over a period of 20 years is marginal compared to the total amount of maintenance costs spent in the same period. The amount of wetland loss under the proposed strategies is estimated at about 385 hectares (950 acre). Without the proposed strategies the wetland loss would be in the order of 1350 hectares (3,300 acre). With 584 hectares (1444 acres) created, the proposed strategies meet the environmental requirements in an ample way.

If a time period of more than 20 years would be considered the costs reduction and the wetland creation would increase compared to doing nothing.

Open water section

The construction of a rubble-mound breakwater is economically unfeasible. The capital costs of a breakwater are by far higher than the maintenance costs reduction. Therefore the construction of a rubble mound breakwater is not recommended.

[38] Length in miles
[39] N: North side of the channel, S: South side of the channel

A submerged geotube breakwater and artificial seaweed could reduce the maintenance costs. However the effects on the sedimentation rate should be studied first (e.g. with a numerical model as SUTRENCH) before a recommendation can be made.

15 Recommendations

An initial cost indication has been given for each alternative, both on the capital costs and the possible cost reduction per mile.
Detailed costs calculations should be carried out to address the capital costs and the cost reduction with more accuracy.

The speed limit alternative could reduce the maintenance dredging costs however the shipping industry should be compensated. An optimum of the most economical speed limit could be addressed, based on the cost reduction and the compensation to the shipping companies.

Section IV Artificial seaweed

14 Introduction

14.1 General

In some coastal areas natural seaweed plays an important role in retaining sand along the coastline. The natural seaweed reduces the shear stresses on the seabed induced by currents and waves. Consequently the sediment transport is reduced. This has led to the concept of using artificial seaweed on the open water section of the MRGO Channel. When implied properly the artificial seaweed could reduce the sediment transport from the tidal flats towards the MRGO Channel. This could in turn reduce the amount of sedimentation in the MRGO channel, resulting in the reduction of the maintenance dredging costs.

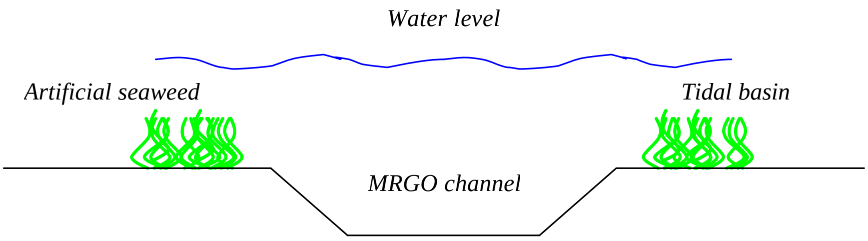


Figure 14-1 Artificial seaweed

In ideal conditions the artificial seaweed reduces the sediment transport by absorbing turbulent shear stress with its leaves. The amount of bed load sediment transport reduces along with the reduction of the shear stress. A reduction in turbulent vertical mixing within the boundary layer established by the seaweed could reduce suspended sediment transport as well.

The effectiveness of the artificial seaweed and the desired maintenance dredging cost reduction can only be addressed roughly. Detailed data on the boundary conditions in the open water section of the MRGO and detailed data on the behavior of the artificial seaweed are required to calculate the cost reduction more accurately.

In this section a preliminary design is made for an artificial seaweed construction tailor made for the open water section of the MRGO channel. Figure 14-2 gives the structure of section IV and the relation of section IV to the other sections.

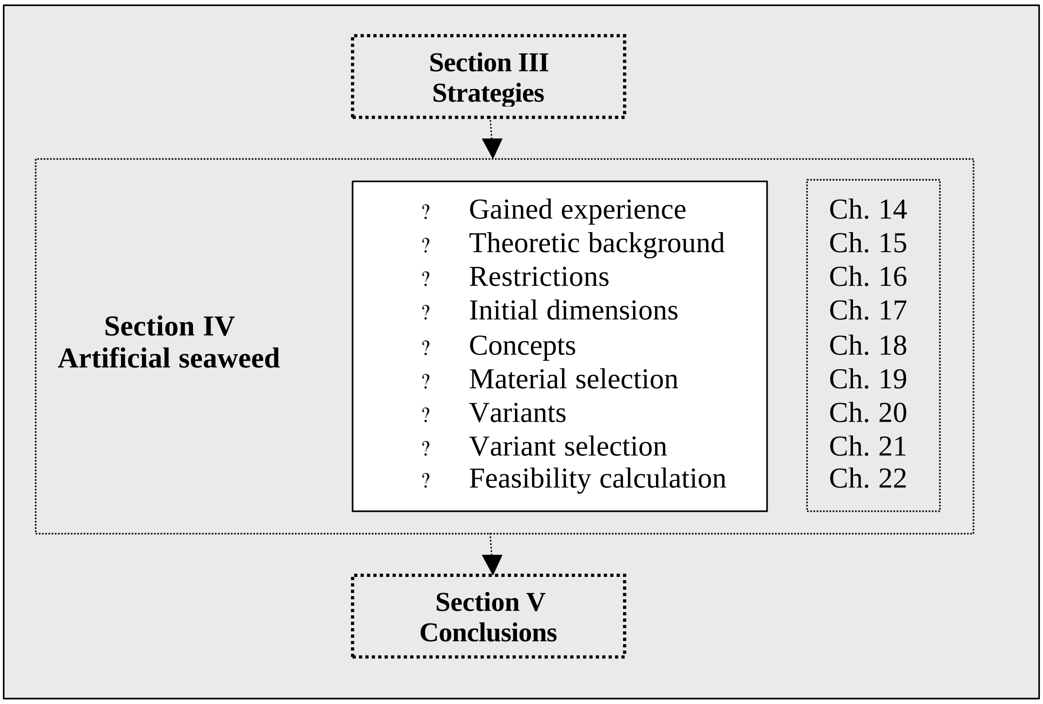


Figure 14-2 Structure section IV

Figure 14-3 gives the actual design process of the artificial seaweed for the MRGO channel.

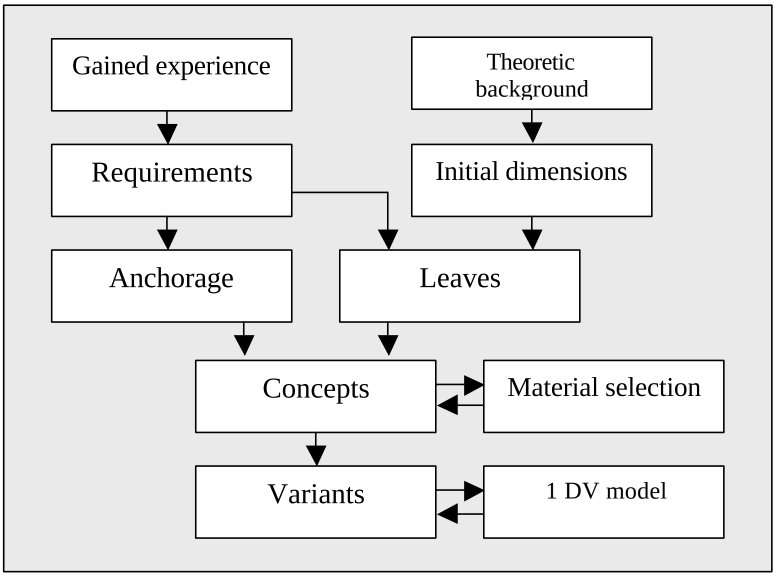


Figure 14-3 Design process artificial seaweed

14.2 Natural vegetation

The use of natural vegetation to achieve the desired sedimentation on the flats surrounding the MRGO would have significant advantages over the use of artificial seaweed. The capital costs for natural seaweed would be lower than the construction costs of artificial seaweed. Moreover natural vegetation would have a positive impact on the ecosystem.
However the use of natural vegetation is limited by the prevailing boundary conditions. Species of aquatic vegetation can only grow and flourish under certain conditions.

Factors that the influence the growth of aquatic vegetation and that determine whether a plant is suitable for a certain location are[1]:

- Light Availability
- Transparency
- Water depth
- Water chemistry[2]
- Sediment chemistry
- Temperature
- Salinity level
- Wave and current attack

Of all factors light is typically considered the most significant factor limiting both distribution and growth of aquatic vegetation [REF APIS]. The amount of light available to submerged aquatic vegetation depends on both the transparency and the water depth. The water depth at the tidal flats around the MRGO is relatively large (7m) for aquatic plants. It’s highly plausible that the water transparency in the Breton Sound is too low for the growth of aquatic vegetation on a large scale due to the presence of suspended sediments (e.g., silt or clay particles). The absence of vegetation on the tidal flats of the Breton Sound makes it plausible that the location is not suitable for the growth of natural vegetation on a large scale.

[1] The list of factors that influence the growth of aquatic plants is based on APIS (Aquatic Plant Information System),
[2] The two most significant components to water chemistry for plant growth are inorganic carbon (dissolved carbon dioxide, carbonate, and other forms) and dissolved plant macro- or micronutrients.

14.3 Gained experience

Experience gained over the past decades indicates that artificial seaweed can be successfully applied for scour prevention around the legs of offshore platforms and around offshore pipelines. In general one of the main engineering problems has been the anchorage of the seaweed on the bottom.

Though successful in scour prevention the use of artificial seaweed has proven unsuccessful in the prevention of beach erosion so far. Experiments with artificial seaweed to prevent beach erosion have been carried out in Barbados (1983/1984) and The Netherlands (Texel, 1975/1976). Appendix 44 gives details on the experience gained in the Netherlands, a summary is given below:

- **Barbados** In Barbados the artificial seaweed was deteriorated within a short period of time as a consequence of perpetual wave attack in the breaker zone. The artificial seaweed was almost erased entirely and the prevention of beach erosion could not be achieved
- **Texel** At the test fields around Texel the results were promising at first. The artificial seaweed clearly enhanced sedimentation. However the nylon fibers (the leaves of the artificial seaweed) absorbed sea-water resulting in an increase in density from 200 kg/m^3 to 1100 kg/m^3. This resulted in the sinkage of the leaves of the artificial seaweed. Consequently when the artificial seaweed rested horizontally on the sea bottom it enhanced erosion instead of preventing it.

Experience gained from other experiments and applications with artificial seaweed are summarized in Table 14-1.

Concepts	Implemented	Experience gained
Cegrass Synthetic seaweed made of foamed polypropylene, attached to open grid mat, held to seafloor by ballasts.	- Germany 1985 - Italy - Victoria USA 1989	Successful in the prevention of scour (around pipelines).
MARIRON sea-grass Synthetic seaweed attached to open grid mat, held to seafloor by ballasts.	- Norway - Japan	Successful in the prevention of scour around pipelines
Nylon strings[3] Nylon strings attached to a tube held to seafloor by ballasts.	- Netherlands 1975/1976 (Texel North and Vlieland)	Partly successful in accumulation of sediments
Seascape Synthetic seaweed, plastic threads attached to a bag which is filled with sand to anchor the construction.	- Cape Hatteras, NC 1981 - Barbados 1983/1984	Unsuccessful in the prevention of beach erosion

Table 14-1 Experience gained on with artificial seaweed

[3] Nylon strings with a diameter of about 3mm and a height of about 1m placed 600m seaward of the coastline. [ref conversation with "Rijkswaterstaat"]

15 Theoretical background

15.1 Sediment transport without artificial seaweed

Sedimentation in a trench, as the open water section of the MRGO, mainly depends on the abrupt change in waterdepth between the trench and the surrounding flats (Chapter 7.2.7.). When a current (tidal, longshore or wind-induced) crosses a channel perpendicular the water velocity will decrease as the waterdepth increases[4].
This rapid decrease in current velocity has significant impact on the sediment transport perpendicular over the channel. The sediment transport consists of bed load sediment transport and suspended load transport.

15.1.1 Bed load transport

Bed load transport consists of sediments rolling over the bottom, dragged along by the current. The bottom transport mainly depends on the bottom shear stress (in turn depending on the current velocity) and the grain size of the sediments. When the current velocity decreases the shear stress decreases as well. Consequently smaller amounts of sediments are lifted from the bottom.

15.1.2 Suspended load transport

Relative smaller sediments (with a relative smaller fall velocity) remain in suspension over a considerable period of time. Suspended sediment transport can be described quite generally as the product of the current velocity and the sediment concentration [REF 4]. The sediment concentration depends (among others) on vertical mixing. The boundary layer established by the artificial seaweed could reduce the amount of vertical mixing and consequently the amount of suspended load sediment transport.

[4] The same amount of water through a larger cross-section results in a lower current velocity.

15.1.3 Sediment balance

Figure 15-1 shows a balance area with a part tidal flat and a part of the MRGO cross section. The current velocity at the boundary “In” is higher than the current velocity “Out”. Consequently the amount of bottom load transport and the amount of suspended sediment transport decrease as the current velocity decreases. Figure 15-1 shows that the sediment inflow is larger than the sediment outflow for the balance area. Consequently sedimentation occurs within the area.

$S_{in} = S_{out}$ + sedimentation

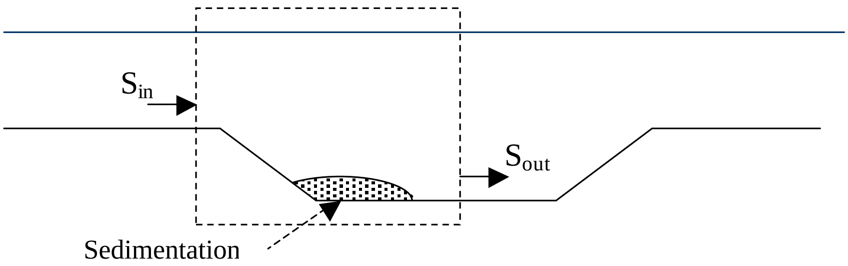


Figure 15-1 Sedimentation balance **without** artificial seaweed

15.2 Artificial seaweed

The impact of the artificial seaweed on the current velocity is discussed first, using the hydraulic roughness of the artificial seaweed. Consequently the effects of the artificial seaweed on the sediment transport are addressed.

15.2.1 Hydraulic roughness of vegetation

THE CALCULATION OF THE HYDRAULIC ROUGHNESS IS BASED ON THE APPROACH OF KLOPSTRA ET AL. (1987), MEIJER & VAN VELZEN (1999) AND STOLKER & VERHEIJ (2000). [REF 68, 69 AND 70]

The calculation of the hydraulic roughness is essential in calculating the cost-optimized dimensions of the artificial seaweed. This paragraph explains the calculations of the hydraulic roughness and serves as a foundation for paragraph 17.1.

Figure 15-2 shows the current velocity distribution for a flow through artificial seaweed (cylindrical stalks). The velocity distribution is logarithmic above and slightly in the vegetation (the depth to which the logarithmic velocity distribution enters into the canopy is defined as h_s).

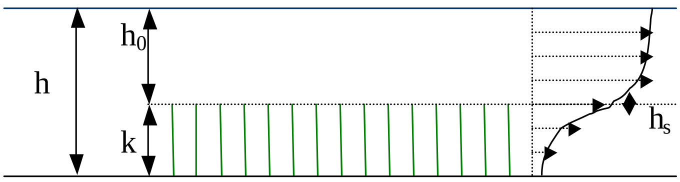


Figure 15-2 Velocity distribution through and above the canopy

For this **top layer** (h_0+ h_s) a simplified White-Colebrook-type formulation can be used to calculate the Chezy value [REF 65 & 66]:

$$C_0 \; ? \; 18\log\frac{12(h \; ? \; k \; ? \; h_s)}{k_t}$$

For the flow **through** the vegetation the roughness can be derived from the drag force from the plants[5] (for h = k, emerged vegetation) [REF 65 & 66]:

$$C_v \; ? \; \sqrt{\frac{2g}{C_d mdh}}$$

[5] The bottom friction is assumed negligible compared to the friction of the artificial seaweed

The flow through and above the vegetation layer can be described by a combination of both mean velocities. This approach combines both formulations by taking the weighted average over the depth (for h > ksubmerged vegetation) [REF 65 & 66]:

$$C ? \frac{\overline{U}}{\sqrt{hi}} ? \frac{(k ? h_s)U_v ? (h ? k ? h_s)U_0}{h\sqrt{hi}}$$

With the mean velocities:

$$U_0 ? C_0\sqrt{(h ? k ? h_s)i} \qquad \text{and} \qquad U_v ? C_v\sqrt{hi}$$

Chezy becomes:

$$C ? \frac{(k ? h_s)\sqrt{\frac{2g}{C_d mdh}}\sqrt{hi} ? (h ? k ? h_s)18\log ?\frac{12(h ? k ? h_s)}{k_t}? \sqrt{?h ? k ? h_s ?i}}{h\sqrt{hi}}$$

And consequently:

$$C ? \frac{(k ? h_s)\sqrt{\frac{2g}{C_d md}} ? (h ? k ? h_s)18\log ?\frac{12(h ? k ? h_s)}{k_t}? \sqrt{?h ? k ? h_s ?}}{h\sqrt{h}}$$

The equation to estimate the Chezy value for submerged vegetation has two unknown parameters, the height h_s (the depth to which the logarithmical velocity distribution progresses into the vegetation) and the roughness height for the top of the vegetation k_t. Stolker and Verheij (2000) found a relation between k and k_t [ref 46]: $k_t = 0.6k^{0.45}$ Consequently the h_s can be calculated using the method given in appendix 36.

Symbol	Unit	Explanation
C	$[m^{½}/s]$	Chezy coefficient
C_d	[-]	Drag coefficient of the vegetation[6]
d	[m]	Leave diameter
h	[m]	Water depth
h_0	[m]	Water depth above vegetation
h_s	[m]	Intrusion depth of the logarithmical velocity distribution in the vegetation
i	[-]	Slope
k	[m]	Height artificial seaweed
k_t	[m]	Nikuradse roughness height for the top a the vegetation layer
m	$[m^{-2}]$	Plant density, number of plants per square meter

Table 15-1 Calculation hydraulic roughness of artificial seaweed

[6] Based on measurements by Tsujimoto & Kitamura (1990) [ref 67 (p42)] a drag coefficient of 1.4 has been used to calculate the hydraulic roughness of the artificial seaweed.

15.2.2 Velocity distribution

In uniform flow conditions the velocity distribution over the depth is logarithmical. The velocity distribution changes significantly for a flow through artificial seaweed. The flow experiences an increased friction between the artificial seaweed[7]. Consequently the current velocity between the artificial seaweed is lower than the current velocity above the seaweed.

The velocity distribution is calculated with the 1DV-model, appendix 45 gives details on the theoretic background of the model.

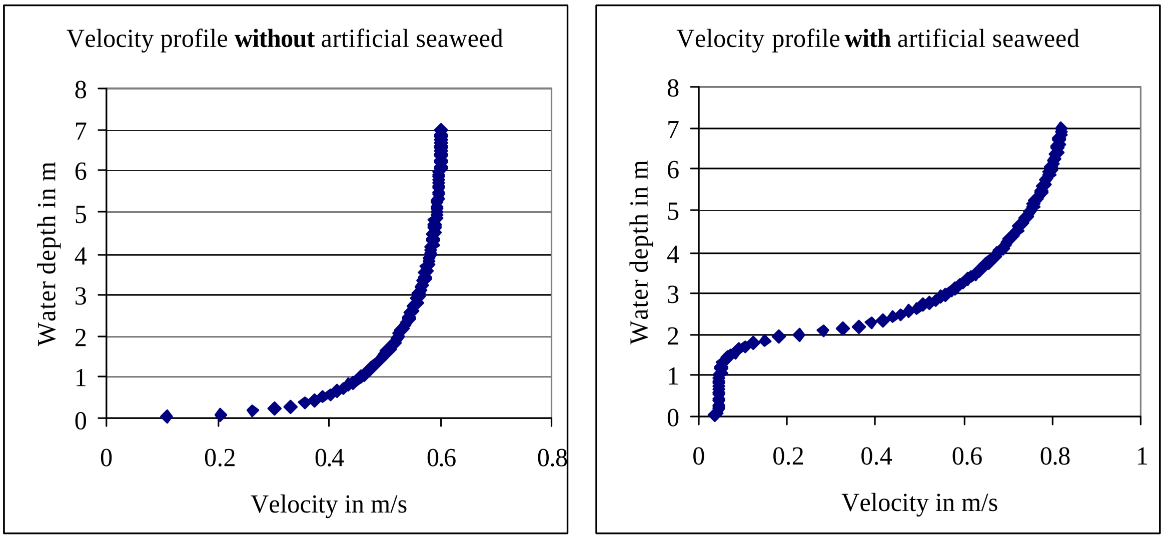


Figure 15-3 Velocity distribution with and without artificial seaweed

Figure 15-3 shows a logarithmical velocity distribution in uniform flow (figure left) and a velocity distribution[8] at a location of artificial seaweed[9] (figure right).
The depth averaged current velocity in both figures is 0.5 m/s. Figure 15-3 shows clearly that the current velocity between the artificial seaweed is lower than without the artificial seaweed.

[7] The area of friction is increased by the surface of the artificial seaweed.
[8] The velocity in Figure 15-3 is the averaged velocity for a certain waterdepth. The actual current velocity between the leaves is slightly higher since the flow area is slightly reduced by the surface of the artificial seaweed. However this effect is negligible for a small cross section of the artificial seaweed.
[9] Figure 15-3 has been made using the 1DV model. Uniform flow conditions, u = 0.5 m/s. The artificial seaweed has been modeled as cylindrical stalks with a height of 2m, a diameter of 0.05m, and a density of 10 stalks/m^2.

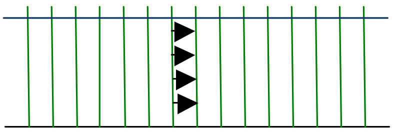
15.2.3 Turbulence

Turbulence is caused by a velocity gradient perpendicular to the main flow direction. This gradient can exist between an object and the flow (wall/ wake turbulence) and between two flow layers (free turbulence) [REF 2].

Wake turbulence[10] occurs when the water flows between the artificial seaweed. Free turbulence occurs when two layers of fluid move along each other with different velocities. The relative fast flowing top layer endures friction from the flow that passes through the artificial seaweed.

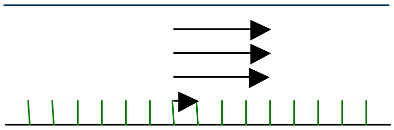
The relative dominance between the wake turbulence and free turbulence (above the artificial seaweed) mainly depends on the height of the artificial seaweed. The following three scenarios can be identified [REF 63 and REF 64]:

I. Emerged canopy



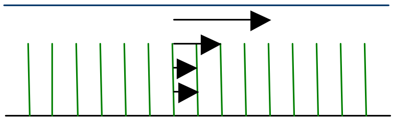
When the height of the artificial seaweed is larger than the waterdepth wake turbulence is the only form of turbulence.

II. Deeply submerged canopy



When the height of the artificial seaweed is negligible relative to the waterdepth the vertical turbulent transport of momentum from overlying flow controls the flow within the artificial seaweed [REF 63]. Wake turbulence is negligible compared to the free turbulence.

III. Submerged canopy



For other heights of artificial seaweed both wake and free turbulence influence the current pattern. The influence of the free turbulence increases towards the top of the artificial seaweed. In the lower flow zone the turbulence is dominated by wake turbulence. In case the artificial seaweed has sufficient height the free turbulence is not able to reach the bottom. The depth to which the turbulence penetrates into the artificial seaweed is $2 \cdot h_s$ [REF 68]

[10] Induced by the flow around the artificial seaweed

15.2.4 Sediment transport

The velocity distribution with and without artificial seaweed clearly shows that the current velocity between the artificial seaweed is lower than without the artificial seaweed (paragraph 15.2.2).
A lower current velocity results in lower shear stress on the bottom. Consequently smaller amounts of sediments are lifted from the bottom. Hence the amount of sediment transport (bed load transport) is reduced.
Shields found that there is a threshold shear stress, below which virtually no sediment transport takes place [REF 2].
If the height of the artificial seaweed is sufficient the free turbulence will not affect sediments on the sea bottom. Wake turbulence between the leaves could increase the amount of suspended materials. However the low current velocity would cause the sediments to settle quickly. Moreover the sediments would not be able to reach the fast flowing top layer.

The objective of the artificial seaweed is to limit sedimentation in the open water section of the MRGO channel by reducing the amount of sediment transport towards the channel.

Next to balance area "tidal-flat/MRGO" (balance area II in Figure 15-4, discussed in paragraph 15.1.3) the balance area "artificial seaweed" (balance area I in Figure 15-4) is included in the sediment transport balance.

The amount of sediment transport determined by the boundary conditions of the Breton Sound (S_{in} I) remains unchanged compared to the situation of no artificial seaweed.
S_{out} II is smaller than S_{in} I which results in sedimentation in balance volume I.
However S_{in} II (equal to S_{out} I) is smaller than in the scenario of no artificial seaweed
If S_{in} II could be reduced (close) to the S_{out} II the amount of sedimentation in the MRGO channel would be reduced.

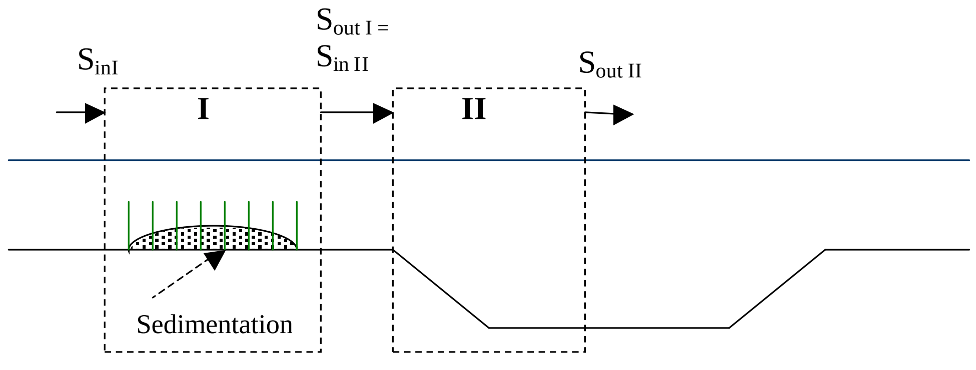


Figure 15-4 Sedimentation balance **with** artificial seaweed

S_{in} I = S_{out} I + sedimentation
S_{out} I = S_{in} II
S_{in} II = S_{out} II

Without sufficient data on the boundary conditions and the sediment characteristics the amount of sediment transport can not be calculated. However the objective of the artificial seaweed is to reduce the sediment transport $S_{out\ I}$ to a value close to $S_{out\ II}$. This can be achieved by decreasing the current velocity within volume I. This in turn can be achieved by increasing the roughness in volume I.

16 Restrictions

16.1 Requirements

Ecological

- The artificial seaweed system should remain fixed at its designated location.
- The material should not contaminate the ecosystem under any circumstance (even in case of deterioration of the artificial seaweed the materials should not contaminate the surrounding ecosystem).
- The use of recycled materials has preference above the use of non recycled materials.

Functional

General

- The artificial seaweed should enhance sedimentation.
- The seaweed should withstand severe weather conditions (hurricane conditions).
- The anchorage system should remain fixed at its designated location.
- The anchorage system should be protected against scour.
- The location of the artificial seaweed area should be marked to prevent vessels sailing over the artificial seaweed.

Material

- The material should provide sufficient buoyancy for the leaves to remain in their upright position (either by a low specific density or buoyancy parts).
- The material should be resistant against:
    - salt water
    - prevailing ph values
    - ultra violet
    - current and wave attack
- The material should have a minimum lifespan of 20 years.
- The material should maintain its required buoyancy over the considered lifespan.
- The material should prevent the growth of algae and bacteria on the surface of the artificial seaweed.

Economical

- Standardized construction and execution methods are preferred to reduce the capital costs.

Execution

- The placement of the artificial seaweed on the sea bottom from standard, presently available, seaborne equipment is preferred.

Law

- The design should not violate any active patent.
- The design should not violate any U.S. laws.

16.2 Starting conditions

- The direction of the tidal currents is perpendicular to the channel.
- To simplify the velocity distribution calculations the average current velocity is set equal in both directions

16.3 Assumptions

- The amount of sediments transport is assumed in the same order of magnitude[11] in both directions (perpendicular over the channel).
- The 1DV model can be used to calculate the velocity distribution over the depth for locations with artificial seaweed.
- The average current velocity perpendicular to the channel is **assumed** to be 0.5 m/s (both directions).
- The D_{50} of the sediments at the surrounding flats is **assumed** to be 100 µm.
- Current velocity during extreme weather conditions is 1.4 m/s [REF 45].

[11] This assumption might not hold since the current velocity changes direction as the MRGO progresses towards the Gulf of Mexico (chapter 3.2.3.5.).

17 Initial dimensions

Initial dimensions of the artificial seaweed are addressed before the variants of the artificial alternative are generated. The initial dimensions of the artificial seaweed are derived from a cost optimization. For a required functionality (paragraph 17.1) a cost optimization is carried out in paragraph 17.3.
In this chapter the method of the cost optimization is explained. Initial dimensions of the artificial seaweed are calculated merely to illustrate the cost optimization process.
In chapter 20 a cost optimization is carried out for three different variants with the use of the method explained in this chapter.

17.1 Functionality

The required functionality is related to the enhanced sedimentation between the artificial seaweed. The sedimentation rate depends on the following three dimensions of the artificial seaweed:

- Density of the leaves (number of leaves per square meter)
- Diameter of the leaves[12]
- Height of the artificial seaweed[13]

The main dimensions of the artificial seaweed have their impact on the sediment transport through different relations; an overview is given in Figure 17-1.

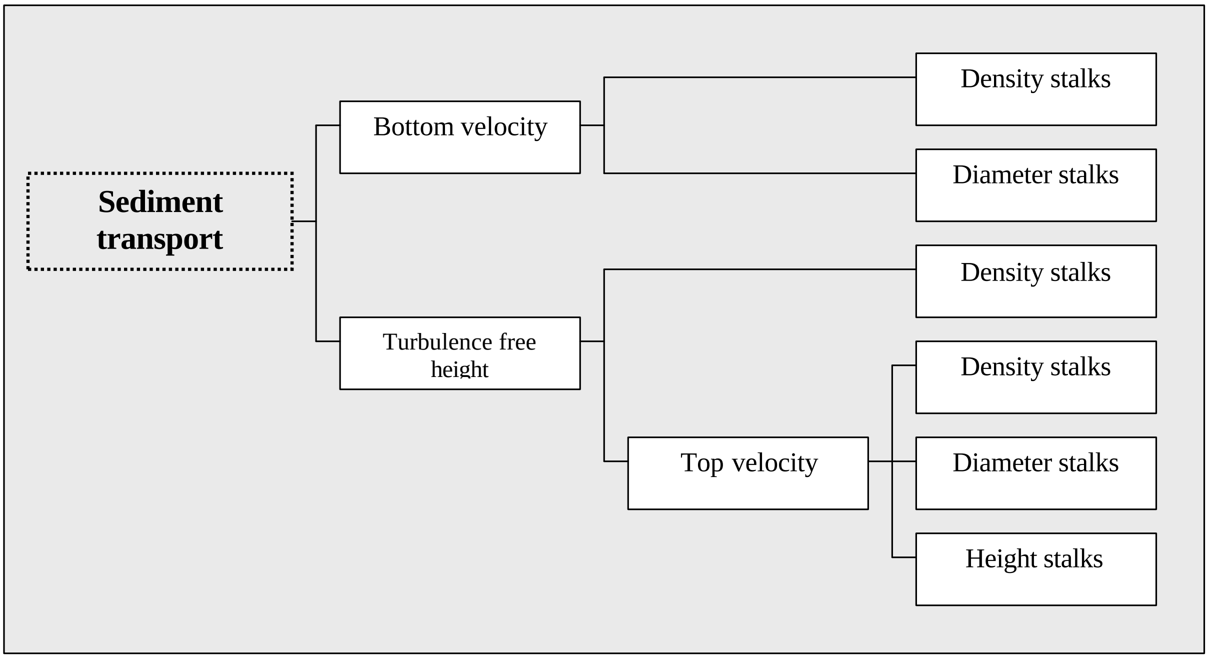


Figure 17-1 Relation between main dimensions and sediment transport

[12] A cylindrical shape of the artificial seaweed is used in the hydraulic roughness calculations.
[13] The length of the artificial seaweed leaves.

The objective of the artificial seaweed is to enhance sedimentation between the artificial seaweed in order to reduce the sedimentation in the MRGO channel. This objective can be translated into a required functionality. The required functionality of the artificial seaweed can be expressed in a maximum bottom velocity (and consequently the bottom shear stress) and a minimum turbulence free height[14].

The actual translation of the required sedimentation reduction in the MRGO channel into a value for the maximum bottom velocity and a minimum turbulence free height requires detailed data on the natural boundary conditions of the considered area.
So far sufficient data on the current velocities and the sediment characteristics is not available. In paragraph 16.3 assumptions are listed used in the calculation of the dimension optimization of the different variants.

The relation between the bottom velocity and dimensions of the artificial seaweed (density and diameter) is:

$$U_v ? \sqrt{\frac{2gi}{C_d m d}}$$

The turbulence free height can be derived form the turbulence intrusion. The turbulence intrusion can be addressed after calculating the current velocity above the artificial seaweed. Given the prevailing boundary conditions the current velocity above the artificial seaweed can be calculated with the approach of Klopstra et al, explained in paragraph 15.2.1.
The depth to which the turbulence penetrates into the artificial seaweed is $2 \cdot h_s$ REF 68
The relations between h_s and the dimensions of the artificial seaweed are given in appendix 36, the calculation of the hydraulic roughness, essential to calculate h_s, is given in paragraph 15.2.1.

[14] Over this turbulence free height the turbulence induced by the flow above the artificial seaweed is not capable of entering the bed.

17.2 Construction costs

The construction costs of the artificial seaweed depend (among others) on the anchorage cost and material cost[15]. The construction costs highly depend on the shape and the construction material of the artificial seaweed. To simplify the cost optimization only the anchorage and the material costs are considered. Other aspects like the complexity of the structure or the construction method are not regarded in this study.

Figure 17-2 shows the relation between the main dimensions and the construction costs.

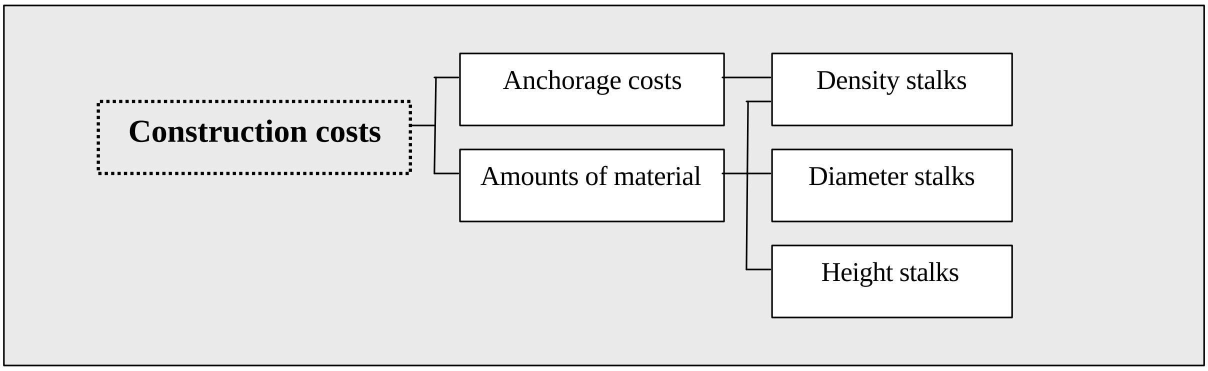


Figure 17-2 Relation between main dimensions and costs

Anchorage costs

The anchorage costs depend on the specific anchorage system and the density of the artificial seaweed[16].

Material costs

The material cost (per square meter seafloor) is equal to the volume of one leave multiplied by the density of the leaves multiplied by the cost per cubic meter.

[15] The construction costs are assumed to be the sum of the anchorage cost and the material cost
[16] Anchorage costs = costs per anchorage·density

17.3 Cost optimization

For a required functionality (a specific bottom velocity and a specific turbulence free height) a cost optimization can be carried out.

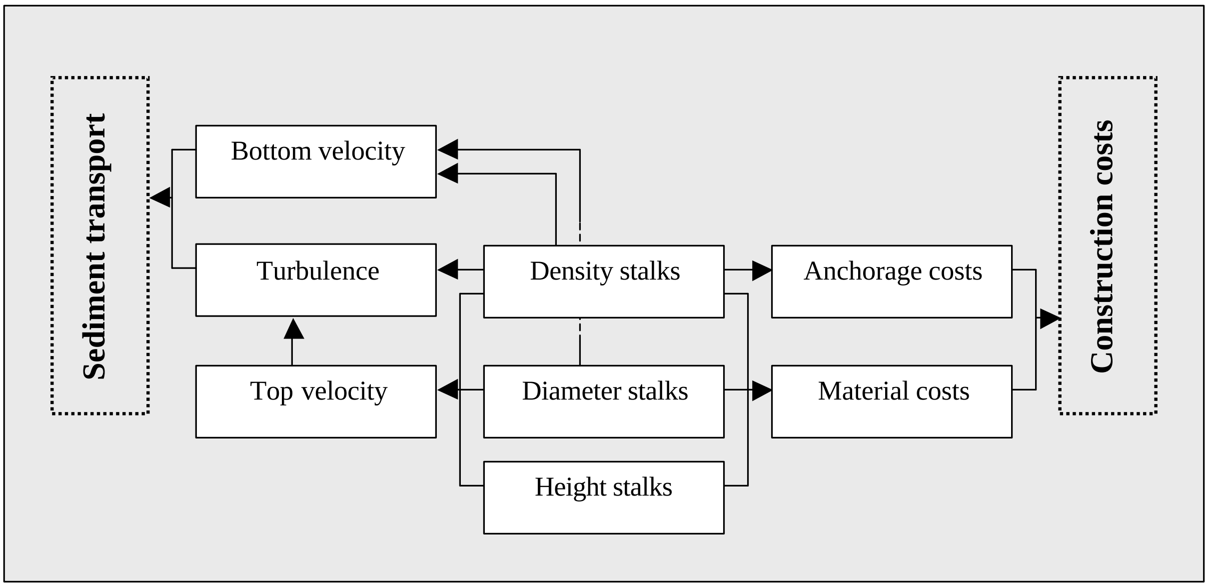


Figure 17-3 Dimensions related to sediment transport and construction costs

A range of potential values is given for each dimension based on practical conditions[17]. The bottom velocity and the turbulence free height are calculated for each possible combination of the three different dimensions. This gives a three dimensional space of possible combinations of dimensions. Combinations that do not meet the constraints of the required bottom velocity and the required turbulence free height are removed. The result is a three dimensional solution space that meets the constraints. Finally the construction costs are calculated for each point within the solution space. The dimensions that correspond to the point in the solution space with the lowest construction costs are taken as the initial dimensions.

[17] For example: The height of the artificial seaweed is limited by the waterdepth or navigation requirements

17.4 Cost optimized initial dimensions

The process of the cost optimization is outlined in paragraph 17.1 to 17.3. In this paragraph the initial dimensions are optimized to illustrate the cost optimization process. The cost optimized dimensions have been calculated based on the boundary conditions and assumptions from Table 17-1.

Conditions/ assumptions	Value	Unit
Waterdepth	7.00	[m]
Material cost per cubic meter	10,000	[$]
Cost per anchorage	20	[$]
Present $U_{average}$	0.50	[m/s]
Present Chezy	50	[$m^{0.5}$/s]
Present i	2.29?10^{-4}	[-]
Drag coefficient	1.4	[-]

Table 17-1 Conditions and assumptions dimension calculation

The boundaries of the three-dimensional solution space are set by the constraints and requirements from Table 17-2.

Constrains	Min	Max	
Vegetation velocity	0.01	0.50	[m/s]
Turbulence free height	1.50	7.00	[m]
Height seaweed	0.10	3.50	[m]
Diameter seaweed	0.02	0.50	[m]
Density seaweed	1.00	1000	[m^{-2}]
Cross section area	0.00	1.00	[m^2]

Table 17-2 Constraints and requirements dimension calculation

Consequently the cost optimized initial dimensions are given in Table 17-3.

Dimension	Optimized value	
Height seaweed	3.50	[m]
Diameter seaweed	0.09	[m]
Density seaweed	5.04	[m^{-2}]

Table 17-3 Cost optimized dimensions

Figure 17-4 gives the velocity distribution over the depth for artificial seaweed with the cost optimized initial dimensions.

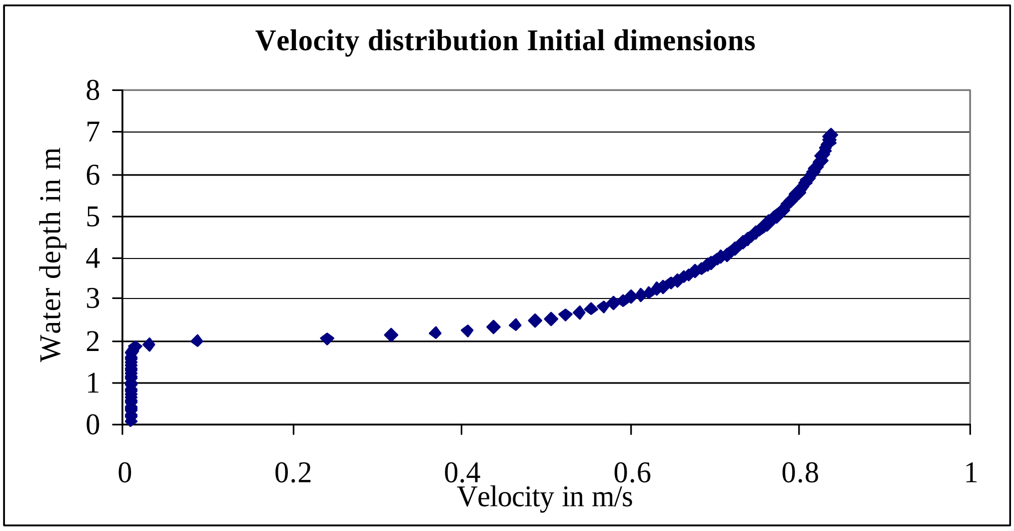


Figure 17-4 Velocity distribution for the cost optimized initial dimensions

18 Concepts

The artificial seaweed consists of leaves and an anchorage system. The leaves have to induce sufficient friction to reduce the current velocity. An anchorage system is needed to keep the artificial seaweed on a fixed location at the bottom of the sea. Important aspects in the generation of the concepts are:

- Flexibility
- Leaves
- Anchorage system

18.1 Flexibility

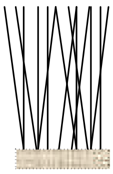
The effectiveness of the artificial seaweed depends among others on the flexibility of the artificial seaweed. Experiences gained from test sections with artificial seaweed (at Texel, The Netherlands) show that when the artificial seaweed remains in the upright position the seaweed is successful in the accumulation of sediments.
However when the seaweed lies flat on the sea-bottom (due to failure or extreme current velocities) the artificial seaweed enhances erosion instead of preventing it.
The position of the artificial seaweed can be derived from the drag-force, the floating-force and the flexibility of the material.

A higher flexibility of the material will result in lower internal forces and lower forces on the anchorage system. However in case the drag forces are dominant over the flexibility and the buoyancy the artificial seaweed will lay flat on the sea bottom. As mentioned above in this case the artificial seaweed will enhance erosion instead of preventing it.

18.2 Leaves

The leaves of the artificial seaweed have to induce sufficient friction to reduce the current velocity. Some promising concepts of leaves are discussed below:

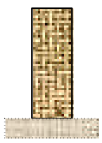
Separate fibers



Numerous individual fibers are attached to an anchorage system. The fibers are thin and have a large flexibility.

Advantages:	- Relative efficient use of material
	- Cost effective and simple construction
	- Low internal forces
Disadvantages:	- Vulnerable to failure

Woven fibers



The fibers are woven together to a geotextile, resulting in high tensile strength.

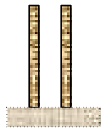
Advantages:	- Cost effective
	- High tensile strength
Disadvantages:	- Low flexural strength
	- Limited leaf thickness

Braided fibers

A rope like construction is formed by braiding the separate fibers together. The ropes have more strength than the separate fibers.

Advantages: - Cost effective
- High tensile strength

Disadvantages: - Low flexural strength
- Only possible in cylindrical shape

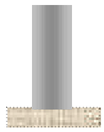


Solid construction

A solid leaf of plastic gives more flexural strength.

Advantages: - Cost effective
- High tensile- and flexural-strength

Disadvantages: - Relative inefficient and expensive use of materials



18.3 Anchorage

Floatability of the anchorage system

The floatability of the anchorage system is crucial in the functionality of the artificial seaweed. The anchorage system should have sufficient floatability to prevent sinkage in the soft sea bottom.
On the other hand should the total weight of the anchorage system be sufficient to ensure a fixed position on the sea bottom, even during extreme conditions. Therefore the weight of the anchorage system should be larger than the sum of the drag force (during extreme conditions) and the buoyancy of the leaves.

Rigid versus flexible

The connection between the leaf and the anchorage can be rigid or flexible. A rigid connection can force the leaf to remain in the upright position, which could lead to a higher functionality. However the forces on the anchorage system are higher for a rigid connection than for a flexible connection.

Single anchorage

A relative small system (for a small number of leaves) like small geotube could be used to anchor the artificial seaweed to the sea bottom. The main advantage of a single construction is the relatively simple placement of the artificial. The artificial seaweed could be placed on the sea bottom from almost any seaborne structure. Moreover a single anchorage system is less vulnerable to settlement.

The single anchorage system would have to be protected against local scour induced by turbulence around the leaves of the artificial seaweed.

Geotextile anchorage system
One other option to anchor the artificial seaweed to the sea bottom is the use of a geotextile. The leaves can be attached to a geotextile which is kept to the bottom by ballast elements. This would prevent scour around the anchorage system.
Moreover the structure is more resistant against the drag forces during extreme conditions. However the placement of the structure would require special equipment. The artificial seaweed could be attached to the geotextile on forehand or on the boat just before sinkage.

18.4 Concepts
Different combinations between the anchorage system and the leaves are possible. A score is given to each combination (score range from --,-, + to ++) based on the feasibility of a combination.

Leaves Anchorage	Separate fibers	Woven fibers	Braided fibers	Solid construction
Rigid and single	-	+	-	+
Rigid and geotextile	--	-	--	+
Flexible and single	++	+	+	++
Flexible and geotextile	-	-	-	++

Table 18-1 Combinations leaves and anchorage systems

The three most promising combinations are discussed in chapter 20.
An overview of the three most promising combinations of leaves and anchorage systems is given in Table 18-2.

	Variant	Combination
1.	sea-grass	Separate fibers attached to a flexible and single anchorage system
2.	rigid-flaps	Solid construction attached to a flexible anchorage system (singe or geotextile)
3.	bending-finger	Solid construction attached to a flexible anchorage system (singe or geotextile)

Table 18-2 The most promising combinations of leaves and anchorage systems

19 Material selection

The material selection has been carried out parallel to the generation of concepts. Different concepts require other material characteristics. The material selection is mainly based on the following aspects:

- Mechanical characteristics (flexibility, toughness, water absorbance etc.)
- Density
- Durability
- Costs

Potential materials

Potential materials that could be used for the construction of artificial seaweed are:

- Polyethylene (PE)
- Polypropylene (PP)
- Polyamide (PA)

Mechanical characteristics

Polyethylene (PE)

Polyethylene is one of the most commonly used polymers thanks to its high toughness, ductility, excellent chemical resistance and very low water absorbance.

Polypropylene (PP)

Polypropylene has a similar structure compared to polyethylene. However polypropylene is harder and has a higher elasticity than Polyethylene. A unique characteristic of polypropylene is the resistance against repeating bending.

Polyamide (PA)

Polyamide, or nylon, has a relative high resistance against wear, since polyamide is able to withstand high mechanical and thermal stresses. However polyamide is vulnerable to water absorption.

Table 19-1 gives an overview of the different materials and their characteristics.

Characteristics / Materials	Density	Durability	Relative costs [18]
Polyethylene (PE)	950 kg/m^3	High	$ 1536.-
Polypropylene (PP)	910 kg/m^3	High	$ 1364.-
Polypropylene (gas injected)	200 kg/m^3	High	$ 1364.-
Polyamide (PA)	1130 kg/m^3	Low	$ 1291.-
Polyamide (gas injected)	200-700 kg/m^3	Low	$ 1291.-

Table 19-1 Material characteristics

[18] Price per 100 kg [REF 76]

Density
The density of the artificial seaweed has to be smaller than the density of salt-water in order to obtain the upright position of the seaweed. Experiments have been carried out by Delft Hydraulics [REF 74 and 75] to address the influence of the density (of the artificial seaweed) on the critical current velocity. Measurements show an almost equal amount of velocity reduction for artificial seaweed with a density between of 200 kg/m^3 and 950 kg/m^3. The densities of the different plastics can be adjusted by the injection of gas during the extrusion process. Consequently the density of the materials is not the dominant selection criterion.

Durability
The artificial seaweed has to withstand the current-induced-forces on the material. Some concepts require material that can bend persistently, polypropylene is extremely suitable for this requirement. Most synthetic polymers are sensitive to light (ultraviolet), oxygen, moisture and heat. Carbon or UV stabilizers can be added to make the material resistant against ultraviolet [REF 76]. Nylon is vulnerable to the absorption of water which reduces the durability of the material significantly.

Costs
The cost of the construction mainly depends on the shape of the construction and the construction method, the unit price per 100 kg is comparable for the different potential materials.

20 Variants

20.1 Sea-grass variant

The sea-grass variant is the most simple of the proposed variants. The sea-grass variant has been designed with the emphasis on simplicity and low construction costs.

20.1.1 Leaves

The leaves of the sea-grass variant consist of separate nylon fibers (PA, Polyamide) in a relative high density (number of leaves per square meter). The leaves are placed in a single row and attached to a single anchorage system. The anchorage system consists of a small geotube. The leaves have a high flexibility and their flexural strength is negligible. The position of the nylon threads is equal to the combination of the buoyancy force and the drag force of the current. Not as effective as in the vertical position, the nylon threads will still reduce the shear stress on the sea bottom.

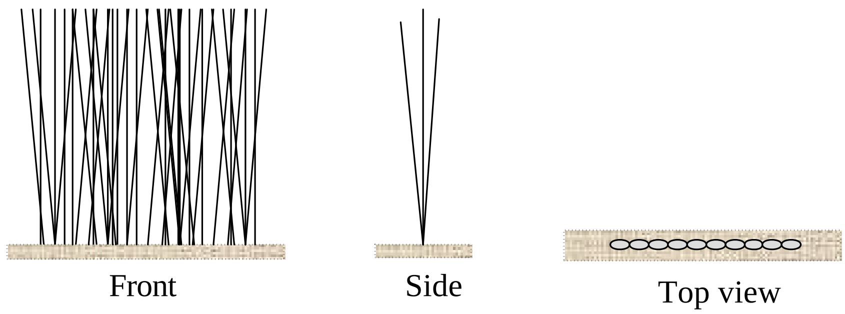


Figure 20-1 Impression of the sea-grass variant

20.1.2 Anchorage

The anchorage of the sea-grass variant is simple. The geotube gives the required downward force to keep the artificial seaweed on a fixed position. A balance between the bearing capacity of the bottom the buoyancy of the leaves and the drag forces under extreme weather conditions. The width of the anchorage system should be larger than its height to prevent the anchorage system from flipping over (even if the anchorage would settle and roll over the nylon threads would regain their vertical position, and the functionality would not be lost totally). Furthermore flexibility in the length-direction of the anchorage system should be guaranteed to allow the geotube to adapt the shape of the sea bottom in order to prevent tear of the geotextile or erosion underneath the anchorage system. This flexibility can be achieved by not totally filling the geotube.

20.1.3 Execution

Construction method

The nylon threads are attached to a geotube. The nylon threads can easily be attached on the geotextile by sewing the middle of the thread on a geotextile mattress. In this way one thread will form two leaves and is strongly attached to the middle of the mattress.

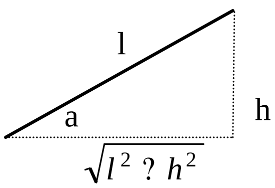
Consequently the geotube is filled with sand and sewn together. Appendix 47 gives a detailed explanation of the construction method.

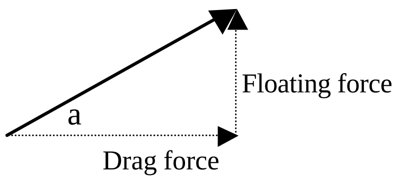
Placement

The placement of the sea-grass variant can be done from any seaborne equipment. The prefabricated geotubes can be lowered gently in the water with the nylon threads faced upwards. The nylon threads will prevent the geotube from rolling over during the sinkage. The geotube will adapt the shape of the sea bottom as it lands on the bottom. The nylon threads will adjust to their vertical position even if the geotube lies on an angle.

20.1.4 Dimensions

When the flexural strength is assumed negligible (which is the case for nylon threads) the artificial seaweed will adapt the same shape as the combined drag- and floating-force. Only the vertical height (h) of the seaweed will contribute to the reduction of the shear stress on the bottom. The height can be calculated using:





$$\cot \alpha = \frac{F_d}{F_f} = \frac{\sqrt{l^2 - h^2}}{h}$$

$$F_f = l \cdot \frac{1}{4} \cdot \pi \cdot d^2 \cdot g \cdot (\rho_w - \rho_s) \quad \text{and} \quad F_d = \frac{1}{2} \cdot C_d \cdot \rho_w \cdot h \cdot d \cdot v^2$$

Symbol		Unit	Explanation
F_f	-	[kN]	Floating force
F_d	-	[kN]	Drag force
l		[m]	Length artificial seaweed
h	-	[m]	Height artificial seaweed above the bottom
d	0.01	[m]	Leave diameter
C_d	1.4	[-]	Drag coefficient of the vegetation[19]
ρ_w	1030	[kg/m^3]	Density (salt)water [REF 4]
ρ_s	500	[kg/m^3]	Density artificial seaweed (Polyamide, gas injected)
v	-	[m/s]	Current velocity

Table 20-1 Position of the artificial seaweed

[19] Based on measurements by Tsujimoto & Kitamura (1990) [ref 67 (p42)] a drag coefficient of 1.4 has been used to calculate the hydraulic roughness of the artificial seaweed.

For a current velocity of 0.5 m/s and a thread length[20] of 4.5 m the vertical height is 2 m.

The dimensions of the sea-grass variant are optimized using the method explained in paragraph 17.4. In calculating the optimized dimensions of the sea-grass variant the diameter of the artificial seaweed is set on forehand.
The diameter is set at 1 cm, a typical diameter for nylon cords [REF 62], with an effective height of 2 m.
Other constrains, requirements and assumption for the calculation of the dimensions of the sea-grass variant are given in appendix 46. The cost optimized dimensions are given in Table 20-2.

Dimension	Optimized value	Unit
(Effective) height seaweed	2.00	[m]
Diameter seaweed	0.01	[m]
Density seaweed	714	[m^{-2}]

Table 20-2 Cost optimized dimensions sea-grass variant

Consequently the velocity distribution is calculated for the optimized dimensions using the 1 DV model (appendix 45).

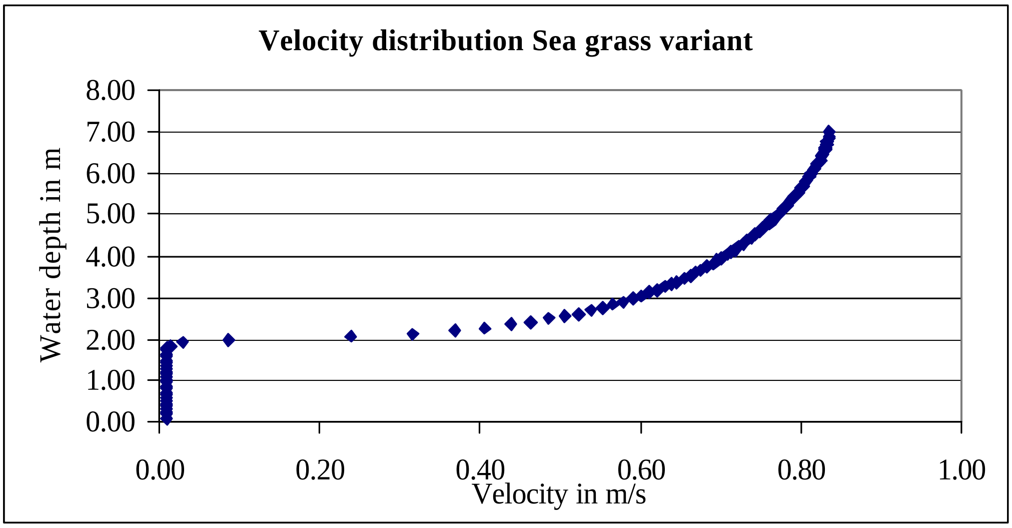


Figure 20-2 Velocity distribution sea-grass variant

[20] The actual length of the nylon thread is 9 m since a thread forms two leaves

20.1.5 Evaluation

The sea-grass variant has been designed with the emphasis on simplicity and low construction costs. The main advantages and disadvantages of the sea-grass variant are:

Advantages

- The individual anchorage system results in a high flexibility of the density (amount of leaves per square meter).
- Low construction costs (standard materials dimensions).
- Simple construction methods (limited parts of the construction).
- Simple and economical placement (placement possible from any sea borne equipment).

Disadvantages

- Nylon threads are vulnerable to the absorption of water (which leads to failure to enhance sedimentation).
- The attachment of the nylon threads to the geotube is vulnerable (which could lead to the release of the threads).

Points of attention

- Special measures should be taken to prevent the growth of algae on the surface of the leaves (the large surface in comparisons to the buoyancy makes this variant especially vulnerable to the growth of algae)

20.2 Rigid-flaps variant

The rigid-flaps variant has been designed with the emphasis on functionality and low construction costs.

20.2.1 Leaves

Solid leaves made of polypropylene are attached to a geotextile mattress. Polypropylene (PP) is chosen as the construction material for its unique resistance against repeating bending. The combination of the high flexural strength and the high buoyancy (low density of the material when injected with gas) will ensure that the leaves remain in a vertical position. Only under high drag forces (extreme current velocities) will the leaves bend and lose their functionality for a short period of time.

Figure 20-3 Impression of the rigid-flaps variant

20.2.2 Anchorage

The rigid flaps are attached to a geotextile mattress. The geotextile mattress is kept on the sea bottom by special ballast material. The connection between the rigid flaps and the mattress is stiff to ensure the upright position of the leaves. This will result in high forces on the anchorage system which have to be transmitted to the mattress.

20.2.3 Execution

Construction method

The attachment of the rigid flaps to the geotextile mattress requires skilled labor and specific equipment, appendix 47.

Placement

The mattress with the attached flaps can be rolled or placed on the sea bottom from specific sea borne equipment, appendix 47.

20.2.4 Dimensions

The dimensions of the rigid-flaps variant are optimized using the method explained in paragraph 17.4. The maximum length of the leaves is set at 2.5m the minimum diameter at 0.1 m and the maximum diameter is set at 0.5m.
Other constrains, requirements and assumption are given in appendix 46. The optimized initial dimensions of the rigid-flaps variant are given in Table 20-3.

Dimension	Optimized value	Unit
Height seaweed	2.50	[m]
Diameter seaweed	0.10	[m]
Density seaweed	7.55	[m^{-2}]

Table 20-3 Cost optimized dimensions rigid-flaps variant

Consequently the velocity distribution is calculated for the optimized dimensions using the 1 DV model (appendix 45), the results are shown in Figure 20-4.

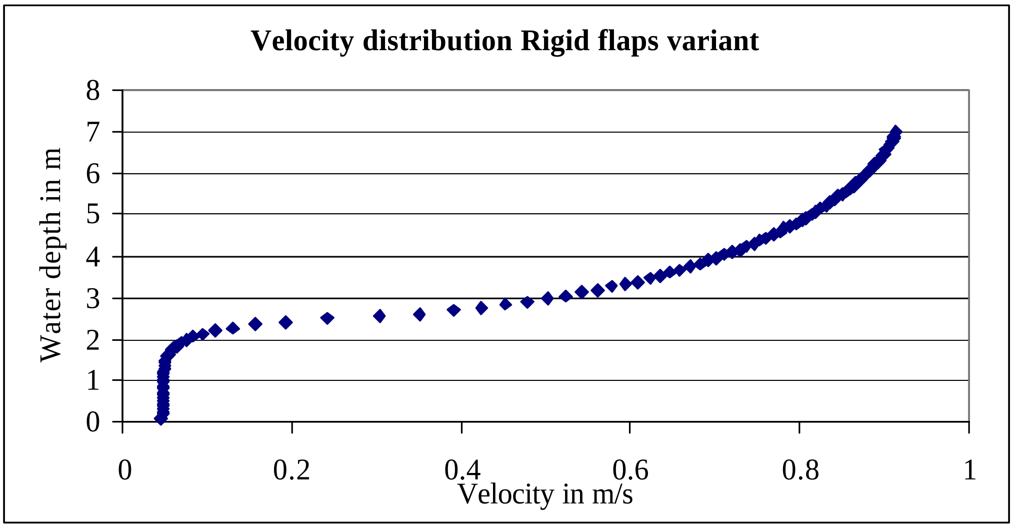


Figure 20-4 Velocity distribution rigid-flaps variant

20.2.5 Evaluation

Advantages

- Simple construction method

Disadvantages

- Construction costs
- Not functional during extreme conditions
- Complicated and uneconomical placement (placement requires special equipment).
- Anchorage system is vulnerable to failure (tear of geotextile mattress).

20.3 Bending-finger variant

The bending-finger variant has been designed with the emphasis on functionality.

20.3.1 General

The sediment transport is perpendicular to the alignment of the MRGO channel[21] and changes direction along with the direction of the tidal current. The direction of the sediment transport is Northeast during ebb and Southwest during flood.

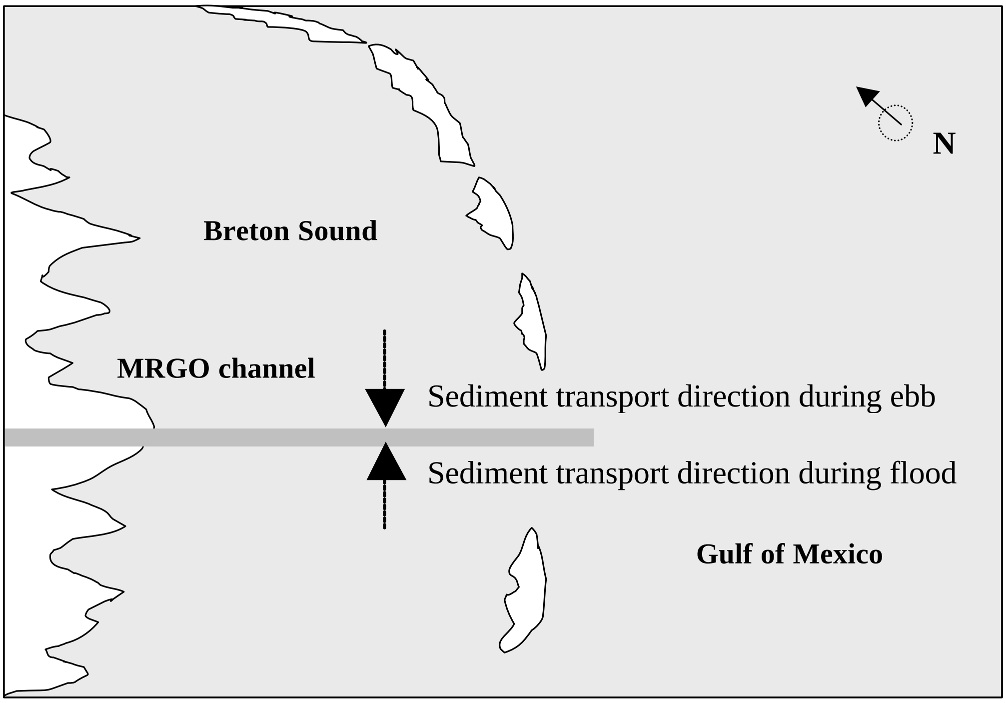


Figure 20-5 Direction of the sediment transport

This change in flow direction has led to the bending-finger variant. The concept of the bending-finger variant is based on:

1. The fact that the artificial seaweed would be most effective in reducing the sedimentation rate in the MRGO channel if the seaweed would prevent sediment transport towards the channel and enhances sediment transport away from the channel.
2. The fact that artificial seaweed prevents erosion when its leaves are in a vertical position and that the artificial seaweed enhances erosion when positioned flat on the sea-bottom[22].

[21] Starting condition paragraph 16.2.
[22] Experiments by Rijkswaterstaat near Texel (The Netherlands) in 1975 and 1976 showed an increase in erosion rate for locations with artificial seaweed lying horizontally on the sea bottom.

The bending-finger consists of leaves that are capable of bending in one direction. Without a current the artificial seaweed has a sufficient floating capability to remain in the upright position. With a current the leaves either stay in the upright position or bend horizontally to the sea bottom. Depending on the direction of the current the artificial seaweed reduces or enhances erosion.

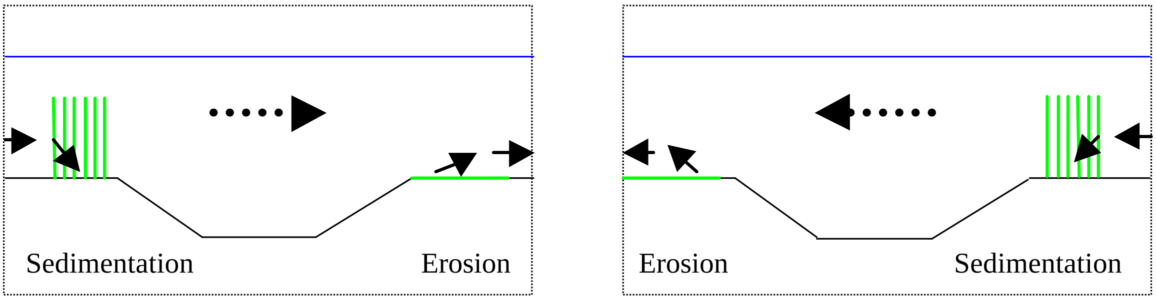


Figure 20-6 Sedimentation and erosion enhanced by the bending-finger variant

20.3.2 Leaves

Blocks made of polyethylene (PE) are attached to a strip of polypropylene (PP). Polyethylene is chosen for its low water absorption (water absorption would decrease buoyancy leading to possible failure) and polypropylene is chosen for its unique resistance against repeating bending.

Multiple bending points are recommended. This to allow bending over accumulated sediments and to reduce the forces on the bending points. However the construction itself is more vulnerable and expensive with more bending points.

The requirement that the leaves should only bend in one direction can be achieved in various ways. In this study a leave with multiple blocks attached to a flexible strip is proposed. Bending in the direction of the strip is possible since the strip is highly flexible. In the opposite direction bending is prevented by the blocks.

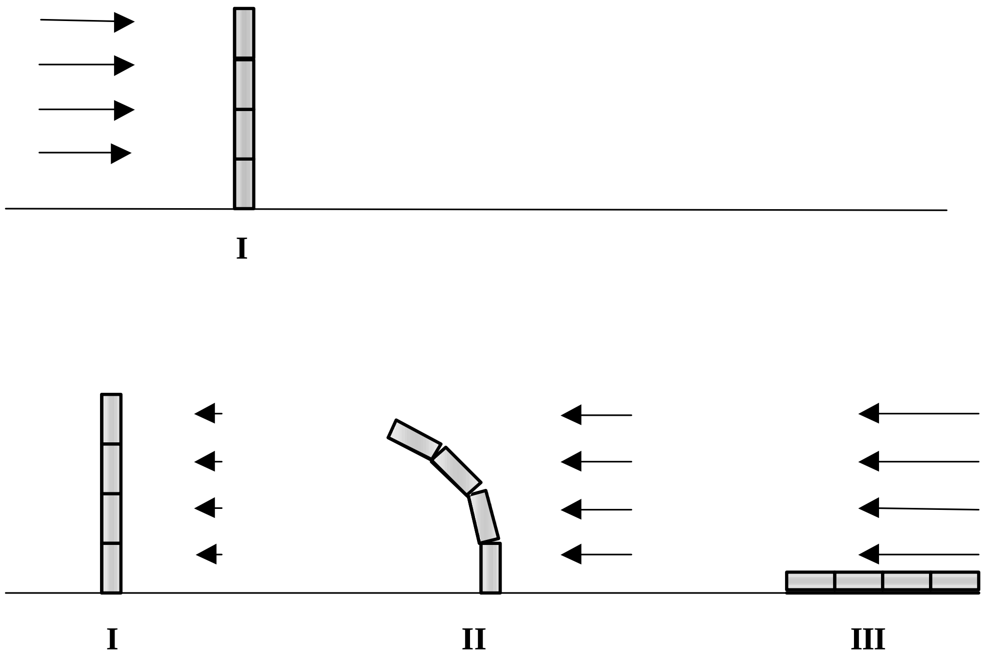


Figure 20-7 Position of the artificial seaweed depending on the current direction and velocity

20.3.3 Anchorage

The bending-fingers are attached to a geotextile mattress. The geotextile mattress is kept on the sea bottom by special ballast material. The connection between the bending-fingers and the mattress is stiff to ensure the upright position of the leaves. This will result in high forces on the anchorage system which have to be transferred to the mattress.

20.3.4 Execution

Construction method
The attachment of the rigid flaps to the geotextile mattress requires skilled labor and specific equipment, appendix 47.

Placement
The mattress with the attached flaps can be rolled or placed on the sea bottom from specific sea borne equipment, appendix 47.

20.3.5 Dimensions

The dimensions of the bending-finger variant are optimized using the method explained in paragraph 17.4. The maximum length of the leaves is set at 2.5m the minimum diameter is set at 0.2m and the maximum diameter at 0.5m.
Other constrains, requirements and assumption are given in appendix 46.
The optimized initial dimensions of the bending-finger variant are given in Table 20-4.
Appendix 48 gives more details on the dimensions of the bending-finger variant.

Dimension	Optimized value	Unit
Height seaweed	2.50	[m]
Diameter seaweed	0.20	[m]
Density seaweed	3.81	[m^{-2}]

Table 20-4 Cost optimized dimensions bending-finger variant

Consequently the velocity distribution is calculated for the optimized dimensions using the 1 DV model (appendix 45), the results are shown in Figure 20-8.

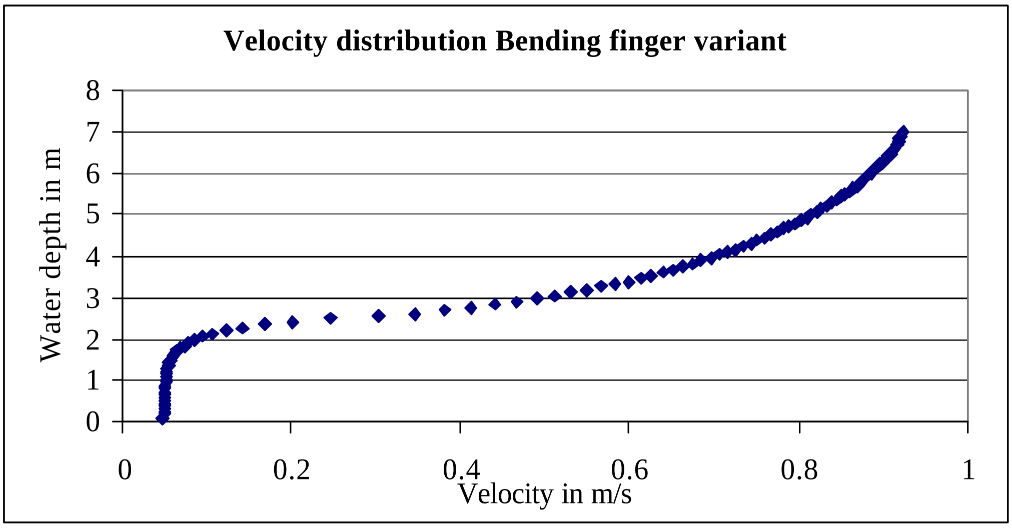


Figure 20-8 Velocity distribution bending-finger variant

20.3.6 Drag force and buoyancy

The forces on the bending-finger variant are induced by the drag force of the current and the buoyancy of the polyethylene blocks. The drag force depends on the current velocity and the buoyancy on the density of the material.

The connection between the blocks, the polypropylene strip, can be modeled as a flexural free bending point. The combined forces will change the position of a particular block and exert a resulting force on the consequent block and the anchorage system. Appendix 49 gives an overview of the forces on the structure.

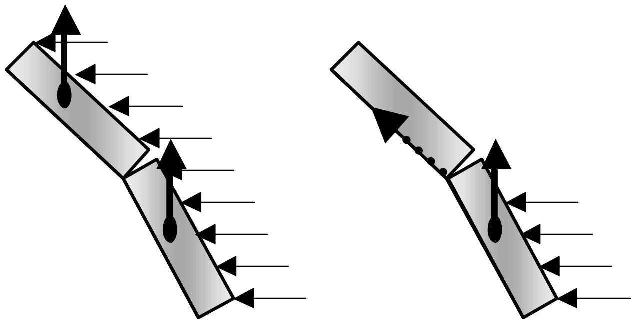


Figure 20-9 Forces on the blocks of the bending finger variant

As the current velocity increases (in the direction in which bending is possible) the artificial seaweed will bend towards the sea bottom. The relation between the current velocity and the vertical height of the artificial seaweed is shown in Figure 20-10, appendix 49.

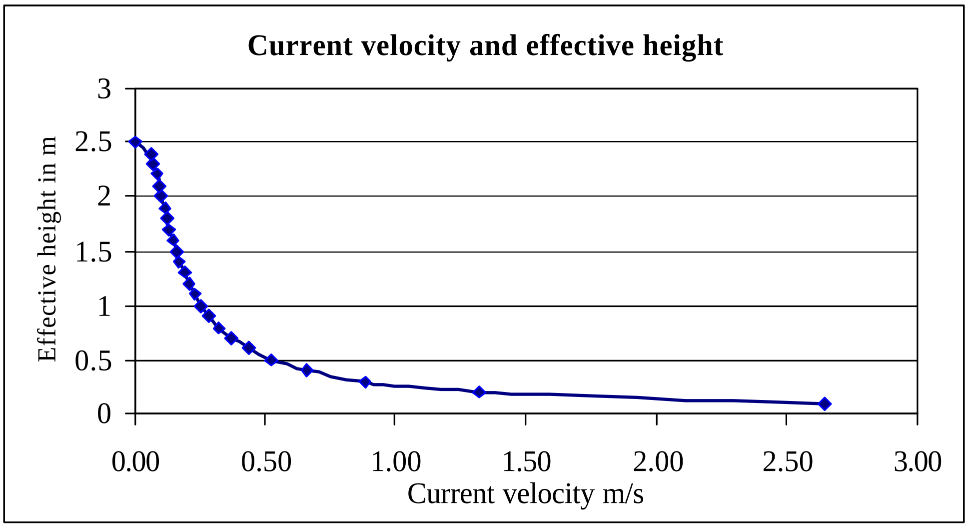


Figure 20-10 Current velocity and effective height (bending finger with an initial height of 2.5 m)

Figure 20-10 shows that the vertical height of the seaweed is 0.5 m for a current velocity of 0.5 m/s. Hence the leaves of the seaweed are not entirely flat on the sea bottom. (Research has to indicate the effectiveness in enhancing erosion in a slightly bended position, chapter 24).

Consequently the relation between the current velocity and the resulting force on the anchorage system is calculated. The relation between the current velocity proves to be linear (the square-relation between the current velocity and the drag force is compensated by the adjusted position of the block).

20.3.7 Evaluation

Advantages

- High functionality even during extreme current velocities
- High functional lifespan when working properly
- Polyethylene-blocks are resistant against water absorption

Disadvantages

- High construction costs
- Complicated construction methods (requires skilled labor).
- Complicated and uneconomical placement (placement requires special equipment).
- Anchorage system is vulnerable to failure (tear of geotextile mattress).
- Leaves are vulnerable to failure (breaking of the polypropylene-strip).

Points of attention

- Sediments could accumulate on top of the artificial seaweed when laying flat on the bottom (One side of the blocks (opposite to the strip) is curved to prevent sediments accumulating on the blocks, moreover the blocks have sufficient buoyancy to overcome the weight of a small amount of sediments).
- Sand accumulating between the blocks could prevent the artificial seaweed to bend back in the upright position. This can be avoided by a small plastic foil around the bending point, (appendix 49).
- The blocks should have a sufficient surface to ensure the blocks do not slide next to each other.
- Special measurements should be taken to prevent the growth of algae on the surface of the leaves

21 Variant selection

The three variants have been designed with a different emphasis resulting is specific advantages and disadvantages. Table 21-1 gives the advantages and disadvantages for each variant.

Variant	Advantages	Disadvantages
Sea-grass	- economic and simple construction - economic and simple placement	- limited functionality - low durability
Rigid-flaps	- relative economic construction	-complex and costly placement - limited functionality
Bending-finger	- high functionality - high durability - high functional lifespan	- complex and costly construction - complex and costly placement

Table 21-1 Advantages and disadvantages variants

The sea-grass alternative is economic and simple. However its functionality is limited. Moreover the durability of the sea-grass variant is low. The surface of the sea-grass leaves is large compared to the volume of the leaves. This makes the variant vulnerable to water absorption and the growth of algae on the surface of the threads. Both would result in sinkage of the leaves and consequently failure of the artificial seaweed.
The sea-grass variant has been abandoned so far due to its low durability (however if the durability could be increased the variant would have strong economical advantages).

The rigid-flaps and the bending-finger variant both have similar disadvantages with the placement and forces on the geotextile mattress. The bending-finger variant is more complex and more costly than the rigid-flaps variant. However the bending-finger variant has a potential in effectively reducing the amount of sedimentation in the MRGO for larger period of time than the rigid-flap variant.

Conclusion
The sea-grass variant is rejected due to its limited durability. The bending-finger variant has a higher effectiveness in reducing the sedimentation in the MRGO channel and a higher functional lifespan than the rigid-flap variant for little extra costs.

22 Feasibility calculation

A rough estimation is made on the economic feasibility of applying artificial seaweed on the open water section of the MRGO channel to reduce the total amount of maintenance dredging costs.
For the initial feasibility calculation the width of the artificial seaweed field is estimated at a minimum of about 20 m. One field of artificial seaweed on both sides of the channel results in a total area of about 65.000 m^2 per mile[23]. Given the density of 3.81 leaves per square meter, the total amount of leaves per mile would in the order of 250,000[24]. The sum of the estimated annual maintenance costs over a period of 20 years is calculated[25] for the Breton Sound and the Bar Channel, Table 22-1.

Section	Estimated future annual costs per mile	S estimated future dredging costs per mile (period of 20 years) [26]
Breton Sound	$ 100,000 – $ 300,000	$ 1.4 -4.4 mln.
Bar Channel	$ 300,000 – $ 550,000	$ 4.4 -8.0 mln.

Table 22-1 Estimated future annual costs per mile

Based on the estimation of the future maintenance dredging costs the economic feasibility of the artificial seaweed compared to maintenance dredging can be estimated.

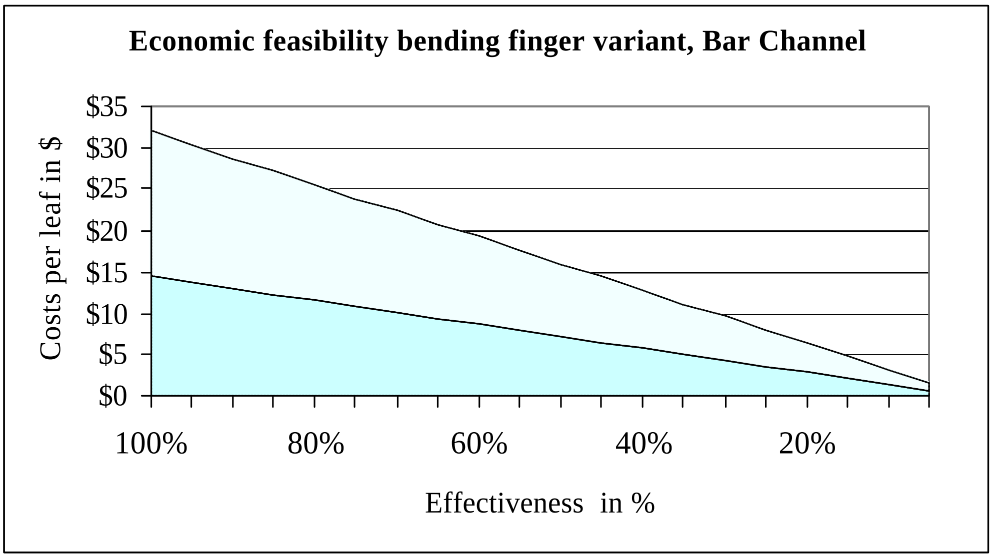


Figure 22-1 Economic feasibility bending finger variant, Bar Channel

[23] 2 fields, width = 20 m, length = 1 mile, 2?20?1609.35 = 64,374 m^2
[24] 3.81? 64,374 = 245,265
[25] Maintenance costs assumed constant and converted to prices of 2002 using an annual average inflation rate of 3% (over the period 2005 -2025).
[26] Costs are in prices of 2002.

To be economical feasible the cost per leave should be less than $ 6 -18 per leave for the Breton Sound and $ 18 -32 per leave for the Bar Channel, for an effectiveness in sediment reduction in the MRGO of 100%, Figure 22-1. For a lower effectiveness of the artificial seaweed the costs per leave would have to be lower.

23 Conclusions

Of the three presented variants the bending-finger variant is the most attractive. The bending-finger variant is technically feasible. Moreover the bending-finger variant has a potential in effectively reducing the amount of sedimentation in the MRGO for a large period of time.

Economic construction and placement methods are required to make the bending finger variant economical feasible compared to dredging.

24 Recommendations

The bending-finger has the potential of effectively influencing morphological processes by enhancing sedimentation for a specific flow direction. In theory the bending-finger variant could reduce beach erosion or prevent sedimentation in trenches when properly designed.

However research is needed before the bending-finger variant can be implemented. Especially research in the following field is essential:

- The behavior of the bending-finger variant for fatigue (repeating bending)
- The effectiveness of the artificial seaweed in enhancing sedimentation in the upright position.
- The effectiveness of the artificial seaweed in enhancing erosion when laying flat on the sea bottom.
- The effectiveness of the artificial seaweed in enhancing erosion in a slightly bended position (paragraph 20.3.6).
- Effectiveness when the leaves are laying on top of each other
- Use of recycled materials as construction materials.
- detailed cost analysis
- Environmental impact study
- Other locations/applications were the artificial seaweed could be used
- A pilot study should be carried out to gain experience with the concept of artificial seaweed capable of bending in one direction only.

Section V Conclusions and recommendations

25 Conclusions

The two objectives of the thesis have been realized:

- To address the root causes of the existing maintenance dredging costs.
- To create a strategy to control and reduce the current maintenance dredging costs while limiting the negative environmental impact the MRGO channel has on the surrounding wetlands for a period of 20 years.

Maintenance dredging costs

The maintenance dredging costs along the channel can be explained by variations in unit rate and amounts of materials to be dredged, Table 25-1.

Section	Amounts of dredged materials (1970-2001)	Percentage	Total dredging costs (1970-2001)	Percentage	Unit rate ($\$/m^3$)
Inland Reach	95 mln. m^3	36.3 %	$ 127 mln.	33.7 %	$ 1.35
Breton Sound	101 mln. m^3	38.8 %	$ 119 mln.	31.4 %	$ 1.18
Bar Channel	65 mln. m^3	25.0 %	$ 132 mln.	34.9 %	$ 2.03
Total	261 mln. m^3	100 %	$ 378 mln.	100 %	$ 1.46

Table 25-1 Maintenance dredging amounts and costs 1970-2001

The unit rate depends on the execution method, size and characteristics of the dredging works. The amounts of materials to be dredged mainly depend on the sedimentation rate. The sedimentation in the MRGO Channel is a function of different and interacting sources of sediment and causes of sedimentation.
The conclusion was drawn that bank erosion, caused by ship-induced waves, is the dominant cause of sedimentation in the Inland Reach. During a hurricane- or extreme storm-surge condition sediments from the surrounding wetlands and from the open water section enter the Inland Reach.
Sedimentation in the open water section is primarily caused by (tidal) cross currents.

Proposed strategies

Inland Reach

The proposed strategy for the Inland Reach is a combination of stepped bottom alternative, the pile screen alternative and the breakwater alternative.
The breakwater alternative has the highest intangible value of the different alternatives and is especially promising in the creation of new wetland area, since a vegetation strip is constructed between the breakwater and the channel banks.

The pile screen has the lowest costs/value ratio (in other words the pile screen alternative gives the best value for money) and is promising in reducing the maintenance dredging costs for relative low capital costs.

The goal of maintenance dredging costs reduction is achieved under the proposed strategy. However the cost reduction of $ 1.8 million over a period of 20 years is marginal compared to estimated future maintenance dredging costs. The proposed strategies would reduce the amount of wetland loss by 70% compared to doing nothing.

Open water section
The construction of a (submerged) rubble-mound breakwater is economically unfeasible. The capital costs of a breakwater are by far higher than the maintenance dredging costs reduction that could be achieved by a (submerged) breakwater over a period of 20 years.

A new concept of artificial seaweed has been designed to reduce the amount of sedimentation in the open water section. The designed construction is capable of bending in one direction only. Without a current the artificial seaweed has a sufficient floating capability to remain in the upright position. With a current the leaves either stay in the upright position or bend horizontally to the sea bottom.
The artificial seaweed in the vertical position enhances sedimentation and in the horizontal position causes erosion, resulting in a reduction of the sediment transport towards the trench.
Economic construction and placement methods are required to make this concept economical feasible relative to maintenance dredging.

26 Recommendations

The relations between the sedimentation rate and the possible causes have been addressed qualitatively in general and quantitatively where possible.

26.1 Critical assumptions

Throughout the different section assumptions have been made. Consequently conclusions have been drawn based on these (sometimes) critical assumptions. All assumptions should be checked by further studies; in particular the following assumptions:

- In paragraph 4.3 the assumption was made that the number of ships sailing the MRGO remains relatively constant over the next 20 years.
  This assumption was crucial in the calculation of the channel dimensions.
- The volume of eroded materials has about doubled as the materials settled and formed a fluid mud[1].
  This assumption was crucial in drawing the conclusion that the channel banks are the dominant source of sediment.

26.2 Further research and data collection

As recommended in section I and II more information should be gathered on several aspects like current velocities and soil conditions to address the causes of sedimentation quantitatively. Research is recommended in the following fields:

Sources of sediment

In paragraph 7.3.1. the conclusion was drawn that the bank erosion is the dominant source of sediments under normal conditions. However sediments from the surrounding wetlands or from the open water section could enter the Inland Reach during a hurricane or extreme storm-surge.
To address the causes of sedimentation with more accuracy the amount of materials that enters the Inland Reach during a hurricane or storm-surge should be estimated.
The following data are required for this study:

- Current velocities during hurricanes and storm-surge at the entrance of the Inland Reach and in the Breton Sound.
- Current velocities during hurricanes and storm-surge in the wetland and the bayous.

The amounts of sediments that pass the IHNC lock are highly plausible insignificant. To address the (small) amounts of sediments that enter the MRGO through the IHNC lock the sediment concentration in the lock should be measured.

[1] This assumption does **NOT** hold for miles 45- 49

Sediment characteristics
As stated above the assumption was made that the volume of eroded materials has about doubled as the materials settled and formed a fluid mud. Clearly this volume increase depends on the local soil conditions. Therefore a study is required to determine the characteristics of materials on the channel banks and on the channel bottom and of the dredged materials.

Causes of sedimentation
The conclusion can be drawn from appendix 23 that the ship-induced-wave attack on the channel banks is dominant over ship-induced-current attack.
Further research should address the hydraulic loads quantitatively.

A clear salt-water wedge cannot be observed at the MRGO channel[2]. However it remains possible that under certain conditions, e.g. extremely high rainfall, a salt-water wedge is formed. Flocculation might occur around these locations resulting in an increase local sedimentation rate.
Further research should give clarity on sedimentation caused by differences in salinity.

26.3 Recommendations artificial seaweed
Research is needed before the bending-finger variant could be implemented. Especially research in the following field is essential:

- The behavior of the bending-finger variant for repeating bending (testing on failure of the construction)
- The effectiveness of the artificial seaweed in enhancing sedimentation in the upright position.
- The effectiveness of the artificial seaweed in enhancing erosion when laying flat on the sea bottom.
- Use of recycled materials as construction materials.
- Detailed cost analysis
- Other locations/applications were the artificial seaweed could be used
- A pilot study should be carried out to gain experience with the concept of artificial seaweed capable of bending in one direction only.

[2] Measurements carried out in 1971, appendix 4, indicate a vertical mixed salinity level. Consequently the presence of a salt-water wedge is less likely.

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W4	Title: Website	Louisiana Department of Natural Resources www.dnr.state.la.us
W5	Title: Website	Coastal Wetlands Planning, Protection & Restoration Act www.lacoast.gov/cwppra/index.htm
W6	Title: Website	Coast 2050: Toward a Sustainable Coastal Louisiana www.coast2050.gov
W7	Title: Website	U.S. Army Corps of Engineers - New Orleans District www.mvn.usace.army.mil
W8	Title: Website	National Wetlands Inventory http://wetlands.fws.gov/mapper_tool.htm
W9	Title: Website	Coalition to Restore Coastal Louisiana www.crcl.org
W10	Title: Website	Involved municipalities www.crcl.org/involved/local.htm#10
W11	Title: Website	Office of the Governor www.goca.state.la.us
W12	Title: Website	Department of Environmental Quality www.deq.state.la.us
W13	Title: Website	Department of Transportation and Development www.dotd.state.la.us
W14	Title: Website	Department of Wildlife and Fisheries www.wlf.state.la.us/apps/netgear/page1.asp
W15	Title: Website	Division of Administration www.state.la.us/doa/doa.htm
W16	Title: Website	State Soil and Water Conservation Committee www.ldaf.state.la.us/soil&wtr/soil&wtr.htm

W17	Title: Website	Natural Resource Conservation Service www.nrcs.usda.gov
W18	Title: Website	National Marine Fisheries Service www.kingfish.spp.nmfs.gov
W29	Title: Website	Environmental Protection Agency www.epa.gov
W20	Title: Website	U.S. Fish and Wildlife Service www.fws.gov
W21	Title: Website	Brown Marsh Data Information Management System www.brownmarsh.net/default.htm
W22	Title: Website	Gulf of Mexico Program www.epa.gov/gmpo
W23	Title: Website	National Oceanic and Atmospheric Administration www.nos.noaa.gov
W24	Title: Website	Backgrounds on hurricanes www.lacoast.gov/wetlands/willfulwinds/how.htm
W25	Title: Website	U.S.G.S. National Wetlands Research Center www.nwrc.usgs.gov
W26	Title: Website	The National Ocean Service, information on tides www.co-ops.nos.noaa.gov/tides/tab2ec4.html#108
W27	Title: Website	Conversion factors Metric system www.wsdot.wa.gov/Metrics/factors.htm
W28	Title: Website	USA National Hurricane Center www.nhc.noaa.gov
W29	Title: Website	Louisiana Hurricane History www.srh.noaa.gov/lch/research/lalate20hur.htm
W30	Title: Website	Geology, Hydrology, Sediments, and Engineering of the Mississippi River http://water.usgs.gov/pubs/circ1133/geosetting.html
W31	Title: Website	Publications of the Headquarters, United States Army Corps of Engineers www.usace.army.mil/inet/usace-docs
W32	Title: Website	The NOAA Restoration Center www.nmfs.noaa.gov/habitat/restoration
W33	Title: Website	The Maritime Research Institute Netherlands (MARIN) www.marin.nl

W34	Title: Website	"Closing the MRGO" Environmental and Economic considerations www.agecon-extension.lsu.edu/CaffeyWeb/TopicSeries.htm
W35	Title: Website	The Lake Pontchartrain Basin Foundation www.saveourlake.org/area2.html
W36	Title: Website	American Fisheries Society www.fisheries.org
W37	Title: Website	Ecological Society of America http://esa.sdsc.edu
W38	Title: Website	Society of Wetland Scientists www.sws.org
W39	Title: Website	Consumer Price Indexes (USA) over the period 1965-2002 www.bls.gov/cpi
W40	Title: Website	Patent database www.delphion.com
W41	Title: Website	Artificial seaweed units, Barbados, 1985 www.unesco.org/csi/act/cosalc/shore-ero.htm
W42	Title: Website	Cegrass artificial seaweed www.nre.vic.gov.au/coasts/coastkit/ch3/maritime.htm
W43	Title: Website	Grand banks yachts www.grandbanks.com
W44	Title: Website	Visser shipyard (fishing-boats) http://www.visser-den-helder.nl/news3u.html
W45	Title: Website	Computational Hydrodynamics Group (CHG) www.imm.dtu.dk/nag/chg/
W46	Title: Website	"Kunststof-online" www.kunststofonline.nl

Section A Table of contents Appendices

Appendix 1 Map of the MRGO channel

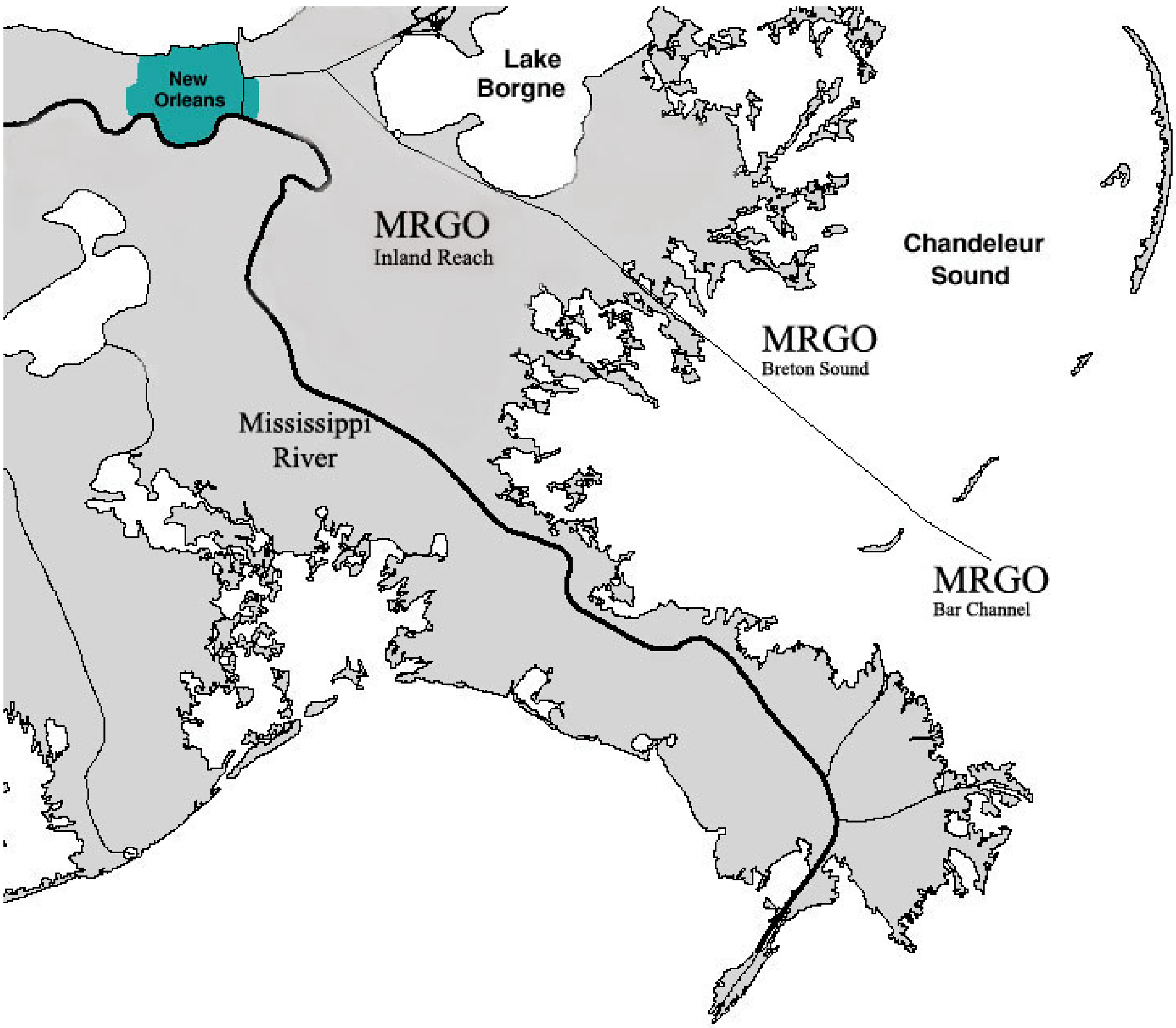


Figure 1-1 MRGO channel

Appendix 2 Conversion rates

Conversion rates (US to metric system) [REF W27]

Distance

• 1 inch	= 0.00254 m	
• 1 foot	= 0.03048 m	
• 1 yard	= 0.9144 m	
• 1 fathom	= 1.8 m	
• 1 mile (US statute)	= 1.609 km	
• 1 mile (nautical)	= 1.852 km	

Area

• 1 square foot	= 0.092903 m^2	
• 1 square yard	= 0.836127 m^2	
• 1 acre	= 0.004047 km^2	= 0.40469 hectare
• 1 square mile	= 2.58999 km^2	= 258.999 hectare

Volume

• 1 cubic foot	= 0.0283169 m^3	
• 1 cubic yard	= 0.764555 m^3	
• 1 gallon	= 0.00378541 m^3	

Miscellaneous

• 1 knot	= 0.514444 m/s	= 1.852 km/hr
• 1 pound per square foot	= 0.0479 kPa	
• 1 grain per gallon (US)	= 0.0171181 kg/m^3	

Appendix 3 Waterways in the project area

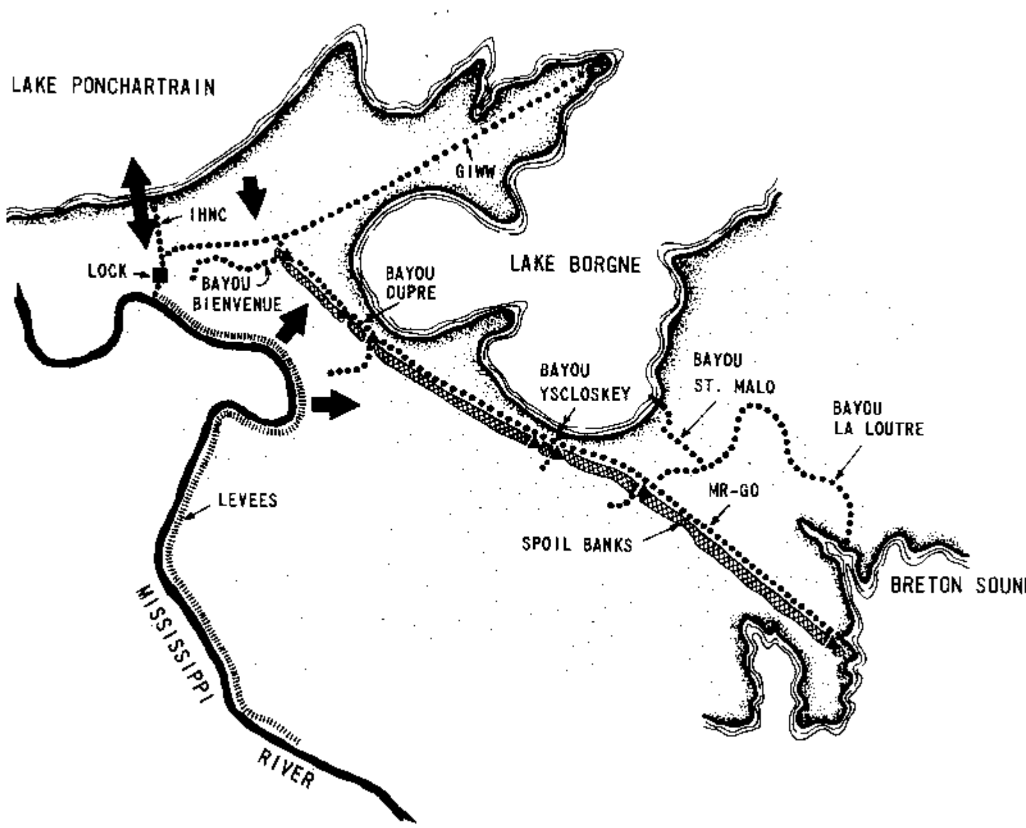


Figure 3-1 Waterways in the project area

Appendix 4 Salinity level

Figure 4-1 shows the salinity level in the project area directly after the construction of the MRGO channel (measurements were carried out in 1971).

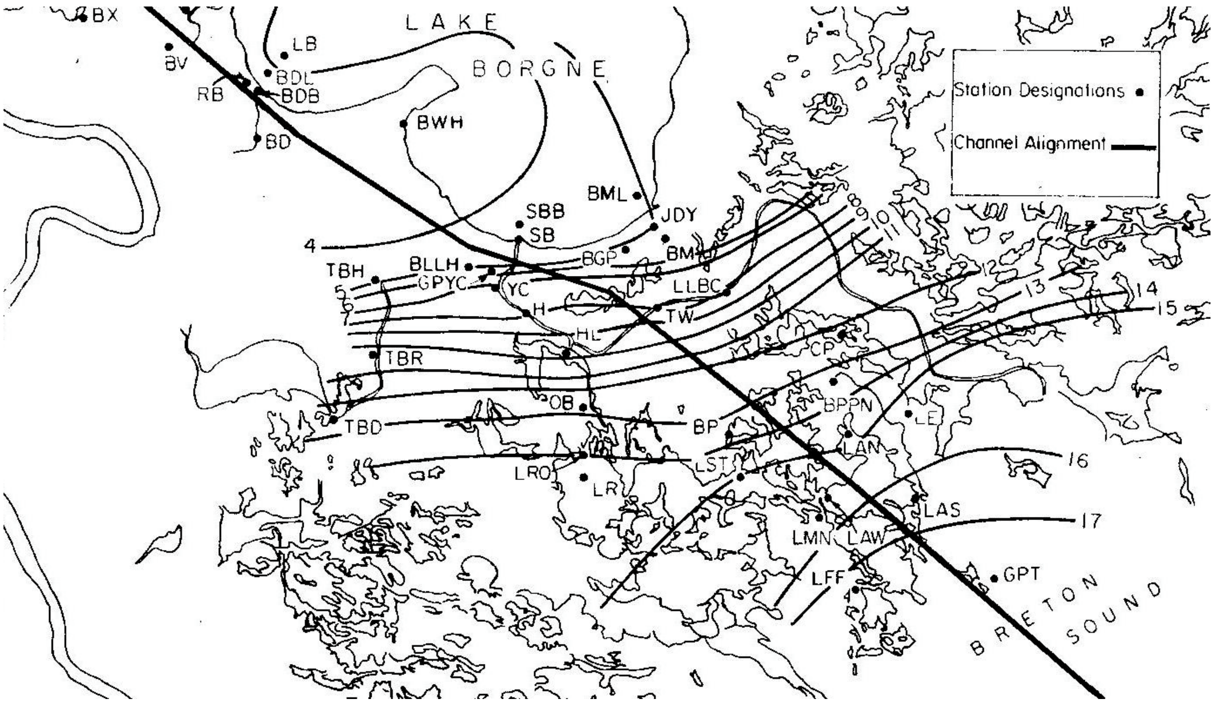


Figure 4-1 Salinity level MRGO (1971)

Appendix 5 Vegetation zones

Salinity, the concentration of dissolved salts in the water, is a determining element for the variety of vegetation in a coastal zone. The map below shows the salinity levels in the project area and the table below gives an impression of the most common vegetation for each vegetation zone.

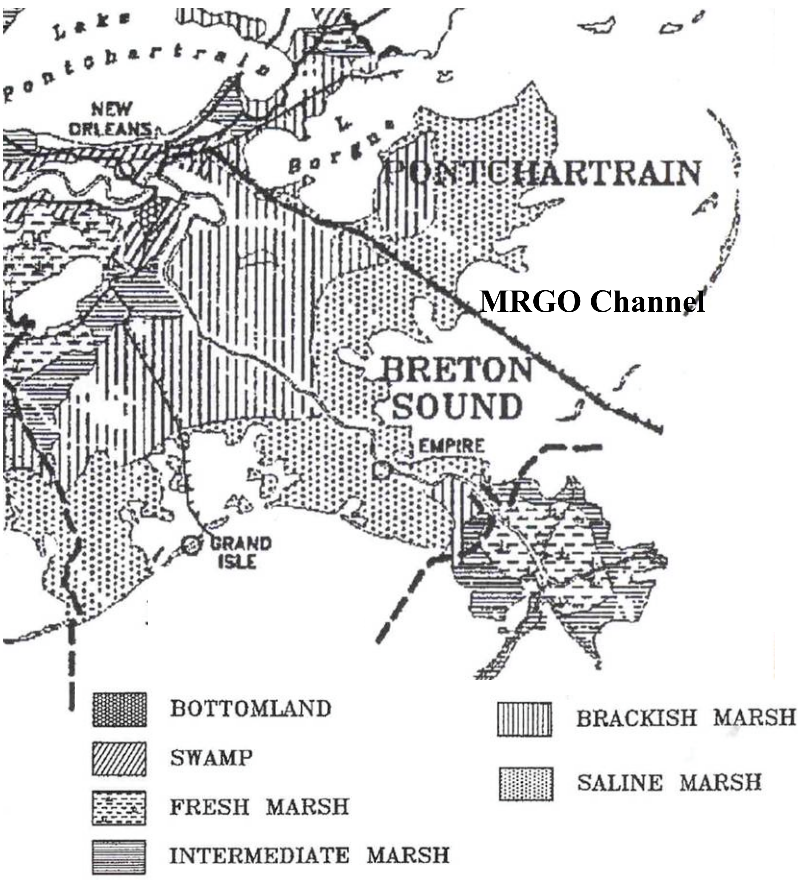


Figure 5-1 Vegetation zones in the project area

Habitat type	Salinity range	Major plant varieties REF 11
Fresh swamp	0-1 p.p.t.	Taxodium distichum, Nyssa aquatica
Fresh marsh	0-3 p.p.t.	Panicum hemitomon, Sagittaria falcate
Intermediate marsh	2-5 p.p.t.	Sagittaria falcate, Spartina patens
Brackish marsh	4-15 p.p.t.	Spartina patens, Scirpus americanus
Saline marsh	12+ p.p.t.	Spartina alterniflora, Distichlis spicata

Table 5-1 Vegetation zones

p.p.t.: Salinity is measured as a ratio of slats to water, and is expressed in the unit "parts per thousand," or "p.p.t.," which means the number of parts of salts per thousand parts of water. There are three main categories of salinity: fresh water (0 -0.5 p.p.t.), brackish water (partly salty or 0.5 - 30 p.p.t.) and salt water (full seawater, greater than 30 p.p.t.).

Appendix 6 The Mississippi Delta

THE TEXT IN APPENDIX 6 IS BASED ON THE THEORETIC BACKGROUND FROM REF 12 AND REF 4, SOME PARTS HAVE BEEN COPIED FROM REF 12.

Coastal Louisiana is made up of two wetland-dominated ecosystems the Deltaic Plain of the Mississippi River and the Chenier Plain [REF 12]. In this study only the Deltaic Plain of the Mississippi will be discussed.

When a river enters a sea we can either speak of a delta or an estuary. The difference in the two is determined by the fact whether the coast is progressive or transgressive. In the prograding case, the landside is on the winning hand, either due to a sea level fall or an excessive sediment supply. The transgressive coast is the exact opposite of the prograding coast, in this case the land lost to the sea. The Mississippi River mouth is a clear delta due to the excessive sediment supply.

The configuration of a delta depends on the interaction between the flow and distribution of the river sediment, wave and tidal currents. As the water flows from the river mouth, the water velocity decreases and sedimentation occurs. The coarse materials settle first, followed by the finer sediments. At the seaward edge of the delta front, the suspended sediment in the river water finally settles out into the deeper coastal water. This mud accumulation is generally very thick and extends across part of the continental shelf.

The configuration of the delta depends on the relative roles of the interacting river, wave, and tidal currents. According to William Galloway's triangular [REF 4] deltas can be classified into the following three:

- River dominated
- Wave dominated
- Tide dominated

The Mississippi River mouth is a clear river dominated delta as can been seen from the bird foot shape.

The Delta cycle

The Delta cycle consists of four separate phases:

- Active delta
- Erosion headland with flanking barriers
- Transgressive barrier island arc
- Inner shelf shoal

Phase 1 The Active Delta
The sand carried by the river settles and forms a sand-bar just seaward of the river and causes the river to split. Meanwhile banks on the riverside arise. The newly formed sand deposits affect the water level. The water will rise over its banks and new channels are formed. Each distributary channel then continues to transfers massive amounts of fine-graded sediment to the coastal area. When this newborn delta is situated in an environment with little tide and wave action it can grow out into a bird foot type of delta as the Mississippi River delta. The newly formed land becomes colonized by wetland vegetation. The vegetation in turn reduces the velocities even further and the accumulation of sediments occurs at a higher rate. In this way a sub-delta lobe is formed and protrudes seawards.

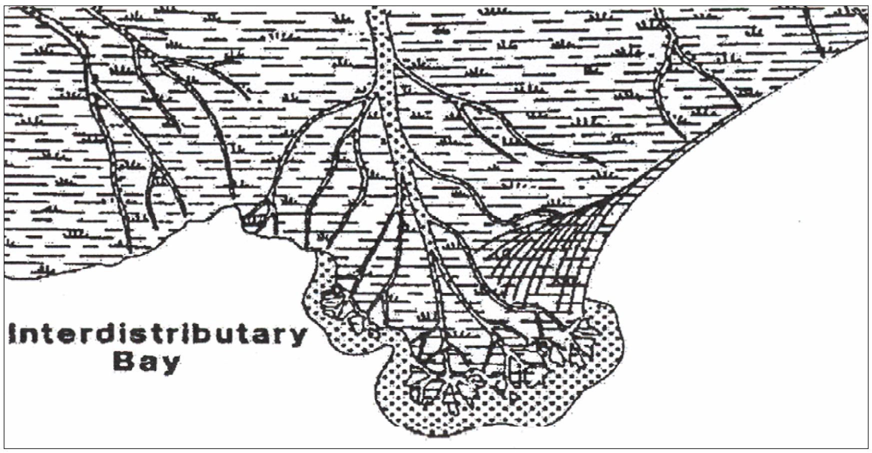


Figure 6-1 The active delta

Active delta-building areas are, in general, dominated by fresh turbid water. As the lobes increase the development of vegetation becomes the dominant process in the upper part of the system. Between the distributary channels continuous unbroken mats of marsh grass are formed.
The vegetation reduces the currents significantly and dams the channels. Surface streams become rare and also drainage is reduced to a low level. As result the water becomes anaerobic and stained by tannic acid [REF 12]. These conditions are favourable for the formation of peat.

The delta gradually increases trough a combination of the following processes:

- Alluvial processes (over-bank flooding, sedimentation)
- Vegetation growth (peat accumulation)
- Biochemical processes
- Continuation of the processes is essential to maintenance of the deltaic area. As long as the delta-building conditions remain favourable, the shore advances seawards.

Phase 2 Erosion headland with flanking barriers
The next phase in the delta cycle is the deterioration phase. The deterioration phase begins with the natural closure of the distributary feeder channels at their heads. The supply of fresh water and transported sediment is cut off and no longer reaches the seaward edge of the subdelta. The newly deposited deltaic sediments subside rapidly and marine processes become dominant. Wave conditions in the lower end of the system become brackish and saline. Waves and longshore currents erode the newly formed deltaic area. As a result the fine particles erode and the sand particles form beaches, barrier islands, spits and shoals. The action of waves and currents forms island arcs that curve around the delta.

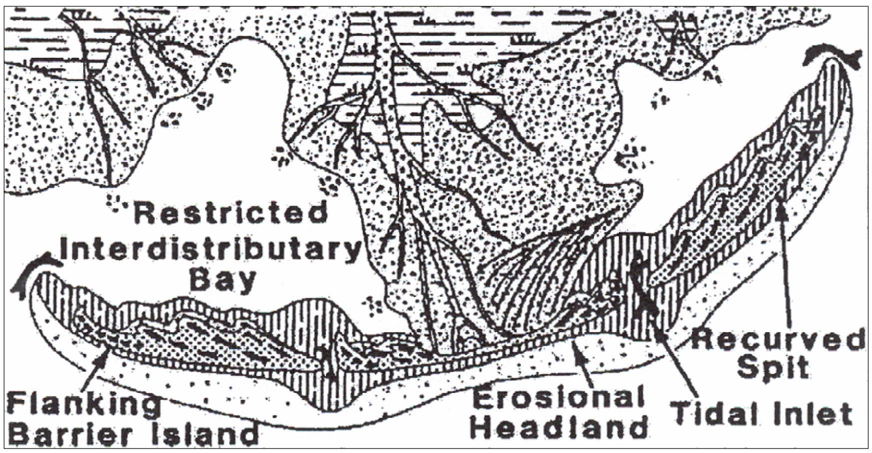


Figure 6-2 Erosion headland with flanking barriers

Transgressive barrier island arc
Landward of the barrier islands the tide causes erosion of the wetlands. Under natural conditions, the erosion is slow and mainly driven by large storms and subsidence. The freshwater marshes and swamps undergo two changes: Soft substrate areas (e.g. floating marshes) give way to ponds, which in turn enlarge to lakes and bays. Fresh water vegetation is replaced by saline vegetation. For the Mississippi Delta this third phase of the Delta Cycle has been accelerated significantly by the construction of the MRGO channel. The construction of the channel has speeded the transformation from fresh to salt water dramatically.

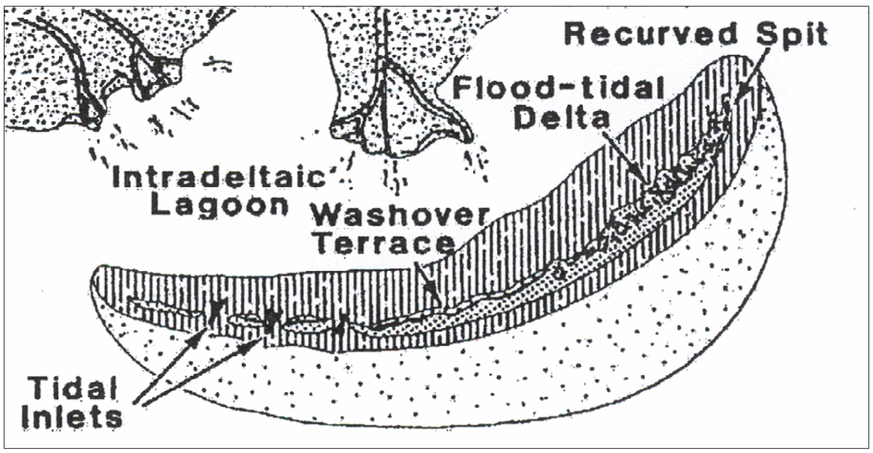


Figure 6-3 Transgressive barrier island arc

Inner shelf shoal
The advanced deterioration phase of the delta cycle is reached when the barrier island begin to diminish in size and fragment, and the estuarine bays separating the barrier arc from the mainland become broad and open.

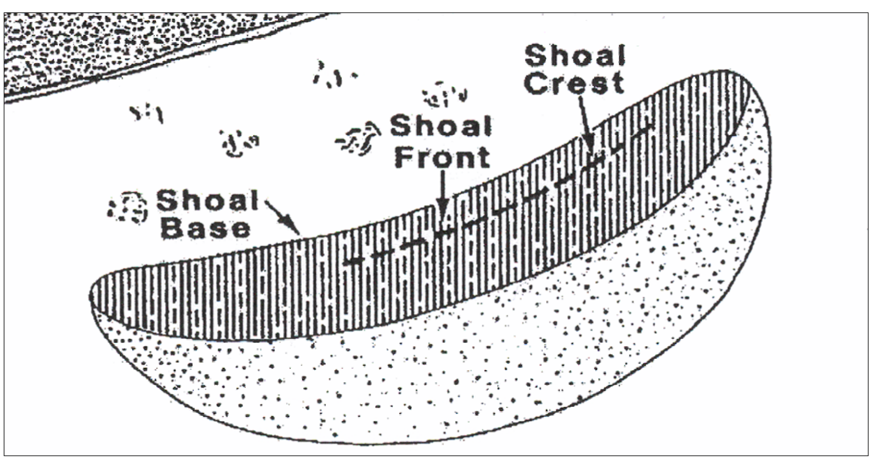


Figure 6-4 Inner shelf shoal

Eventually the barrier islands become shoals and the gulf shore moves inland to the heads of the estuarine bays. Fresh water conditions may persist in the landward leftovers of the lobe from local rainfall, but the system no longer receives fresh water and sediment input through the original distributary system. The brackish and saline bays marshes are the dominant components of the current system. Although the major part of the delta transfers to open water conditions during this phase, geometry and bottom conditions are a product of the delta building process (phase 1).

The shallow water, the leftovers of wetlands and the islands are ideal conditions for marine life as fish and marine birds. Shell forming molluscs are particularly important since they add coarse-grained sediment. These coarse-grained sediment, build of calcium carbonate, form reefs and wash up to contribute to island and beaches.
From this point on the cycle starts at the beginning and the delta progresses by the sediment, transported by the river.

Under natural conditions, at any particular time different parts of the Delta area are in different stages of the delta cycle. The different phases occurring at the same time result in a maximum variety of animals and vegetation.

The mudstream
Every active subdelta has a mudstream [REF 12]. This mudstream consist of the fine-grained sediments, silt and clays, that stay in suspension beyond the immediate area of the active distributary outlets and move along the coast in response to coastal currents.

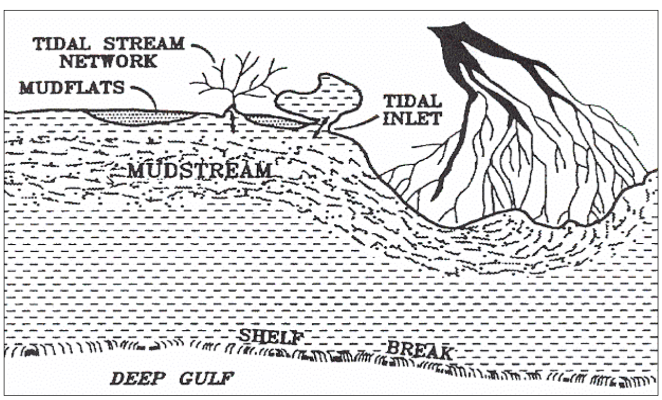


Figure 6-5 Mudstream I

Twenty-five percent, or more, of the transported sediment escapes deposition in the immediate area of the distributary outlets and is carries away in the mudstreams. If the subdelta is building into shallow waters of a bay or the inner continental shelf, longshore currents may transport these fine-grained sediments. If the mudstreams flows along the fronts of barrier islands or the gulf shore, tidal action may move some of the turbid waters into inter-distributary areas through tidal passes and tidal networks. Sediments transported by the mudstream are too fine grained to contribute to the sand budgets of the islands. Some of the mudstream may eventually form mudflats along the open shore of the gulf.

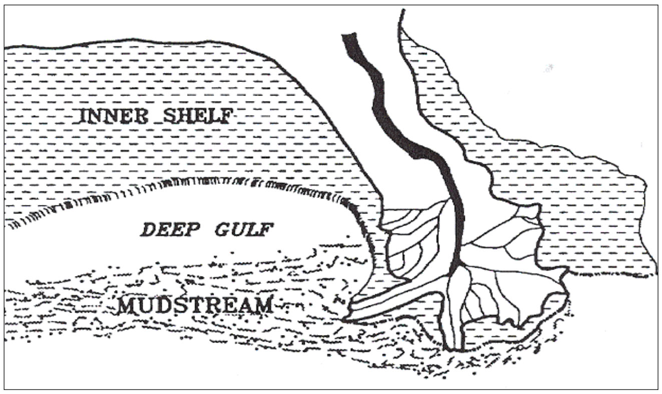


Figure 6-6 Mudstream II

If the distributary outlets discharge into deep waters, far out on the continental shelf or even beyond the shelf edge as in the case of the modern bird-foot delta, deposition resulting from the mudstream may be on the sea bottom of the shelf or into the depths of the gulf. In the latter case, the mudstreams are largely lost. The dominant longshore drifts along the Louisiana coast are from east to west.

THE TEXT IN APPENDIX 6 IS BASED ON THE THEORETIC BACKGROUND FROM REF 12 AND REF 4, SOME PARTS HAVE BEEN COPIED FROM REF 12.

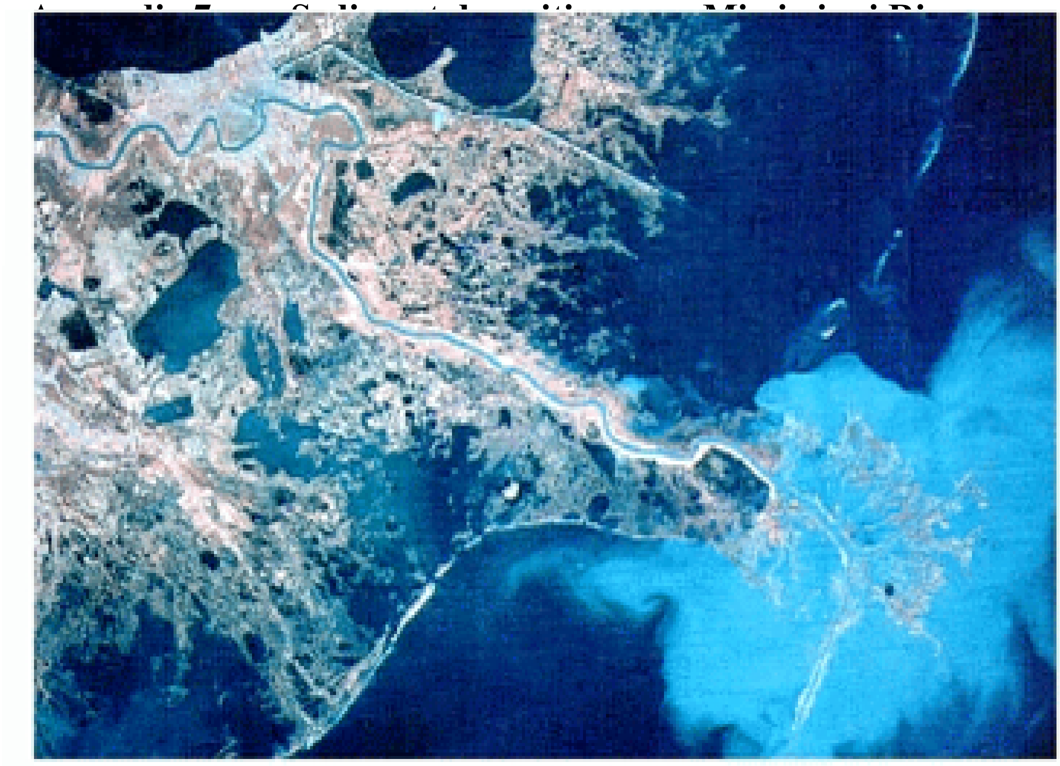


Figure 7-1 Sediment deposition area Mississippi River

Appendix 8 The Economic Impact of the MRGO Channel

The MRGO channel is a very important part of the water transportation system of the New Orleans area and provides ocean going container vessel access to the Port of New Orleans. The economic impact stretches out from the city of New Orleans to the whole state of Louisiana. The direct economic impact of the channel is hard to measure, but data are available on the economic impact of the Port of New Orleans and its maritime industry.
In a study [REF W1] done by Mr. T.P. Ryan, University of New Orleans, the following assumption is made: “Ports officials have estimated that we could lose permanently 80% of this cargo if the MRGO is closed to ocean going traffic”. Although the number of 80% appears to be rather high, the MRGO Channel clearly plays a dominant factor in the maritime economy of New Orleans and the state of Louisiana, as can be seen in the following paragraphs. In the next paragraph a brief impression of the Port of New Orleans is given, followed by a brief economic impact assessment.

The Port of New Orleans

General

Ideally located at the mouth of Mississippi River, the Port of New Orleans has been a center for international trade since 1718 when it when it was founded by the French.
The cargo throughput consists of 30% export versus 70% import [REF W1]. The trade is truly global and the counties of origin are equally represented; Europe 35%, Latin America 33%, Middle East and Asia 27% and a minor part to Africa and Australia.

The port is connected to the hinterland by a comprehensive railroad system (‘The Port of New Orleans is the only deepwater port in the United States served by six class one railroads. This gives port users direct and economical rail service to or from anywhere in the country”) and by a 23,330-kilometer inland waterway system.

Steel is the largest handled commodity of the Port. More than five million tons of imported steel moved through the Port of New Orleans in 2000.
All major commodities that are handled in the port can be categorized as followed:

General cargo	Iron and steel Forest products Rubber Coffee
Bulk cargo	Grain Copper
Containerized cargo	Containers

The volumes of cargo handled show a steady growth in the nineties with clear top in 1998. After the year 1998 a downward trend can be identified. (Data from the homepage of The port of New Orleans [REF W1])

	General (in tons)	Bulk (in tons)	Total tonnage	Ship calls
1990	6,913,000	24,515,000	31,428,000	2,372
1991	6,868,000	24,271,000	31,139,000	2,344
1992	7,449,000	24,298,000	31,747,000	2,461
1993	7,472,000	24,330,000	31,802,000	2,372
1994	10,375,000	23,578,000	33,953,000	2,485
1995	10,487,000	26,580,000	37,067,000	2,509
1996	10,038,000	30,513,000	40,551,000	2,436
1997	10,286,000	27,752,000	38,038,000	2,371
1998	14,089,000	28,283,000	42,372,000	2,536
1999	11,212,000	25,509,000	36,721,000	2,345
2000	12,235,000	26,791,000	39,026,000	2,336
2001	8,863,882	24,731,776	33,595,658	2,020

Table 8-1 Cargo throughput Port of New Orleans

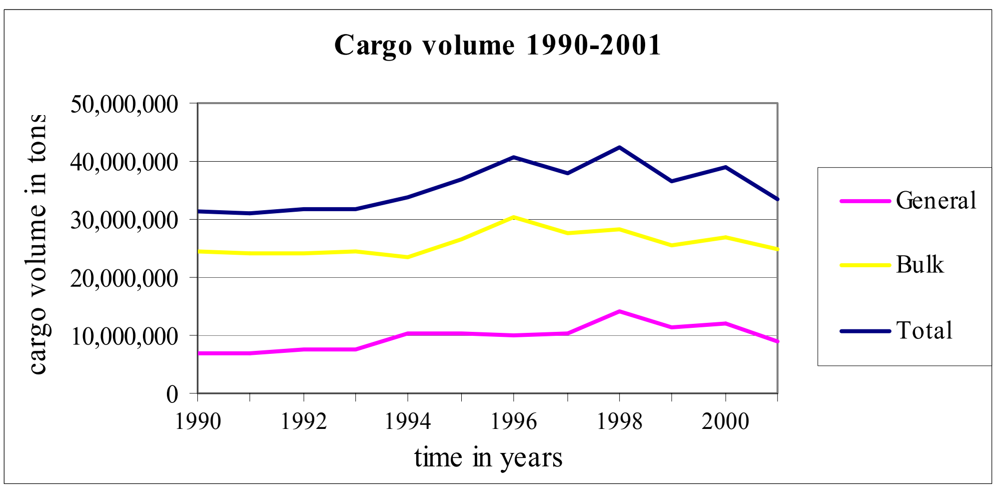


Figure 8-1 Cargo volume 1990-2001

Figure 8-2 gives the ship calls in the period 1990-2001 for general and bulk cargo

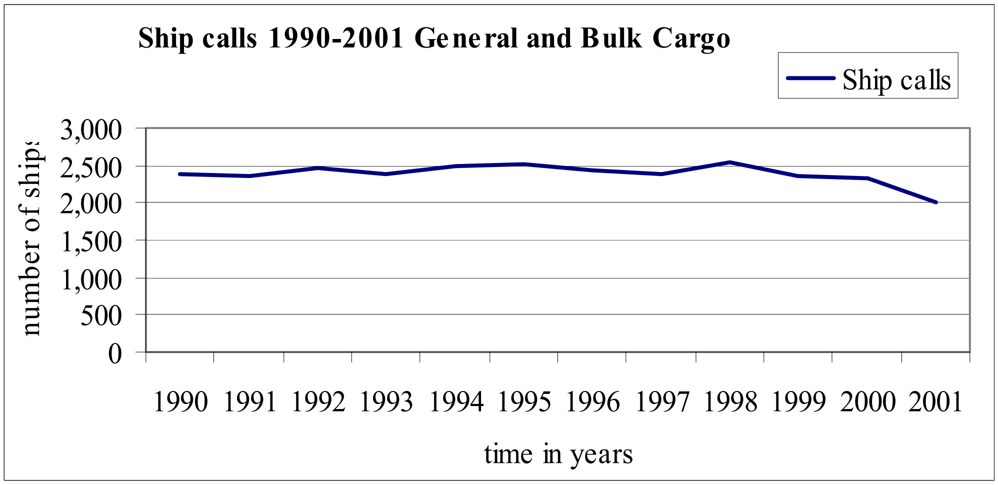


Figure 8-2 Ship calls 1990-2001

This downward trend is not only present for the general and bulk cargo, but also the containerized trade shows a slowdown, Figure 8-3

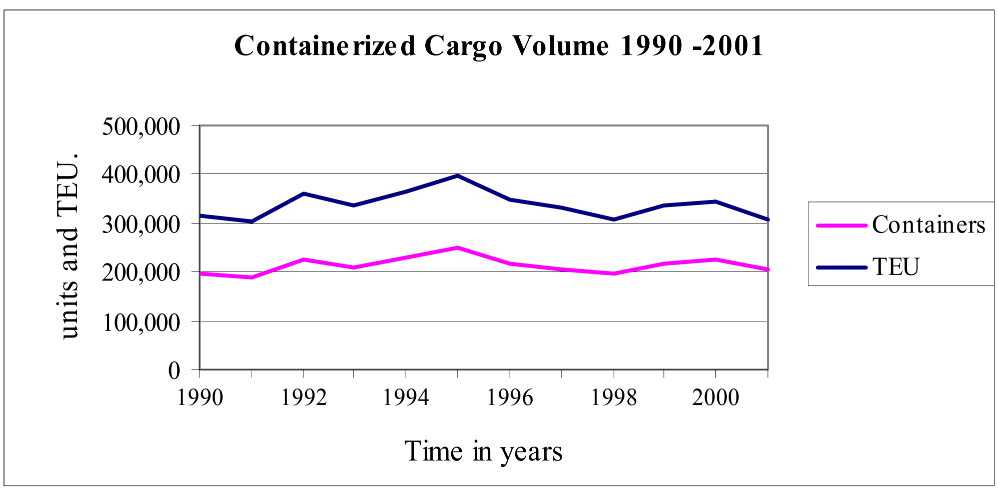


Figure 8-3 Containerized cargo volume 1990-2001

The economic impact

In this paragraph a brief impression is given of the economic impact the Port of New Orleans has on the city and on the state of Louisiana.
First the different kind of economic entities are recognized and categorized, and subsequently a quantitative impression is presented.
A categorization can be made to economic activity and to actor groups.

The economic impact of the Port of New Orleans includes the following areas of economy activities:

Cargo handling	Stevedoring, stevedoring suppliers Rail and road terminals Towage and pilot-service
Transport	Shipping and transport companies Forwarding agents Ship repair
Logistics	Logistic service providers Warehouse facilities
Production	Production activities related to commodities Supplier services for production
Trade	Trading companies for commodities

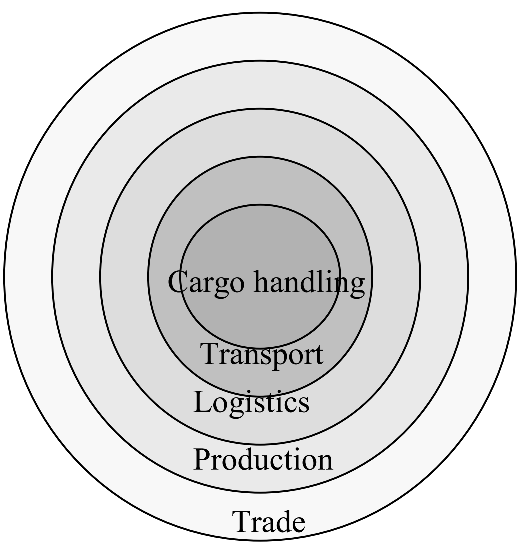


Figure 8-4 Economic activities in the Port of New Orleans **(FIGURE COPIED FROM REF 56)**

The economic impact of the Port of New Orleans includes the following areas of actor groups:
Port Industry; includes shipping companies, stevedoring companies, railroad, tugboats and barge companies and freight forwarders.
Board Tenants; include businesses that lease land and facilities from the Port.
Port Users; include warehouses that store goods for import or export, manufacturing firms that use the river and the port.

A quantitative summary of Economic Impact Port of New Orleans and the New Orleans Maritime Industry 2001 is given in the tables below. (Data copied from REF W1)

Employment (number of jobs)	Metro Area	State of Louisiana
Port industry	25,101	31,339
Board tenants	6,567	6,567
Port users	28,420	69,439
Total	60,088	107,345
Earnings ($ millions)	Metro Area	State of Louisiana
Port industry	$ 567.88	$ 708.53
Board tenants	131.82	131.82
Port users	597.31	1,459.24
Total	$1,297.01	$ 2,299.59
Spending ($ millions)	Metro Area	State of Louisiana
Port industry	$ 3,164.09	$ 3,931.46
Board tenants	503.77	503.77
Port users	3,660.88	9,003.48
Total	$ 7,328.74	$ 13,438.72
Taxes ($ millions)	Metro Area	State of Louisiana
State Taxes	$ 85.53	$ 150.08
Local Taxes	51.98	81.42
Total	$ 137.51	$ 231.50

Table 8-2 Economic impact Port of New Orleans

Conclusion
The Port of New Orleans had a significant impact on the economy of New Orleans and the state of Louisiana. Maritime activity within the Port of New Orleans is responsible for more than 107,000 jobs, $2 billion in earnings, $13 billion in spending and $231 million in taxes state-wide. The economic impact of the Port depends to a large[1] extent on the presence of the MRGO Channel, since practically all deep draft vessels (except cruise ships) sail the MRGO to reach the Port of New Orleans from the Gulf of Mexico.
Hence the MRGO Channel plays a dominant function in the maritime industry of New Orleans and the state of Louisiana.

[1] A study carried out in 1993 by T.P. Ryan indicates that 80% of the cargo handled in the Port of New Orleans would be lost if the MRGO channel would be closed [REF 77].

Appendix 9 Impression of wetland degradation

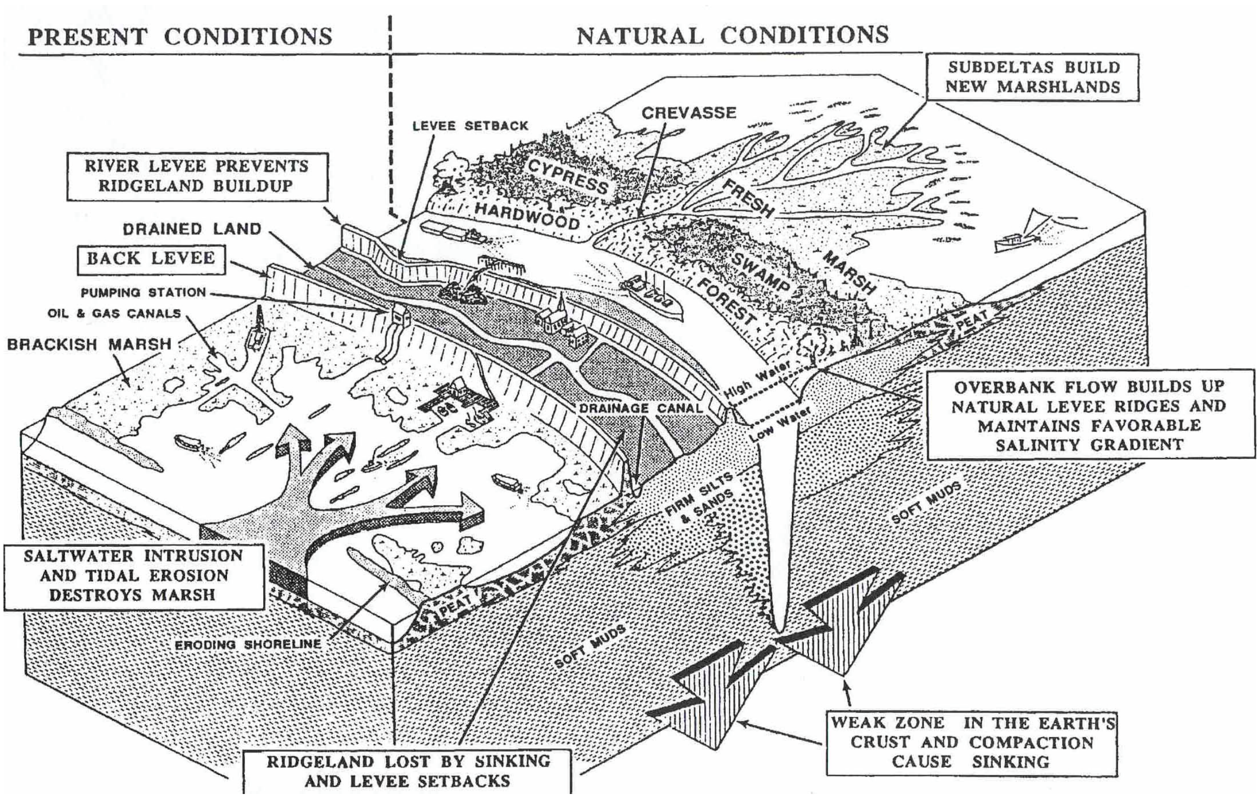


Figure 9-1 Impression of wetland degradation

Appendix 10 Involved Parties

General
The MRGO channel has a large impact on both economic as well as environmental aspects in the State of Louisiana. Therefore many different parties are related to the project. Most of the involved parties have their own interest in the project, which might be conflicting with the interest of other parties. If the needs of the different parties are not recognized the project will almost certainly fail. This chapter describes the different parties and their interests.

The Parties
Several parties have interests related to the MRGO channel. Below the most important parties are introduced:

- Environmental activists
- Local municipalities, coastal residents
- Financiers
- Consultants and advisors
- Louisiana Wetlands Authority (State)
- Breaux Act Task Force (Federal)
- US Army Corps of Engineers (USACE)
- Industry and business
- Fishers, hunters, and other user groups
- Contractors

Environmental activist
The activists represent a certain part of the public opinion that focuses on environmental aspects. A mix of local and national environmental groups, civic organizations have formed the “Coalition to Restore Coastal Louisiana” (For more information REF W9). Their foremost interest is to protect and restore the wetlands in the state of Louisiana.

Local municipalities
There is a general perception that the local municipalities are subjected to increase hurricane vulnerability, where their protection levees could be overtopped by storm surges. It is in the interest of the municipalities to reduce/eliminate these risks. Many of the local residents have a job related to the MRGO channel, and have therefore interest in the economic development of the channel. Moreover is the wetland area use by the local residents for recreational purposes. The local residents have both economic as environmental interests.
The two municipalities in which the MRGO is located are Plaquemines and St. Bernard. (For more information REF W10).

Financers
Financiers are commonly banks or government departments. They provide loans or provide the necessary money for the project. The objective of private financers, such as banks, is to gain as much profit as possible.
The majority of coastal restoration projects are funded through the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA). More details on this act, better known as the Breaux

act, are given in Appendix 14. Most likely the funding for the MRGO channel project can be acquired through the CWPPR act. In that case the funding is mostly federal [REF W5].

Consultants
Consultants design and plan during the development phase. Their point of view is commercial and their advice is Technical, Financial and organizational. For this project the complex Technical, Financial and organizational knowledge is present at the involved State and Federal agencies. The impact of external consultants will be very limited, if present at all.

Industry and business
The professional users of the channel are the ships that sail from the Gulf of Mexico to the Port of New Orleans, or vice versa. They are mainly active during the exploitation phase and have demands for the navigability of the channel.

Louisiana Wetlands Authority (Louisiana State Departments)
Six state agencies plus the Office of the Governor manage wetland protection and restoration activities in Louisiana as members of the Louisiana Wetlands Authority.
- Louisiana Wetland Conservation and Restoration Authority
- Office of the Governor
- Department of Natural Resources
- Department of Environmental Quality
- Department of Transportation and Development
- Department of Wildlife and Fisheries
- Division of Administration
- State Soil and Water Conservation Committee

(A list of websites of the Louisiana State Agencies is given in the Terms of Reference).

Breaux Act Task Force (Federal Agencies)
The Breaux act, or officially called the Coastal Wetlands Planning, Protection and Restoration Act, (CWPPRA, PL 101-646), was introduced by senator Breaux to protect and restore the wetlands in the state of Louisiana. The Breaux Act Task Force is responsible for the construction of projects aimed at creating, protecting and restoring the state's wetlands. The Task Force contains of one member of the State of Louisiana and one member of each of the following five Federal Agencies:
- Natural Resource Conservation Service
- Army Corps of Engineers
- National Marine Fisheries Service
- Environmental Protection Agency
- U.S. Fish and Wildlife Service

(A list of websites of the Federal Agencies is given in the reference).

US Army Corps of Engineers
Besides involvement through the Breaux Act Task Force, the US Army Corps of Engineers is responsible for the management and maintenance of the MRGO channel. They have responsibilities both on the navigability demands and on the environmental demands. The Corps of Engineers has interest in reducing the Operation and Maintenance cost while protecting and restoring the wetland areas.

Fishers, hunters
Over 50,000 people are engaged in wetland dependent fisheries, with a total value about $1 billion annually. The annual shrimp and oyster harvest supplies 35 to 40 percent of the total needs in the USA. [REF W 14]
The Louisiana wetlands provide winter habitat for 50% of the Mississippi flyway waterfowl population, and almost 20% of the entire U.S. winter population of ducks and geese. The wetlands support an annual $200 million sport hunting industry. [REF W5]

Constructors
These parties are the actual builders of the construction. They have a purely commercial point of view and try to execute the work for a minimum of cost and seek a maximum profit.

Project phases
The involvement of the parties is time dependent and will change over the lifetime of the project. Therefore the projects lifetime is divided into 4 different phases: Orientation phase, Development phase, Realization phase and the Exploitation phase.

In the **Orientation phase** the problem is identified. The public opinion rises and activists undertake their actions. The problems (effects, duration and responsibilities) become clear and initial solutions are proposed. During the **Development phase**, information is gathered and different methods are used to find the best solution. While in the **Realization phase** all party agree in the final solution and the realization can be started. And again the design is controlled to see if an efficient and effective construction is built. In some events the chosen solution seemed inadequate and the development phase was started again.
In last phase, the **Exploitation phase**, the construction is ready to be used.

When the channel was build in the late 1960's each of the phases has already been gone through. In fact we are now in the exploitation phase of the original project, however new problems have been identified, so a new cycle has began. In other words one could say that the project cycle for the MRGO channel is truly cyclical.

Parties	Orientation phase	Development phase	Realization phase	Exploitation phase
Environmental activists	X			
Local municipalities	X	X	X	X
Financiers	X			X
Consultants and advisors	X	X	X	
Louisiana Wetlands Authority	X			X
Breaux Act Task Force	X			X
US Army Corps of Engineers	X	X	X	X
Industry and business	X		X	X
Fishers, hunters			X	X
Contractors		X	X	X

Table 10-1 Involved parties throughout different project phases

In general the interest can be categorized Economic interest, Environmental interest and miscellaneous interest.

The economic interests are for example:
- Cost minimization
- Maintenance cost
- Operation cost
- Short and efficient waterways routes
- Attraction of economic activities
- Expansion of the Port facilities
- Accessibility of deep draft ships
- Navigation requirements

Environmental interest
- Protecting and restoring the affected ecosystem
- Prevention of erosion
- Protection of biodiversity
- Regulation of the salinity level
- Reduction of the current velocities

Miscellaneous interest
- Safety requirements
- Protection against flooding
- Protection against hurricanes
- Protection against ship accidents
- Private interest
- Profit maximization

As we have seen above all the parties have their own interest. There are conflicting interests among different parties. But also parties themselves might have conflicting interest. For example the USACE; a major interest is to minimize the dredging cost, on the other hand does the USACE have environmental interest and an interest in the navigational requirements of the channel. In the figure, on the next page, the most conflicting interest, economic and environmental, are given with the relations to the parties.

Conclusion

As we have seen above all the parties have their own interest. The users of the channel and the financiers only have pure economic interest, the environmental activist have an absolute environmental interest. The other parties are either unambiguous, such as the contractor and advisors or have both economic and environmental interest, such as the USACE.

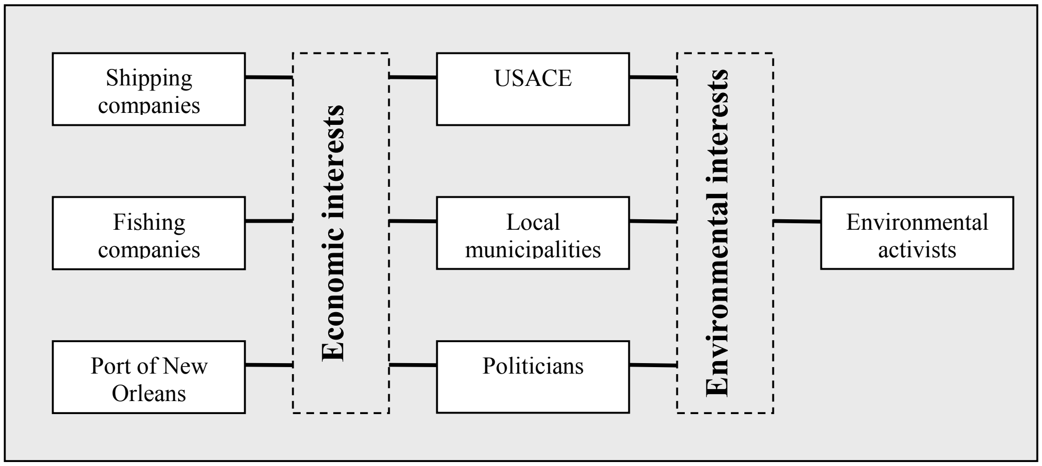
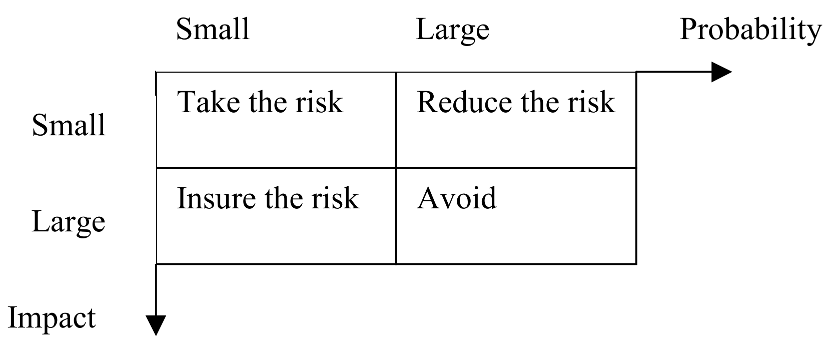


Figure 10-1 Parties and interests

Appendix 11 Risk analysis

During the lifetime of a project different events can occur that have a negative impact on the project. Negative events can range from financial fiascos, environmental catastrophes to serious technical malfunctions. The product of the Probability and the Impact of a certain event is called the Risk of that event. With good risk management the negative impact on the project can be significantly reduced.

Good risk management focuses both on the reduction of the probability and on the reduction of the impact. The combination of the probability and the impact determines what counter measurements can be taken to reduce the negative impact on the project. The figure below [REF 13] shows how good risk management deals with different combinations of probability and impact:



In the table below the risks for the MRGO channel are given on a qualitative basis, to give a brief impression of the risks and their significance.

Risk qualification	Phase in the project	Probability	Impact	Risk
Regulations				
Possibility of claims from shipping companies	Exploitation	Low	Low	Low
Possibility of claims from municipals	Realization/ Exploitation	Low	Low	Low
Financial				
Maintenance cost exceeding the estimates	Exploitation	Medium	High	High
Reduction of revenues for the Port of New Orleans.	Exploitation	Low	High	High
Setback in shipping traffic	Exploitation	Low	High	Medium

Table 11-1 Risks analysis I

Risk qualification	Phase in the project	Probability	Impact	Risk
Environmental risk				
Increase in salinity level	Realization /Exploitation	Medium	High	High
Increase in currents in the wetland area	Realization /Exploitation	Low	High	Medium
Loss in vegetation variety	Realization /Exploitation	Low	High	High
General				
Natural disaster e.g. earthquake, hurricane	Realization /Exploitation	Low	High	Medium
Ship crash	Realization /Exploitation	Low	High	Medium
Change in political priorities	Development /Realization	Low	Low	Low
Organization				
Incompleteness of contracts	Development /Realization	Low	Medium	Medium
Bankruptcy of sub contractors	Realization	Low	Medium	Low
Strike by employers	Realization	Low	Low	Low
Technical				
Breaking down of special equipment (faster than expected)	Realization	Medium	Medium	Medium
Soil measurements inaccurate	Development / Realization	Medium	High	High
Unexpected settlements	Realization/ Exploitation	Low	Medium	Low
Extreme weather conditions during the construction	Realization	Low	Medium	Low
Bombs or mines in dredging area	Realization	Low	Medium	Low
Ships running aground (by changes of channel layout)	Exploitation	Low	Low	Low
Change in sedimentation rate	Realization/ Exploitation	Low	High	Medium
The use of innovative construction (materials)	Realization	Medium	Medium	Medium

Table 11-2 Risks analysis II

Appendix 12 System analysis

The MRGO channel project is related to other projects in the Coastal Zone of Louisiana, and the project should be seen in the perspective of a larger strategy towards a sustainable coastline of Louisiana.
Different functions of the MRGO channel and the surrounding wetland area:

- **Economic**
  The MRGO Channel plays a dominant function in the maritime industry of New Orleans and the state of Louisiana, as can be seen in Appendix 8. Other industries are: oil and gas exploitation, fishery, recreation and hunting related industry.
- **Environmental**
  Coastal habitats such as swamps and barrier islands are the habitat for numerous species such as the waterfowl, wading birds, alligators, and furbearers. Shellfish such as shrimp and crabs and many fish species use coastal wetlands as nursery habitat as well as for spawning and feeding grounds. Moreover provides the wetland area habitat for threatened and endangered species, such as the bald eagle, brown pelican, and piping plover [REF W5].
- **Storm Protection**
  Barrier islands and coastal marshes protect the local municipalities from the threat of flooding brought by storms such as hurricanes. The wetland areas are believed to dissipate the forces of a hurricane and can therefore lessen the impact of hurricanes on the municipalities in the state of Louisiana [REF W24]. Research has shown that for every mile of vegetative wetlands, storm surge height can be reduced by one foot. [REF W5]
- **Recreation**
  The wetlands provide a unique location for recreation activities, such as hiking, hunting, fishing, bird watching and boating.

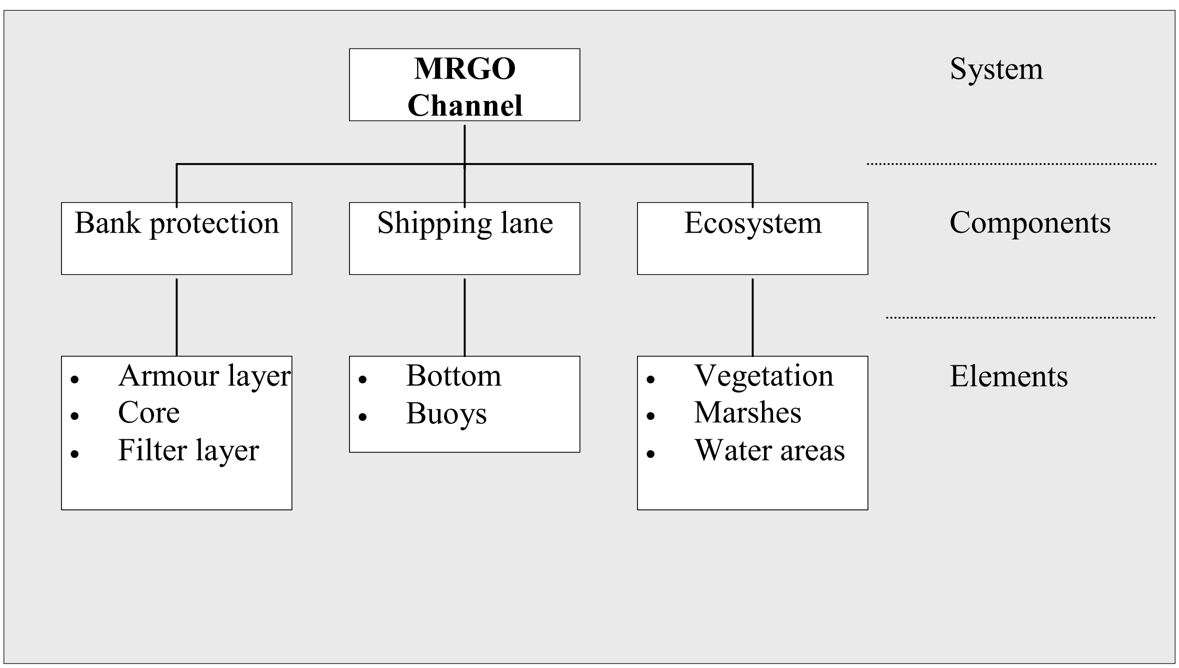


Figure 12-1 System analysis I

It's relevant to identify at what scale level this final thesis will be written. It is far beyond the scope of this thesis to develop a strategy for the coastline of Louisiana or e.g. the total American coastline. However the MRGO channel is part of the latter and it should be clearly understood that the higher scale levels have influence on the MRGO channel. As is regular in identifying scale levels [REF 13], the system that is to be realized is chosen at the highest level in the hierarchy. The problem definition and the project objectives determine the definition of the elements, the relations and the system boundaries.

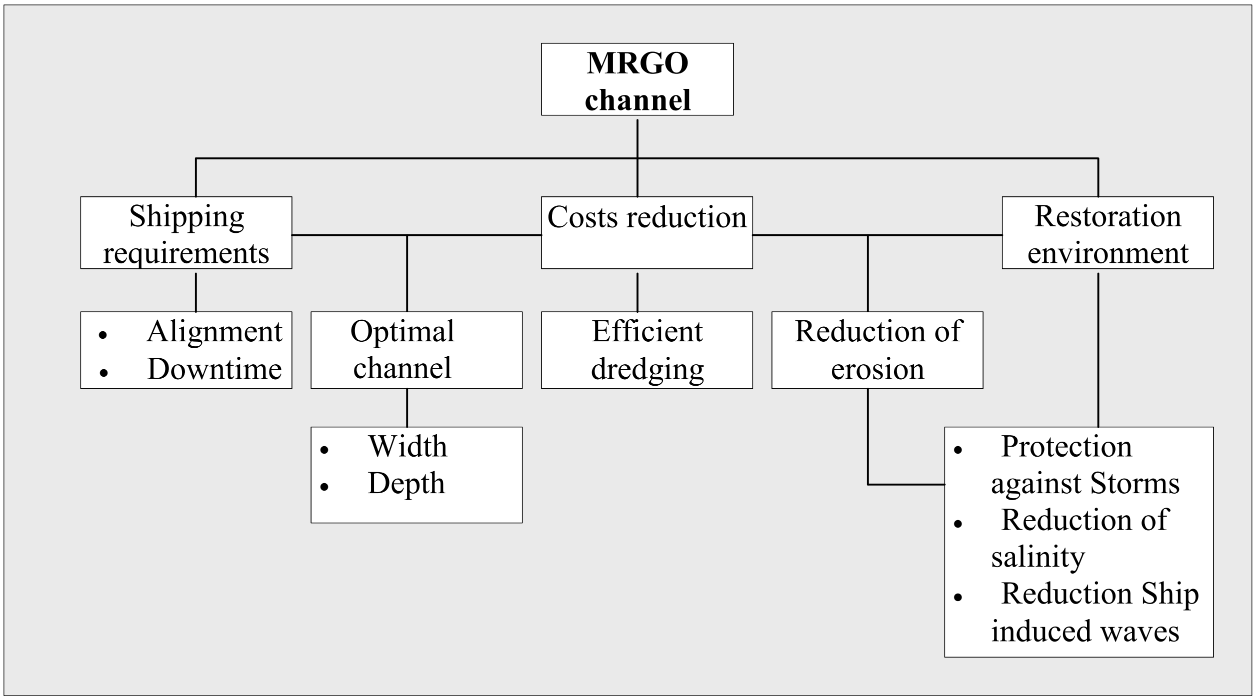


Figure 12-2 System analysis II

Appendix 13 Coast 2050 and the Breaux act

General
In the past decades enormous amounts of wetlands have been lost in the state of Louisiana, by natural and man-induced processes. The Wetland loss has reached catastrophic proportions, with current losses of 25-35 square miles per year.
This final thesis will address a limited part of the wetland improvement strategies.
Before the role of this thesis will be explained, on overview is given of the present acts and plans concerning wetland improvement.

The CWPPRA, Breaux Act
In order to turn the tide to this wetland degradation an important act was signed into law by President George Bush in 1990. This act is called "The Coastal Wetlands Planning, Protection and Restoration Act" (Public Law 101-646, Title III-CWPPRA); also know as the Breaux act (named after Senator Breaux of Louisiana) [REF W6]. The Act directed that a Task Force should, consisting of representatives of five federal agencies and Louisiana, develop a "comprehensive approach to restore and prevent the loss of coastal wetlands in Louisiana" [REF 17].

Part of the Breaux Act provides for the preparation of a coastal wetlands restoration plan. This plan, which was completed in November of 1993, proposed $1.3 billion worth of individual projects that could prevent about 65% of the coastal wetland losses over the next 20 years. The projects are funded by CWPPRA and all focus on marsh creation, restoration, protection or improvement. Presently, 81 projects are approved for construction, of which 78 are active. The combined effect of these projects will have a positive impact on 67,854 acres of wetland.

The funding for CWPPRA projects is partly Federal and partly State, according to the table [REF 17]:

Activity	Federal	Non-federal
Project planning	100 %	0 %
Project construction cost (before approval[2])	75 %	25 %
Project construction cost (after approval)	85 %	15 %

Table 13-1 CWPPRA

Through CWPPRA, $35 million per year is dedicated to help restore and protect Louisiana's coastal wetlands. The Louisiana's Wetlands Trust Fund provides the funds for which the state is responsible. Potential restoration project investments, therefore, can exceed $40 million per year through CWPPRA and state matching funding [REF 17].

Coast 2050
In 1998, the State of Louisiana and its Federal partners approved a coastal restoration plan entitled "Coast 2050, Toward a Sustainable Coastal Louisiana". This plan presents strategies developed by Federal, State, and Local interests to address Louisiana's massive coastal land loss problem. The objectives of Coast 2050 are similar to that of the CWPPRA and the Coast 2050

[2] Projects have to be approved by the task force

plan should be seen as a next step, in the restoration of the coastal area of Louisiana. Whereas the CWPPRA only focuses on marsh protection and enhancement, the Coast 2050 will deal with all aspects of sustainable coastal zone management. The Breaux Task force, which is responsible for the CWPPRA, also plays a key role in the Coast 2050 plan. The organizational structure of the Coast 2050 is rather complex, Figure 13-1.

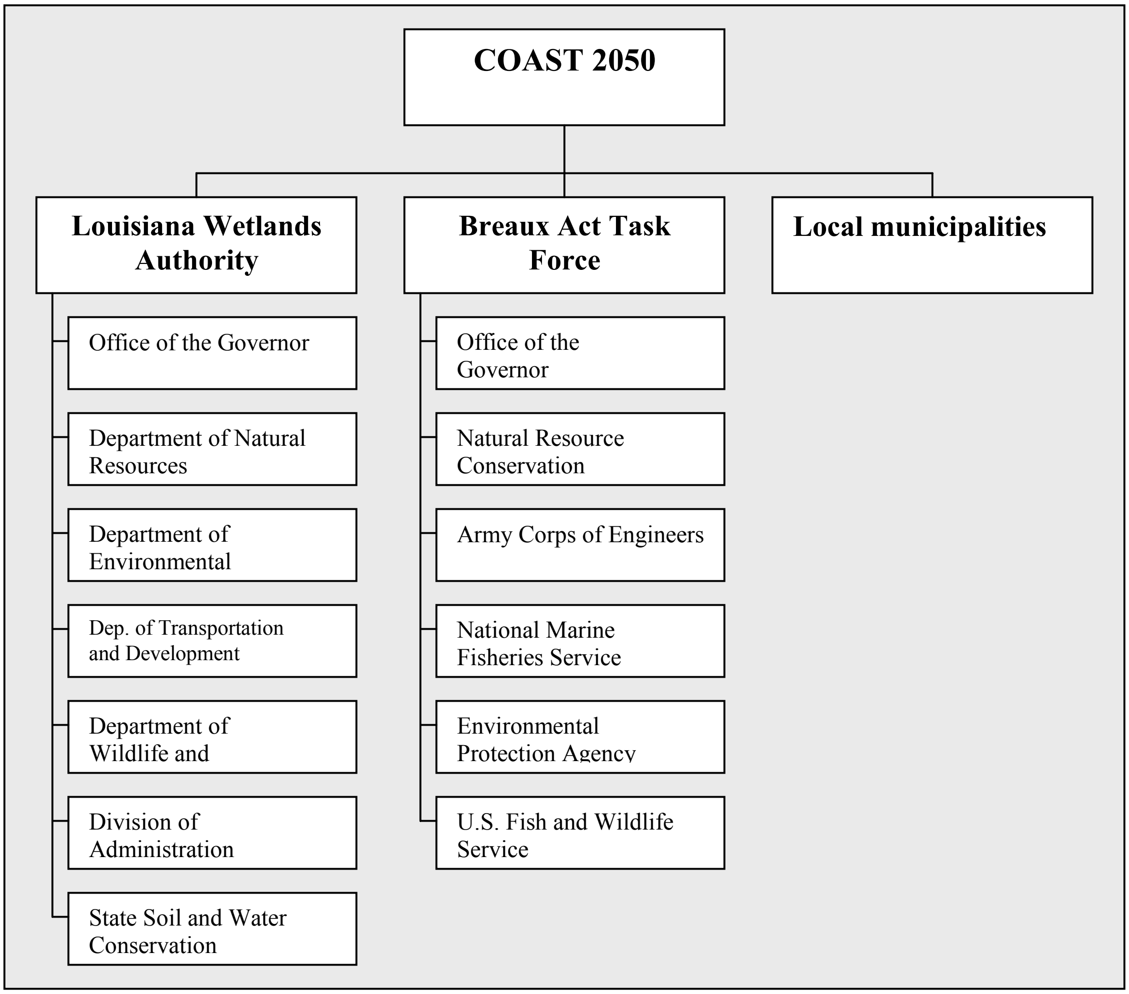


Figure 13-1 Coast 2050

Appendix 14 Federal laws and legislation

THE TEXT IN APPENDIX 14 IS BASED ON INFORMATION FROM EMRIS (Ecosystem Management Restoration Information System)**, LAWS AND REGULATIONS HAVE BEEN COPIED LITERALLY.**

Federal laws and legislation closely related to the project are:

- Archaeological resources protection act of 1979
- Coastal wetlands planning, protection and restoration act (CWPPRA)
- Clean water act
- Coastal barrier resources act
- Coastal zone management act
- Deepwater port act of 1974
- Food Security Act of 1985
- Oil pollution act of 1990
- Sustainable fisheries act
- Watershed protection and flood prevention act

LEGISLATIVE TITLE: Archaeological Resources Protection Act of 1979
UNITED STATES CODE CITATION: 16 U.S.C. § 470 et seq

SUMMARY: The Act was enacted to preserve and protect resources and sites on Federal and Indian lands. It fosters cooperation between governmental authorities, professionals, and the public. The Act prohibits the removal, sale, receipt, and interstate transportation of archaeological resources obtained illegally (i.e., without permits) from public or Indian lands and authorizes Federal agency permit procedures for investigations of archaeological resources on public lands under the agency's control. Permits are required to excavate and remove those cultural remains covered by the Act.

LEGISLATIVE TITLE: Coastal Wetlands Planning, Protection and Restoration Act
UNITED STATES CODE CITATION: 16 U.S.C. §§ 3951 to 3955
Other titles and popular names: Breaux-Johnston Act; Breaux Bill; Title III of PL 101-646, "Non-indigenous Aquatic Nuisance Prevention and Control Act of 1990"
SUMMARY: Sections 303 (16 USC 3952) and 304 (16 USC 3953) direct a Task Force chaired by the Secretary of Army to identify a list of coastal wetland restoration projects in Louisiana to provide for the long-term conservation of such wetlands and dependent fish and wildlife populations in order of priority, based on cost-effectiveness of such projects in creating, restoring, protecting, or enhancing coastal wetlands. The quality of such wetlands and provisions for small-scale projects to demonstrate the use of new techniques or materials for coastal wetlands restoration will also be taken into account (16 USC 3952). The task force is also to develop a plan for a comprehensive approach to restore and prevent loss of wetlands in Louisiana. Section 305 (16 USC 3954) directs the Director of the U.S. Fish and Wildlife Services to make matching grants to any coastal State to carry out cost-shared coastal wetlands conservation projects.

LEGISLATIVE TITLE: Clean Water Act
UNITED STATES CODE CITATION: 33 U.S.C. 1251 et seq.2
This Act is the principle law governing pollution control and water quality of the Nation's waterways. The objective of this Act is to restore and maintain the chemical, physical and biological integrity of the Nation's waters (33 U.S.C. 1251). The following sections of this law are related to the MRGO channel:

- Ocean Discharges. Section 403 of the 1972 amendments (33 U.S.C. 1343) addresses criteria and permits for discharges into the territorial seas, the contiguous zone, and the oceans.

- Permits for Dredged or Fill Material. Section 404 (33 U.S.C. 1344) authorizes a separate permit program for the disposal of dredged or fill material in the Nation's waters, to be administered by the Secretary of the Army, acting through the Chief of Engineers. Under Section 404 of the amended Act, the Corps of Engineers retains primary responsibility for permits to discharge dredged or fill material into waters of the United States. The Act also defines the conditions which must be met by Federal projects before they may make discharges into the Nation's waters. Under the program, permits are to be issued, after notice and opportunity for public hearings for disposal of such material at specified sites. Sites are to be selected in compliance with guidelines developed by EPA in conjunction with the Secretary of the Army. EPA is authorized to forbid or restrict the use of specified areas whenever it determines that disposal of material at a specific site would have an unacceptable adverse effect on municipal water supplies, shellfish, and fishery areas, or recreational activities.

LEGISLATIVE TITLE: Coastal Barrier Resources Act of 1982
UNITED STATES CODE CITATION: 16 U.S.C. § 3501 et seq; 12 U.S.C. § 1441 et seq

SUMMARY: This act reauthorizes and amends the Coastal Barrier Resources Act of 1982 (16 U.S.C 3501-3510). The original act established a policy that coastal barriers, in certain geographic areas of the U.S., and their adjacent inlets, waterways and wetlands resources are to be protected by restricting Federal expenditures which have the effect of encouraging development of coastal barriers. The act provided for a Coastal Barrier Resources System (CBRS) which identified undeveloped coastal barriers along the Atlantic and Gulf Coasts, including islands, spits, tombolos, and bay barriers that are subject to wind, waves, and tides such as estuaries and near-shore waters (the extent of which is defined by a set of maps approved by Congress dated 30 September 1982). Except for specific exempted projects (e.g. dredging, Federal navigation projects, some habitat management and enhancement efforts), no new Federal expenditures or financial assistance are allowed for areas within the system. The purpose was to minimize loss of human life, wasteful expenditure of Federal revenues, and damage to fish, wildlife and other natural resources associated with the development of coastal barriers. The 1990 reauthorization, Coastal Barrier Improvement Act (16 U.S.C. 3501 et seq) provides for the technical revision of maps, modification of boundaries, and additions to the CBRS. A similar resource inventory is to be created for coastal barrier resources of the U.S. Pacific Coast under the Pacific Coast Barrier Resources Study and Mapping. A Coastal Barriers Task Force is created to report on the management of coastal barrier resources.

LEGISLATIVE TITLE: Coastal Zone Management Act of 1972
UNITED STATES CODE CITATION: 16 U.S.C. § 1451-1464

SUMMARY: The Act (as amended) establishes a policy: 1) to preserve, protect, develop and where possible, restore and enhance the resources of the Nation's coastal zone for current and future generations; and, 2) to encourage and assist states in their responsibilities in the coastal zone through development and implementation management programs to achieve wise use of the land and water resources of the coastal zone, giving full consideration to ecological, cultural, historic, and esthetical values, as well as the needs for compatible economic development (16 U.S.C. 1452).

Section 307 (16 U.S.C. 1456(c)(1)(A)) directs Federal agencies proposing activities or development projects including Civil Works activities, whether within or outside of the coastal zone, that are reasonably likely to affect any land or water use or natural resource of the coastal zone, to assure that those activities or projects are consistent, to the maximum extent practicable, with the approved state programs. Non-Federal projects requiring a Federal permit for an activity in or outside of the coastal zone, affecting any land or water use or natural resource of the coastal zone of the state, must provide certification to the permitting agency that the proposed activities complies with the enforceable policies of the states approved program.

State management programs are to provide for: (A) the protection of natural resources, including wetlands, flood plains, estuaries, beaches, dunes, barrier islands, coral reefs, and fish and wildlife and their habitat, within the coastal zone; (B) the management of coastal development to minimize the loss of life and property caused by improper development in flood-prone, storm surge, geological hazard, and erosion-prone areas and in areas likely to be affected by or vulnerable to sea level rise, land subsidence, and saltwater intrusion, and by the destruction of natural protective features such as beaches, dunes, wetlands, and barrier islands; (C) the management of coastal development to improve, safeguard, and restore the quality of coastal waters, and to protect natural resources and existing uses of those waters; (D) priority consideration to coastal-dependent uses and orderly processes for present major facilities related to national defense, energy, fisheries development, recreation, ports and transportation, and the location, to the maximum extent practicable, of new commercial and industrial developments in or adjacent to areas where such development already exists; (E) public access to the coasts for recreation purposes; (F) assistance in the redevelopment of deteriorating urban waterfronts and ports, and sensitive preservation and restoration of historic, cultural, and esthetical coastal features; (G) the coordination and simplification of procedures in order to ensure expedited governmental decision making for the management of coastal resources; continued consultation and coordination with, and the giving of adequate consideration to the views of, affected Federal agencies; (I) the giving of timely and effective notification of, and opportunities for public and local government participation in, coastal management decision making; (J) assistance to support comprehensive planning, conservation, and management for living marine resources, including planning for the sitting of pollution control and aquaculture facilities within the coastal zone, and improved coordination between State and Federal coastal zone management agencies and State and wildlife agencies; and, (K) the study and development, where appropriate, of plans for addressing the adverse effects upon the coastal zone of land subsidence and of sea level rise. (16 USC 1452 (2)).

LEGISLATIVE TITLE: Deepwater Port Act of 1974
UNITED STATES CODE CITATION: 33 U.S.C. § 1501-1524

SUMMARY: This Act provides authority for Secretary of Transportation to issue a license for the ownership, construction and operation of a deepwater port (33 U.S.C. 1503). "Deepwater port" means any fixed or floating manmade structures other than a vessel, or any group of such structures, located beyond the territorial sea and of the coast if the United States, and intended for the loading or unloading and further handling of oil for transportation, except as excluded in 33 U.S.C. 1522. Included are all associated components and equipment, including pipelines, pumping stations, service platforms, mooring buoys, and similar equipment to the extent they are located seaward of the high-water mark. (33 U.S.C. 1502). The Act provides for licenses to be issued if applicants meet the required criteria, including the demonstration that the project will be constructed with the best technology to minimize adverse impacts on the marine environment and compliance with the Clean Water Act, Federal Water Pollution Control Act, Coastal Zone Management Act, and Marine Protection, Research and Sanctuaries Act. The license applications will be coordinated with Federal Agencies and departments with jurisdiction (33 U.S.C. 1504(e).

LEGISLATIVE TITLE: Food Security Act of 1985
UNITED STATES CODE CITATION: 16 U.S.C. 3801-3862

SUMMARY: The 1985 Act contains provisions designed to discourage the conversion of wetlands into non-wetland areas. These provisions collectively, are commonly referred to as the "Swampbuster" provisions (Food Security Act of 1985 (Title XII, Subtitle C)). Swampbuster provisions denied Federal farm program benefits to producers who converted wetlands after December 23, 1985. The Food, Agriculture, Conservation, and Trade Act of 1990 strengthened Swampbuster by making violators ineligible for farm program benefits for that year and subsequent years. The Act also created a system for inadvertent violations allowing farmers to regain lost Federal benefits if they restore converted wetlands.

The Conservation Reserve Program (Title XII) (16 USC 3831) authorizes the Federal government to enter into contracts with agricultural producers to remove highly erodible cropland from production, in return for annual rental payments. The Wetlands Reserve Program (16 USC 3837) authorizes enrolment of wetlands for protection and restoration through permanent and temporary (30 year) easements.

LEGISLATIVE TITLE: Oil Pollution Act of 1990
UNITED STATES CODE CITATION: 33 U.S. Code 2701-2761 et seq

SUMMARY: Spurred by the March 1989 Exxon Valdez oil spill and other large spills occurring within months of that catastrophe, the Oil Pollution Act of 1990 (Public Law 301-308) represents the accumulation of 15 years of congressional efforts to reach a consensus on comprehensive federal oil spill legislation. The Act has six major provisions: an expanded federal role in oil-spill response, contingency planning requirements for vessels and certain facilities, the establishment of the Oil Spill Liability Trust Fund, the increase of liability for spills of oil or hazardous substances from vessels and facilities, the requirements for double hulls on new tankers, and the requirements for increased research and development into spill response technologies.

LEGISLATIVE TITLE: Sustainable Fisheries Act
UNITED STATES CODE CITATION: 16 U.S.C. § 1801 et seq.

SUMMARY: This Act amends the Magnuson Fishery Conservation and Management Act. Among the new findings presented in the act are that certain stocks of fish have declined to the point where their survival is threatened, and other stocks of fish have been so substantially reduced in number that they could become similarly threatened as a consequence of (A) increased fishing pressure, (B) the inadequacy of fishery resource conservation and management practices and controls, or (C) direct and indirect habitat losses which have resulted in a diminished capacity to support existing fishing levels (16 U.S.C. 1801). This amendment adds the facilitation of long-term protection of essential fish habitats to the purposes of the Magnusson Act.

The Act directs the Secretary of Commerce to establish by regulation guidelines (16 U.S.C 1855) to assist the Regional Fishery Management Councils (16 U.S.C. 1852) in describing and identifying essential fish habitat in fishery management plans (including adverse impacts on such habitat) and in considering actions to ensure the conservation and enhancement of such habitat. The term essential fish habitat means those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity (16 U.S.C. 1802). The Secretary of Commerce is to coordinate with and provide information to other Federal agencies to further the conservation and enhancement of essential fish habitat. The Act directs Federal agencies to consult with the Secretary of Commerce with respect to any action authorized, funded, or undertaken, or proposed to be authorized, funded, or undertaken, by such agency that may adversely affect any essential fish habitat identified under this Act.

LEGISLATIVE TITLE: Watershed Protection and Flood Prevention Act
UNITED STATES CODE CITATION: 16 U.S.C. 1001 et seq; 33 U.S.C. 701b

SUMMARY: This Act authorizes the Secretary of Agriculture to cooperate with states and other public agencies in works for flood prevention and soil conservation, as well as the conservation, development, utilization, and disposal of water. It established the Small Watershed Program through which the Natural Resource Conservation Service (NRCS) (formerly the Soil Conservation Service)(7 U.S.C. 6962) constructs dams and implements other measures in upstream watershed for a variety of purposes including flood control.

THE TEXT IN APPENDIX 14 IS BASED ON INFORMATION FROM EMRIS (Ecosystem Management Restoration Information System)**, LAWS AND REGULATIONS HAVE BEEN COPIED LITERALLY.**

Appendix 15 Natural boundary conditions

15.1 Climate

The climate in the project area is Subtropical Marine. This results in long humid summers and short moderate winters. The average annual rainfall is about 1.554 m (Measured at the LSU Citrus Research Centre, St. Bernard) REF 15.
Table 15-1 gives detailed information on monthly temperatures and rainfall (data from REF 45).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Temp[3]	13.3	14.6	17.1	20.9	24.9	27.9	28.6	28.6	26.8	22.6	16.7	13.9
Rainfall[4]	11.2	11.9	15.7	13.7	13.0	14.0	20.1	16.0	15.2	8.1	9.4	11.9
Max rain[5]	32.3	35.1	53.6	37.8	47.5	40.6	46.2	57.7	42.2	63.8	36.6	36.6

Table 15-1 Monthly average of temperature and rainfall

15.2 Sea level rise

As a result of global warming, influenced by the greenhouse effect, the total liquid water mass in the oceans is expanding. Moreover global warming causes the parts of the ice mass at the North Pole and Antarctica to melt. The combined effect of an increase in volume and expansion of the water mass causes the sea level to rise. The relative sea level rise for the project area is estimated at 0.3 m (0.96 ft.) per century REF W5. For the time span of the project (20 years) the effect would be approximately 0.06 m (0.19 ft.) Other estimations give a sea level rise in the same order of magnitude REF 17.

15.3 Salinity level

The salinity level in the project area varies at different locations, appendix 4, ranging from nearly fresh water in the Lake Pontchartrain to salt water in the Gulf of Mexico. The fresh water in the channel comes from local rainfall and Lake Pontchartrain.
The density of the salt water is higher than that of the fresh water; consequently the fresh water is more buoyant and "floats" over the salt water. This phenomenon is called a salt-water wedge, Figure 15-1.

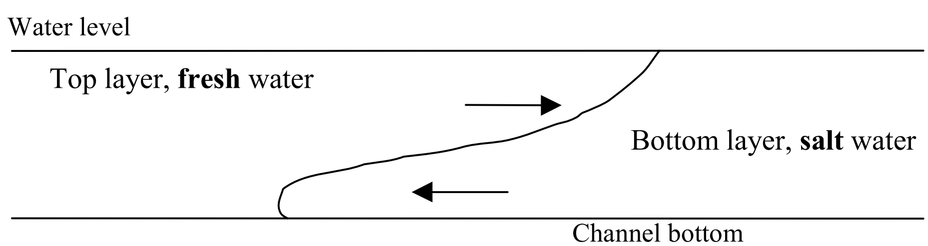


Figure 15-1 Schematization of a salt water wedge

[3] Average monthly temperatures, in degrees Celsius
[4] Average monthly rainfall, in cm
[5] Maximum monthly rainfall, in cm

The salinity level in the MRGO channel can be derived from the tidal exchange between Lake Pontchartrain, other estuaries and the Gulf of Mexico and the fresh water discharge from Lake Pontchartrain.
The salinity level is expressed in p.p.t. (Chlorides, in parts per thousand, relative to water) and ranges from 5.5 p.p.t. in the upper part of the inland reach to 13.1 p.p.t. at the transition to Breton Sound. In the open water section (Breton Sound and the Bar Channel) the salinity level can reach up to 18 p.p.t.

15.4 Soil conditions

Sediments characteristics
The different soil types in the project area can be categorized [REF 72] as shown in Table 15-2.

Material	Grain size min.	Grain size max.
Sand	0.06 mm	2 mm
Silt	0.002 mm	0.06 mm
Clay	0.001 mm	0.002 mm

Table 15-2 Sediment characteristics

The Corps of Engineers performed a geotechnical study in 1976 [REF 45]. Samples were collected from mile 20 to mile 60 from the channel bottom at both sides of the channel and in the centerline. The samples showed an absence of sand particles and consisted completely of clay and silt. The distribution of clay and silt (at the **channel bottom**) along the channel is given in Figure 15-2 and appendix 37.

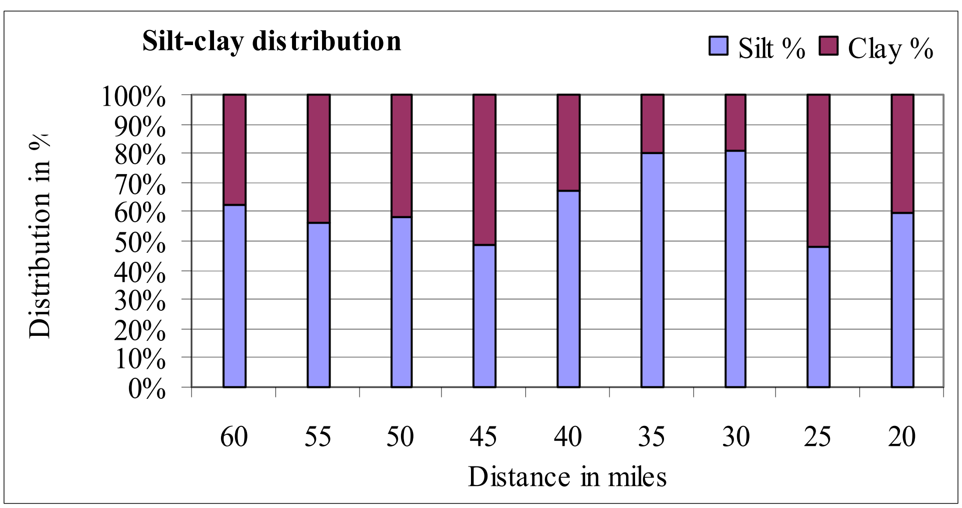


Figure 15-2 Silt-clay distribution along the MRGO

Geological history
Pleistocene deposits are present at a depth of 52 m (below M.S.L.) near the Chandeleur Sound and gradually rise to12 m below M.S.L. near New Orleans [REF 45].
The Pleistocene deposits mainly consist of over-consolidated clays and silts. The strength of the Pleistocene layer in general is generally considered to be stiff, although local conditions vary significantly along the channel. Cohesive strengths of the Pleistocene layer range from 23.9 kPa to 101 kPa (500 to 2,100 pounds per square foot).

The prodelta layer overlies the Pleistocene layer. This layer has a thickness ranging from 3 m near New Orleans to 30.5 m near the Chandeleur Sound. Approximately 95% of this layer consists of normally consolidated clay. The gain size gets smaller towards Chandeleur Sound and at increasing depths. Cohesive strengths of the prodelta layer range from 9.6 kPa to 28.7 kPa (200 to 600 pounds per square foot).

Active delta deposits consist of different soil types of which the interdistributary layer is decisive. The layer has a thickness of 3 to 15 m. The water content in the soil is high, ranging from 50% to more than 160% of the dry weight. The clays tend to consolidate and gain cohesive strength with increasing depth. Cohesive strengths of the interdistributary layer are low and range from 7.2 kPa to 14.4 kPa (150 to 300 pounds per square foot).

The cover-layer of the area surrounding the MRGO consists of marsh and swamp deposits. The marsh deposits consist of peat, other organic materials and clay. The total marsh thickness is 3 m in general. The water content ranges from 80% to 800% dry weight. In general marsh deposits are fibrous and black in color. Swamp deposits contain wood fragments and are often brown, reddish-brown or black in color.

In the Breton and Chandeleur Sounds beach and bay-sound deposits form a bottom-layer of 3 m to 5.2 m. This layer consists of approximately 35% sand, 15% shells, 10% silt and 40% clay [REF 45].

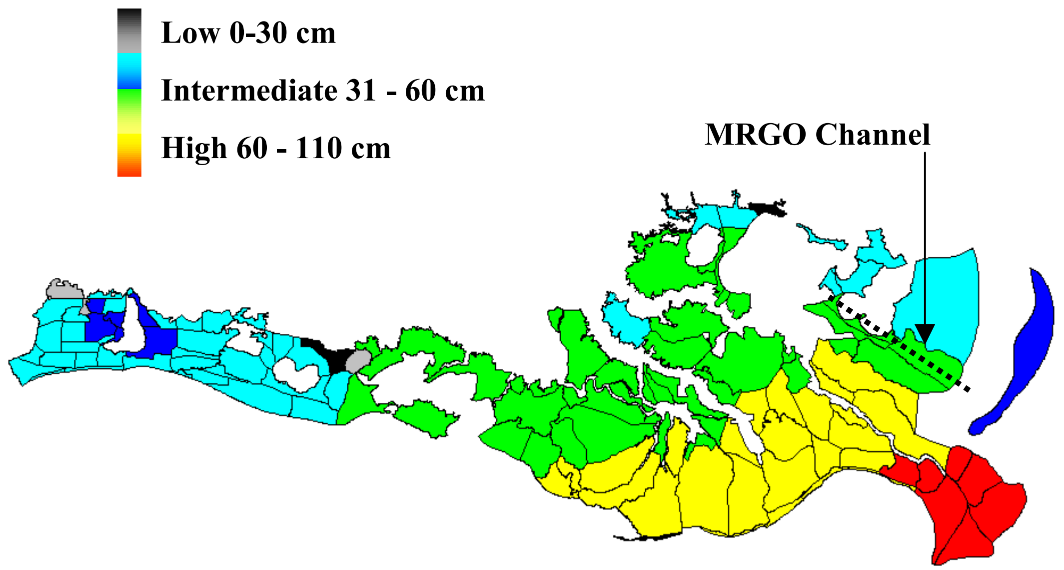
At the transition between the Inland Reach and Breton Sound a natural levee is present. An other natural levee is present at mile 40. The cohesive strengths of these layers are much higher than that of the surrounding marshes, ranging from 38.3 kPa to 62.2 kPa (800 to 1,200 pounds per square foot). The water content and the cohesive strengths of the different soil layers are given in Table 15-3.

Layer	Water content % of dry weight	Cohesive strength **kPa**	Cohesive strength **lbf/ft^2**
Pleistocene layer	-	23.9 -101	500 - 2,100
Prodelta layer	40 - 80	9.6 – 28.7	200 - 600
Interdistributary layer	50 - 160	7.2 -14.4	150 - 300
Cover layer Swamp	60 - 200	Low	Low
Cover layer Marsh	80 - 800	Very low	Very low
Natural levee	20 - 40	38.3 – 62.2	800 - 1,200

Table 15-3 Water content and cohesive strength of soil layers MRGO

15.5 Subsidence

Subsidence occurs when the weight of topsoil-layers compresses the earth below, or when water is pumped from deeper layers. Moreover the exploration and extraction of oil and gas deposits can result in subsidence. The subsidence rate differs along the coastal zone of Louisiana, ranging from 0 to 110 cm per century. Especially the delta zone of the Mississippi is subjected to subsidence. The subsidence in the project area is estimated at 31 -60 cm per century, Figure 15-3 [REF 17]. Resulting in a subsidence of 6 -12 cm for a period of 20 years.



Subsidence in the state of Louisiana*, in cm per century* [REF 17]

Figure 15-3 Subsidence in the state of Louisiana

15.6 Tide

Open water sections

The tide in the Breton and Chandeleur Sound areas is diurnal, which means only one high water and one low water per day. The tides have a normal range of 0.4 m. For the Breton Islands (Latitude 29° 30', longitude 89° 10') the mean tide level is 0.2 m above MLLW, Table 15-4 [REF W26 and REF 11]

Tide levels (open water sections)		Level relative to MLLW	
Highest observed water level (05/05/1981)		0.82 m	2.70 ft.
Mean higher high water	MHHW	0.40 m	1.32 ft.
Mean high water	MHW	0.39 m	1.30 ft.
Mean tide level	MTL	0.20 m	0.66 ft.
Mean low water (Mean Low Gulf (MLG))	MLW	0.003 m	0.01 ft.
Mean lower low water	MLLW	0.00 m	0.00 ft.
Lowest observed water level (02/04/1981)		- 0.40 m	-1.30 ft.

Table 15-4 Tide table Breton Sound

Inland reach

The tidal amplitudes in the Inland section of the channel are significant lower than in the open water section. The tide travels along the MRGO channel as a long wave. Convection, inertia and friction each have influence on the characteristics of the tide. Friction causes the amplitudes of the tide to decrease as the tide progresses along the channel. The reduction over a certain distance, Δx, is equal to $e^{-\mu\Delta x}$. *(in appendix 16 detailed information is given on the muting factor).* Over a distance of 10 miles along the channel the amplitudes of the tide, water level and discharge, are equal to the amplitudes at the beginning of the channel multiplied by a factor 0.85. *(For an Δx of 16,093 m and a μ of $8.8 \cdot 10^{-6}\ m^{-1}$, appendix 16).*The tidal amplitudes along the MRGO are given as a percentage of the amplitudes in Breton Sound in Figure 15-4.

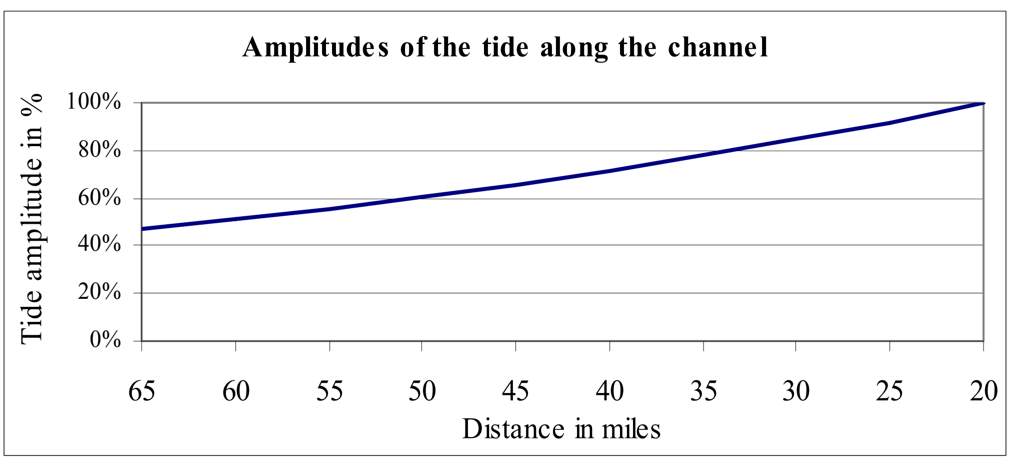


Figure 15-4 Amplitudes of the tide along the MRGO as a percentage of amplitudes in Breton Sound

The reduction of the tidal amplitudes per unit of length is relative small compared to other channels with similar dimensions. The diurnal character of the tide causes the influence of the tide to stretch relatively far into the MRGO channel. During tropical storms, the wind driven tides can reach abnormal heights. Water level rises of 1.8 -2.4 m have been observed and hurricane surges can produce heights of 3.7 m along the coastline of Louisiana [REF 45].

15.7 Currents

Open water section
Field measurements on the current velocities indicate a predominant South- North direction of the current in the Chandeleur Sound, appendix 17.

In the upper part of the Breton Sound Section, current velocities average about 0.1 m. per second annually and about 0.21 m/s during the period July- November (the hurricane season). During hurricanes current velocities can reach up to 1.4 m/s [REF 45]. The dominant current direction in the upper part of the Breton Sound is South- North [REF 45]. In the lower part of the Breton Sound the average current velocities are slightly higher up to 0.5 m/s.

Closer to the Gulf of Mexico, in the lower part of the Breton Sound section and the Bar Channel, the dominant direction of the currents is Northeast- Southwest. This can be derived from the shape of the Breton Islands, appendix 1. However field measurements are not available to confirm this assumption.

Inland reach
The average tidal currents in the MRGO channel are estimated at 370 m^3/s (13,000 ft^3/s) during the flood-tide period and 511 m^3/s (18,000 ft^3/s) during the ebb-tide period [REF 15].
Given the discharge of the tidal currents and the cross-section area, the theoretical waterdepth-averaged water velocities can be calculated. The wet cross section of the channel is; A_c = $2 \cdot ½ \cdot 11 \cdot 38.5 + 11 \cdot 152 = 423.5 + 1672 = 2096\ m^2$.

	Discharge	Surface	Velocity m/s	Velocity ft/s
Flood currents	370 m^3/s	2096 m^2	0.18 m/s	0.58 ft/s
Ebb currents	511 m^3/s	2096 m^2	0.24 m/s	0.80 ft/s

Table 15-5 Discharge and velocity of tidal currents

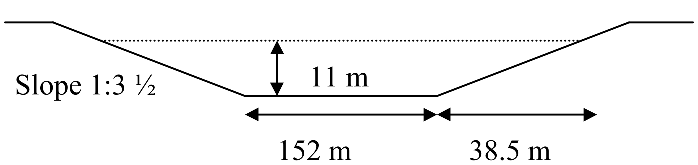


Figure 15-5 Dimensions of the cross-section

The theoretical (water-depth-averaged) current velocities of 0.18 m/s and 0.24 m/s are slightly higher than the measured average of 0.18 m/s

The currents in the MRGO channel are influenced by the freshwater inflow to Lake Pontchartrain. During periods of low stages and inflow, July through November, the tidal currents show a larger discharge.
During the July -November the average velocity of the **surface ebb** current is 0.24 m/s and the average **bottom flood** velocity is 0.52 m/s. Both currents can exceed 0.61 m/s.

15.8 Fauna

The MRGO channel and the wetlands surrounding are the habitat for numerous species such as waterfowl, wading birds, shorebirds, songbirds, alligators and furbearers. Wetlands are major breeding grounds for birds. As birds migrate for their hibernation, the wetlands are used as a stopover. Some threatened and endangered species, such as the bald eagle, brown pelican and piping plover live in the wetland area [REF W5].

Shellfish such as shrimp and crabs and many fish species use the coastal wetlands as nursery habitat as well as spawning area or feeding ground. The fish in the project area are predominant marine *(salt water)* in nature.
A large crab population is present, consisting of the blue crab *(Callinectes Sapidus)* and the mud crab *(Rhithropanopeus Harrisii)* [REF 11].
The population of shrimps consists of the white shrimp *(Penaeus Setiferus)* in the brackish areas, the brown shrimp *(Penaeus Aztecus)* and pink shrimp (*(Penaeus Duorarum)* in the more saline waters [REF 11].

The Nutria *(Myocaster Coypus),* an animal with the size of small dog, was introduced in the wetlands in the 1930. The nutria, originally from Argentina, were kept domestically, but they escaped or were intentionally released into the wetlands. Their numbers have increased dramatically and they form a threat to the wetlands as they aggressively eat vegetation. [REF 18]

15.9 Flora

The wetlands provide an ecosystem with a variety of different vegetation. Some plants can only be found in wetlands, examples are: smooth cord grass, cattails, swamp rose, spider lilies, and cypress trees. The channel banks are presently vegetated by different grass species.

15.10 Lake Borgne and Lake Pontchartrain

Based on data collected from REF 11, the surface area of Lake Borgne is estimated to be 680 km^2 and the average depth of the lake to be 2.4 m below mean low water. The corresponding values for Lake Pontchartrain are 1350 km^2 and 3.6 m.

15.11 Wind conditions

Wind climate

The yearly wind system in the project area is similar to that of the Gulf Coast in general. The general characteristics of the wind are as followed:

- The predominant wind condition is North, Northeast from September through December.
- The predominant wind condition is Southeast from March through June.
- The Northern winds have mean wind intensity greater than the Southern ones despite the fact that the latter are of longer duration.
- Average annual wind velocity = 3.8 m/s.
- Annual wind velocity summary, in percentage of time:

0 -5.5 m/s	= 77.5 %
5.6 -8.4 m/s	= 18.0 %
> 8.5 m/s	= 5.5 %

- Annual wind direction summary, in % of time:

North	= 66.6 %
Southwest	= 22.5 %
Calm	= 10.9 %

A wind rose and wind data are given in appendix 15, based on REF 11 and 15.

Wind set-up

The shallowness throughout the project area makes the water level very sensitive to the wind shear stress. The wind set-up can be calculated with the following formula [REF 4]:

$W= c \cdot U^2 \cdot F/g \cdot h$

The fetch-length (F) is different along different locations and for different wind directions. For a wind speed (U) of 8.5 m/s (19 mph) and an average waterdepth (h) of 11 m (36 ft.) the wind set-up is:

$W = 2.4 \cdot 10^{-6} \cdot F$ [m]

($c = c_w \cdot (\rho_{air}/\rho_{water})$ $c_w = 0.003$, $\rho_{air} = 1.21$ kg/m^3 and $\rho_{water} = 1030$ kg/m^3)

Wind induced wave height
The wind-induced wave height for a wind speed of 8.5 m/s is in the order of 0.15 -0.35 m (with a wave period of about 1.2 -2 s), depending on the fetch length and the average water depth. Figure 15-6 gives the wind induced wave height for different fetch lengths and an average water depth of 4 m.

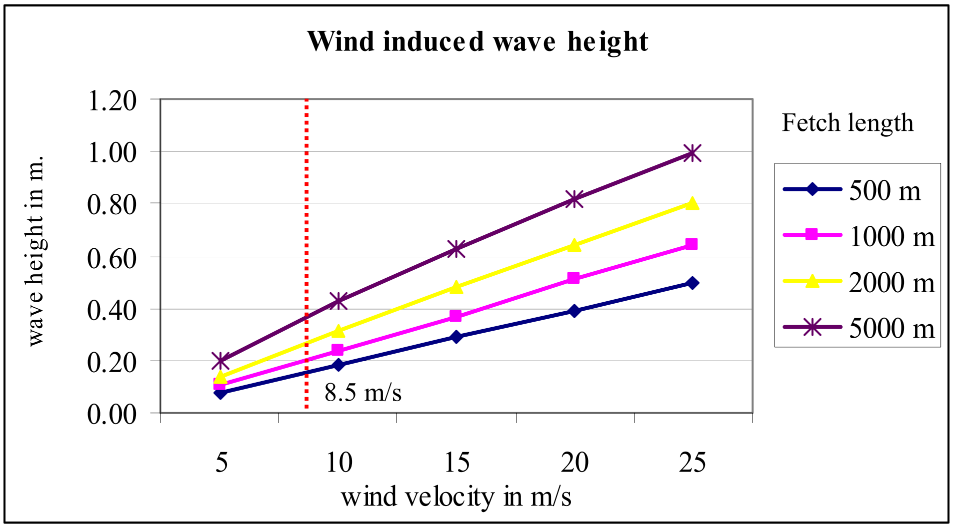


Figure 15-6 Wind induced wave height

Figure 15-6 shows a linear relation between the wind velocity and the wave height, this linear relation allows the interpolation of wind induced wave heights for a wind velocity of 5 and 10 m/s [REF 41] to of 8.5 m/s. Table 15-6 gives the wind induced wave height for a wind velocity of 8.5 m/s for different fetch lengths and water depths.

Fetch length ↓	Water depth →	Wind induced wave height (8.5 m/s)		
		1 m	2 m	4 m
500 m	H_s [m]	0.14	0.14	0.15
	T_p [s]	1.28	1.35	1.38
1000 m	H_s [m]	0.16	0.19	0.20
	T_p [s]	1.48	1.55	1.55
2000 m	H_s [m]	0.20	0.24	0.26
	T_p [s]	1.65	1.75	1.82
5000 m	H_s [m]	0.22	0.31	0.36
	T_p [s]	1.85	2.09	2.19

Table 15-6 Wind induced wave heights

15.12 Wind Data

Average monthly wind velocity, in miles per hour (data copied from REF 45).

M.p.h.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0-7	37.0	33.4	32.1	35.9	45.6	56.0	63.1	63.8	51.9	51.1	42.5	39.2
8-12	33.4	32.8	32.6	33.6	34.3	32.9	28.7	28.1	29.2	28.8	30.2	32.9
13-18	22.3	25.9	27.1	24.8	17.3	10.4	7.4	7.4	15.8	16.1	20.5	21.8
19+	7.3	7.9	8.2	5.7	2.8	0.7	0.8	0.7	3.1	4.0	6.8	6.1

Table 15-7 Wind data

Annual wind velocity summary, in % of time.

0 -12 M.p.h. = 77.5 %
13 -18 M.p.h. = 18.0 %
19 + M.p.h. = 5.5 %
Average annual wind velocity = 8.6 M.p.h.

Annual wind direction summary, in % of time.

North = 66.6 %
Southwest = 22.5 %
Calm = 10.9 %

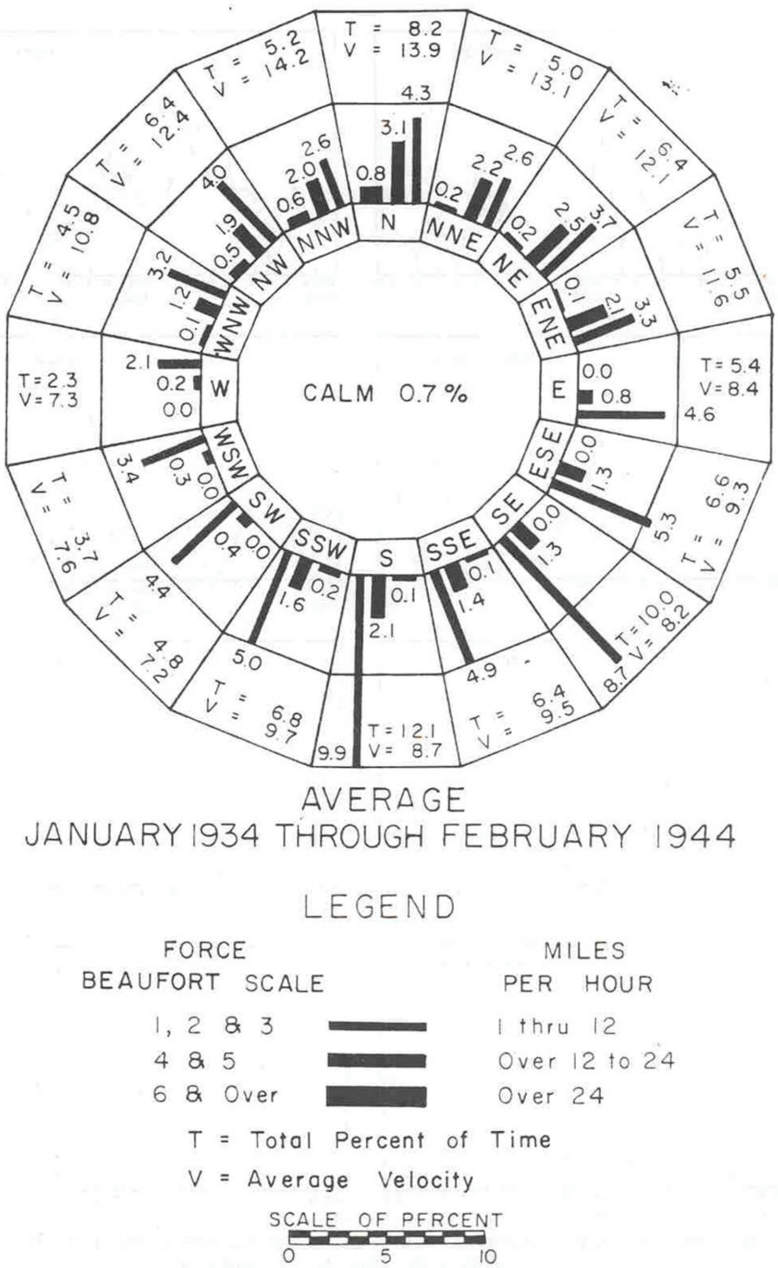


Figure 15-7 Wind rose

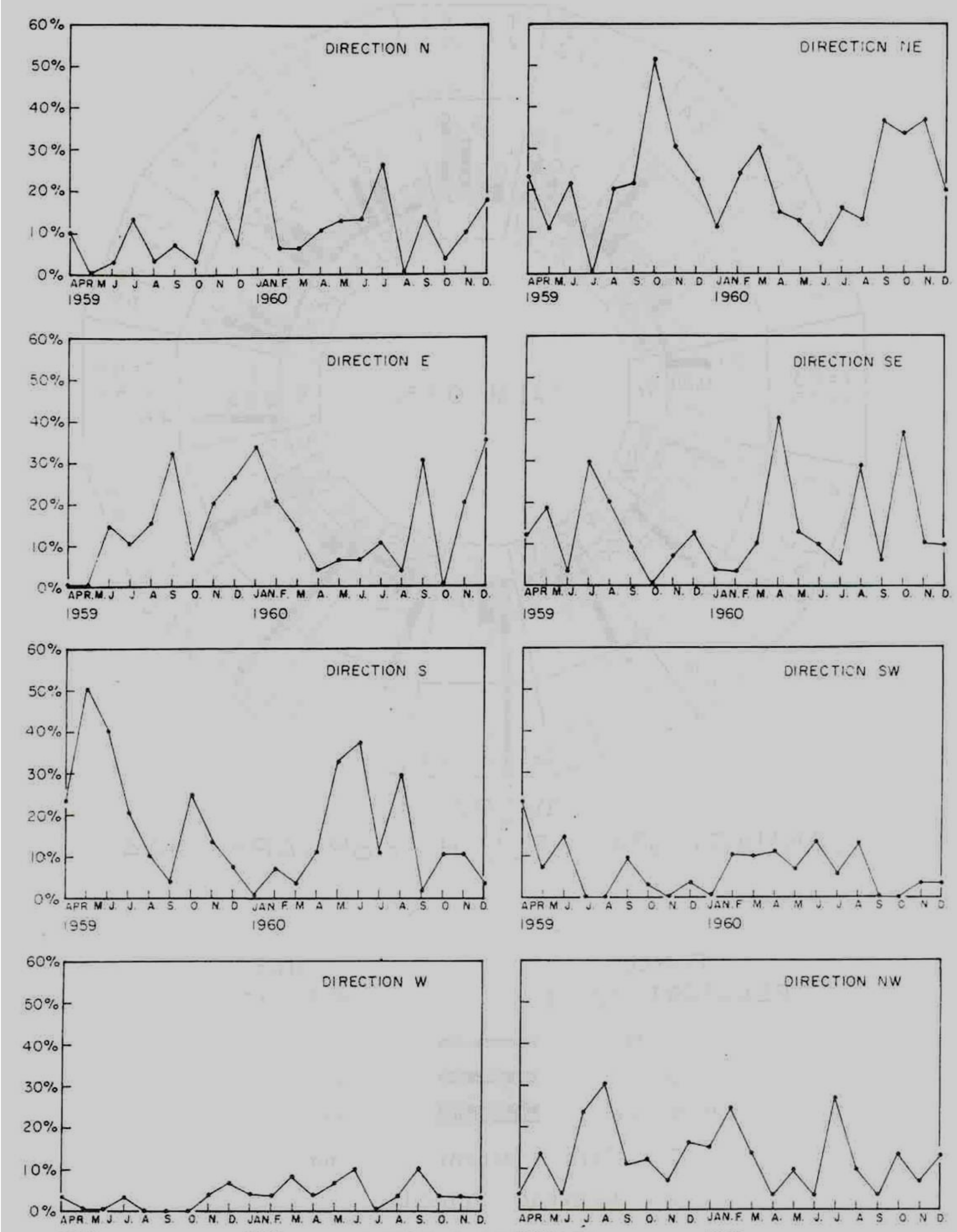


FIGURE 9 WIND FREQUENCY DIAGRAM AT NEW ORLEANS FOR EACH PRINCIPAL WIND DIRECTION BETWEEN APRIL 1959 AND DECEMBER 1960

Figure 15-8 Wind data

Appendix 16 Tidal intrusion

The tide travels along the MRGO channel as a long wave. Convection, inertia and friction each have influence on the characteristics of the tide. How far the influence of the tide stretches into the MRGO channel depends on the muting factor.

To calculate this muting factor, called μ, the ratio between friction and inertia has to be determined first. The following formula gives an indication of this ratio [REF 32]:

$$\sigma \equiv \frac{\kappa}{\omega} = \frac{8}{3\pi} \cdot c_f \cdot \frac{\hat{U}}{\omega R}$$

Symbol	Explanation	Value
C_f	Bottom friction coefficient	0.004
$\hat{U}$	Average water velocity	± 0.5 m/s
T	Period of the tide	M_1 tide, 1440 min, 86400 sec
ω	2π/T	$7.25 \cdot 10^{-5}$ rad/s
D	Depth channel	11 m
A_c	Wet cross section channel	3014 m^2
O	Wet cross section length	400 m
R	Hydraulic beam	7.5 m
σ	Ratio friction to inertia	2,2

Table 16-1 Tidal intrusion calculation I

With this friction-inertia ratio the muting factor can be calculated using [REF 32]:
$\mu = k \cdot \tan\delta$

Symbol	Explanation	Value
c_0	$c_0 = (gA_c/B)^{1/2}$	8.5 m/s
k_0	$k_0 = \omega / c_0$	$8.5 \cdot 10^{-6}$ rad/m
δ	½·arctanσ	32.77°
k	$k = k_0/(1 - \tan^2\delta)^{0,5}$	$1.11 \cdot 10^{-5}$ rad/m
μ	k·tanδ	$8.8 \cdot 10^{-6}$ m^{-1}

Table 16-2 Tidal intrusion calculation II

The amplitudes of the water level and the water discharge reduce as the tide progresses into the channel.
The reduction over a certain distance, Δx, is equal to $e^{-\mu\Delta x}$. Over a distance of 10 km the amplitudes of the tide, water level and discharge, are equal to the amplitudes at the beginning of the channel multiplied by 0.91.
This reduction of the tidal amplitudes is relative small due to the diurnal character of the tide.

Appendix 17 Currents open water section

The current velocities have been measured at two locations north of the MRGO channel in the Chandeleur Sound. Observations were made during a continuous period of 23 months. The measurements are given in the table below: (Data copied from REF 45).

Location A

Current velocities (feet/sec)	No. observations (location A)	North - South component	South - North component
0.34	519	179	340
0.51	139	33	106
0.68	47	13	34
0.85	16	3	13
1.02	2	0	2
Totals	**723**	**228**	**495**

Table 17-1 Open water currents location A

Location B

Current velocities (feet/sec)	No. observations (location B)	North - South component	South - North component
0.34	367	122	245
0.51	99	35	64
0.68	27	3	24
0.85	13	2	11
1.02	3	2	1
1.19	2	1	1
Totals	**511**	**165**	**346**

Table 17-2 Open water currents location B

Conclusion
From this data the conclusion can be drawn that the direction of the currents is predominantly **South – North**.

Appendix 18 Shipping Traffic

The MRGO channel is sailed by both ocean-going and shallow-draft vessels. Shallow-draft vessels include barge tows, commercial fishing boats, oil field crew and supply boats, offshore drilling vessels and pleasure boats. The deep-draft vessels include dry bulk carriers, tankers, general cargo ships and container ships. In the table below the number of ship movements on the MRGO Channel is given according to draft-class.
Ship movements during the period 1986-1994 are copied from reference 15.

The number of ship movements during the period 1998-2001 has been calculated from available data of the Pilots Institution. (Crescent pilots, New Orleans). Data on the vessel dimensions of all vessels that have used a pilot sailing the MRGO have been structured and categorized according to draft class. This analysis only holds under the critical assumption that all vessels with a draft over 20 ft. make use of a pilot.

Year	Draft in feet					Total
	< 20	21- 25	26-30	31-35	36	
1986	4793	553	527	240	9	6122
1987	3291	419	511	187	34	4442
1988	3343	414	589	129	31	4506
1989	3253	337	476	182	45	4293
1990	3478	299	455	197	50	4479
1991	3000	394	506	213	25	4138
1992	3655	440	453	208	13	4769
1993	6826	396	477	274	11	7984
1994	4049	491	399	186	5	5130
Average	**3965**	**416**	**488**	**202**	**25**	**5096**
Percentage	77,8%	8,2%	9,6%	4,0%	0,5%	100%
-	-	-	-	-	-	-
1998	N/A	558	324	159	18	N/A
1999	N/A	360	358	327	11	N/A
2000	N/A	244	333	344	14	N/A
2001	N/A	369	199	232	15	N/A
Average	**N/A**	**383**	**304**	**266**	**15**	**N/A**

Table 18-1 Draft classification

A vessel sailing from the Gulf of Mexico to the Port of New Orleans and back is counted as **two** ship movements.

Appendix 19 Squat calculation

Squat is the combined effect of sinkage and trim due to the forward velocity of a ship. A method to determine the squat in unrestricted waters, is Huuska/Guliev (ICORELS) [REF 16]:

$$squat = 2.4 \frac{\nabla}{L_{pp}^{2}} \frac{F_{nh}^{2}}{\sqrt{1-F_{nh}^{2}}} K_s$$

Symbol	Explanation	Value
∇	Ship's water displacement	$L_{pp} \cdot B \cdot D_s \cdot C_b$ = 750·100·36·0.85 = 2,295,000 feet^3 = 230·30·11·0.85 = 64,515 m^3
L_{pp}	Length between perpendiculars	750 feet (230 m)
F_{nh}	Froude depth number	0.39
G	Gravity acceleration	9.81 m/s^2
K_s	Correction factor	$K_s \cong 1$
V	Velocity of the ship	8 kn (4.1 m/s)
h	Undisturbed water depth	36 feet (11 m)

Table 19-1 squat calculation I

The Froude number:

$$F_{nh} = \frac{V}{\sqrt{gh}} = \frac{4.1}{\sqrt{9.81 \cdot 11}} = 0.39$$

Based on the prevailing boundary conditions, the squat is:

$$squat = 2.4 \cdot \frac{64{,}515}{230^2} \cdot \frac{0.39^2}{\sqrt{1-0.39^2}} \cdot 1 = 0.48m \approx 1.5\,feet$$

(Continued next page)

To check if the validity of the result calculated above, the squat is also calculated using the formula of Barrass. Squat according to the formula of Barrass [REF 6]:

$$squat = \frac{C_B}{30} \cdot S_2^{2/3} \cdot v_s^{2.08}$$

Symbol	Explanation	Value
C_B	Block coefficient	0.85
v_s	Vessel speed	8 kn (4.1 m/s)
S_s	S/(1-S)	0,12
S	Blockage factor = A_s/A_{ch}	0.11
A_S	Wet cross-section of the vessel [6]	3,600 feet^2
A_C	Wet cross-section of the approach channel [7]	22,500 feet^2

Table 19-2 squat calculation II

$$squat = \frac{0.85}{30} \cdot 0.12^{2/3} \cdot 8^{2.08} = 0.52m \approx 1.5\,feet$$

The squat is calculated at 1.5 feet with both formulas.

[6] $A_s = B \cdot D_s = 100 \cdot 36 = 3600$ feet^2

[7] $A_c = 2 \cdot ½ \cdot 36 \cdot 125 + 36 \cdot 500 = 4{,}500 + 18000 = 22{,}500$ feet^2

Appendix 20 Return current and water level depression

When a ship is sailing water is displaced from the front to the back of the ship. The displacement will induce a current along and under the ship. This current, with a direction opposite of the ships sailing direction, is called a return current. The return current results in a depression of the water level, causing a reduction of the nautical depth. The water level depression should be anticipated to prevent any possible grounding incident.
There is a maximum for the amount of water level depression. This maximum is reached when the water depth is equal to the critical depth of flowing water. This maximum of water level depression results in a maximum sailing speed for any self propelled vessel. ("The increase of water velocity and the decrease of water depth would cause an accumulation of water in front of the bow. A self propelled ship is not able to overcome such an accumulation"). [REF 7]

The restrictions of the waterway in depth and width have an impact on the ship.

Limiting speed
The most accurate way of calculating the limiting speed is by use of the following formulas [REF 7]:

$$1-\frac{A_s}{A_c}+\frac{1}{2}\cdot Fr^2-\frac{3}{2}Fr^{\frac{2}{3}}=0$$

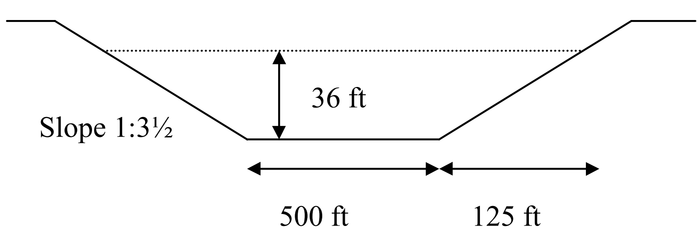
And

$$V_{\lim}=Fr\cdot\sqrt{g\bar{h}}$$

For the prevailing boundary conditions at the MRGO channel (A_s/A_c lies between 0.1 and 0.3) the first formula can be reduced to:

$$Fr=0{,}78\cdot\left(1-\frac{A_s}{A_c}\right)^{2{,}25}$$

The necessary parameters for the equation:



A_s $= B\cdot D_s = 100\cdot 36 = 3600$ feet^2 = 335 m^2
A_c $= 2\cdot½\cdot36\cdot125 + 36\cdot500 = 4{,}500 + 18{,}000 = 22{,}500$ feet^2 = 2100 m^2
H = 11 m

The result is
Fr = 0.60 and V_{lim} = 6.23 m/s =12.1 knots

Maximum return current
U_{lim} can be calculated with [REF 7]:

$$\frac{U_{\lim}}{\sqrt{g\bar{h}}} = \left(\frac{2}{3}\cdot\left(1-\frac{A_s}{A_c}+\frac{1}{2}\cdot\frac{V_{\lim}^2}{g\bar{h}}\right)\right)^{\frac{1}{2}} - \frac{V_{\lim}}{\sqrt{g\bar{h}}}$$

$$\frac{U_{\lim}}{\sqrt{9{,}81\cdot 11}} = \left(\frac{2}{3}\cdot\left(1-0{,}11+\frac{1}{2}\cdot\frac{6{,}23^2}{9{,}81\cdot 11}\right)\right)^{\frac{1}{2}} - \frac{6{,}23}{\sqrt{9{,}81\cdot 11}}$$

U_{lim} = 2.54 m/s

Maximum water level depression
The maximum water level depression can be calculated using the following formula [REF 7]:

$$\frac{Z_{\lim}}{\bar{h}} = \frac{1}{3}\cdot\left(1-\frac{A_s}{A_c}-\frac{V_{\lim}^2}{g\bar{h}}\right)$$

Using the V_{lim} of 12.1 knots as calculated above, the maximum theoretical water level depression is:
Z_{lim} = 1.94 m

Return current and water level depression
However the large containerships will not sail with 12.1 knots (6.23 m/s) through the channel. A vessel speed of 8 knots (4.1 m/s) is more appropriate.
The return current for a speed of 4.1 m/s:

$$\alpha = 1{,}4 - 0{,}4\cdot\frac{V_s}{V_{\lim}} = 1{,}14$$

$$\frac{\alpha\cdot(V_s+U)^2 - V_s^2}{2\cdot g\cdot\bar{h}} - \frac{U}{V_s+U} + \frac{A_s}{A_c} = 0$$

$$\frac{1{,}14\cdot(4{,}1+U)^2 - 4{,}1^2}{2\cdot 9{,}81\cdot 11} - \frac{U}{4{,}1+U} + 0{,}11 = 0$$

The outcome for U can be found through iteration:
U = 0.76 m/s

The water level depression for a speed of 4.1 m/s:

$$Z = \alpha \cdot \frac{(V_s + U)^2}{2g} - \frac{(V_s)^2}{2g}$$

$$Z = 1{,}14 \cdot \frac{(4{,}1 + 0{,}76)^2}{2 \cdot 9{,}81} - \frac{(4{,}1)^2}{2 \cdot 9{,}81}$$

Z = 0.52 m = 1.7 feet

Conclusions
Given the dimensions of the MRGO channel, the theoretical limit conditions of the decisive container ship can be calculated:

Limit conditions			
Limiting speed	V_{lim}	6.23 m/s	12.10 knots
Maximum return current	U_{lim}	0.76 m/s	1.48 knots
Maximum water level depression	Z_{lim}	1.94 m	6.26 feet

Table 20-1 Return current limit conditions

For a container ship sailing with a typical speed of 8 knots the conditions are:

Prevailing conditions			
Vessel speed	V	4.10 m/s	8.00 knots
Return current	U	2.54 m/s	4.94 knots
Water level depression	Z	0.52 m	1.70 feet

Table 20-2 Return current prevailing conditions

The calculations above are carried out with the use of a 1 dimensional approach. One of the assumptions of the 1 dimensional approach is that ships sail midway through the channel. This assumption will not hold for the MRGO channel. The water level depression and the return current will increase slightly as ships sail midways through the channel.

Appendix 21 Transversal wave-height

A ship sailing at a certain speed generates a wave system consisting of a front wave and a stern wave. The front wave is formed by the transition between undisturbed water in front of the vessel and the water-level depression beside it. The total wave height, of this front wave, is slightly greater than the water-level depression. At the transition between the water-level depression, beside the ship, and the normal water level behind the ship a stern wave is formed. (See appendices 20 and 22 for more details on the water level depression).
Both the stern wave and the front wave have a divergent and a transversal component.
The wave crests of divergent and transversal wave interfere where they meet, and form cusps.

The wave height of the transversal waves can be calculated by using [REF 7]:

$$\frac{H_t}{h_0} = \alpha_t \cdot \left(\frac{x'}{h_0}\right)^{-0.5} \cdot \left(\frac{V_s}{\sqrt{g \cdot h_0}}\right)^3$$

H_t height of the transversal waves
x' distance behind the ship
α_t coefficient depending on the shape of the ship

The formula above can be simplified to [REF 7]:

$$H_t = \gamma_t \cdot \frac{V_s^2}{g}$$

In this formula a new coefficient, the γ, is introduced, the γ depends on the vessel dimensions. The ships sailing in the MRGO channel can, very roughly, be divided into the following categories:

Type of ship	Vessel speed	Vessel speed	γ-Factor	H_t
Pull towing boat	16 knots	8.2 m/s	0.085	0.59 m
Loaded formation of 4 barges	10 knots	5.1 m/s	0.145	0.39 m
Container ships	8 knots	4.1 m/s	0.175	0.30 m

Table 21-1 Transversal wave height calculation

Appendix 22 Hydraulic loads on the channel bank

The channel banks are subjected to the hydraulic forces generated by sailing vessels, winds and currents. These forces cause loads in the form of either shear stress or local pressure points. The hydraulic loads can be classified as followed:

Natural hydraulic loads
- Water level changes induced by tides
- Current, discharge Mississippi river
- Tidal currents
- Wind induced currents

Ship induced water motion
- Return current (primary wave)
- Water level depression (primary wave)
- Front wave (primary wave)
- Transversal and divergent stern waves (secondary wave)
- Interference peaks (secondary wave)
- Screw race (screw race)

The ship-induced hydraulic loads on the channel banks are dominant over the natural hydraulic loads. Therefore only the ship induced hydraulic loads are discussed in this appendix.

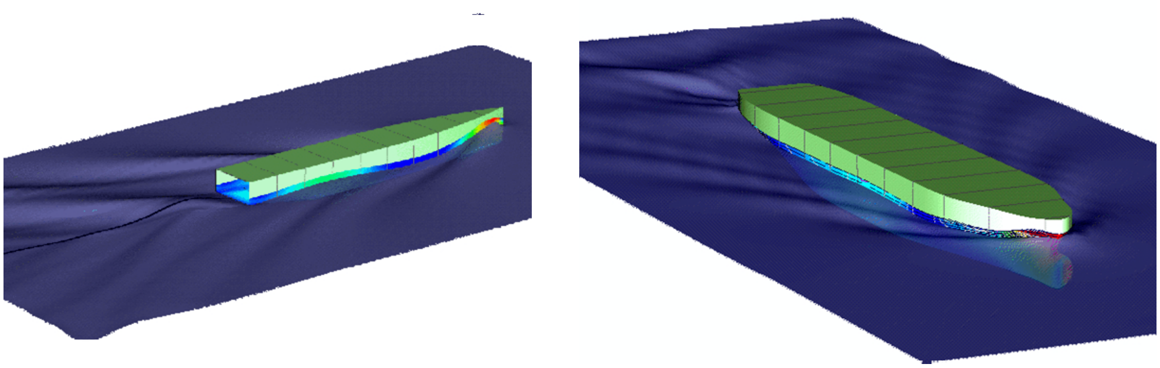


Figure 22-1 Impression of the ship-induced wave pattern **(PICTURES COPIED FROM [ref W45])**

Ship induced hydraulic loads
The water displacement by a sailing results in the following three categories of hydraulic loads:
- Primary wave
- Secondary wave
- Screw race

Primary wave
The primary wave action can be divided in:
- Return current
- Water level depression
- Front wave

The large container vessels that sail the MRGO channel cause very large quantities of water displacement. This water displacement results in a local water level rise in front of the ship and a current along and under the ship. This current, with a direction opposite of the ships sailing direction, is called a return current. The return current results in a depression of the water level, causing a reduction of the nautical depth. There is a maximum for the amount of water level depression. This maximum is reached when the water depth is equal to the critical depth of flowing water.

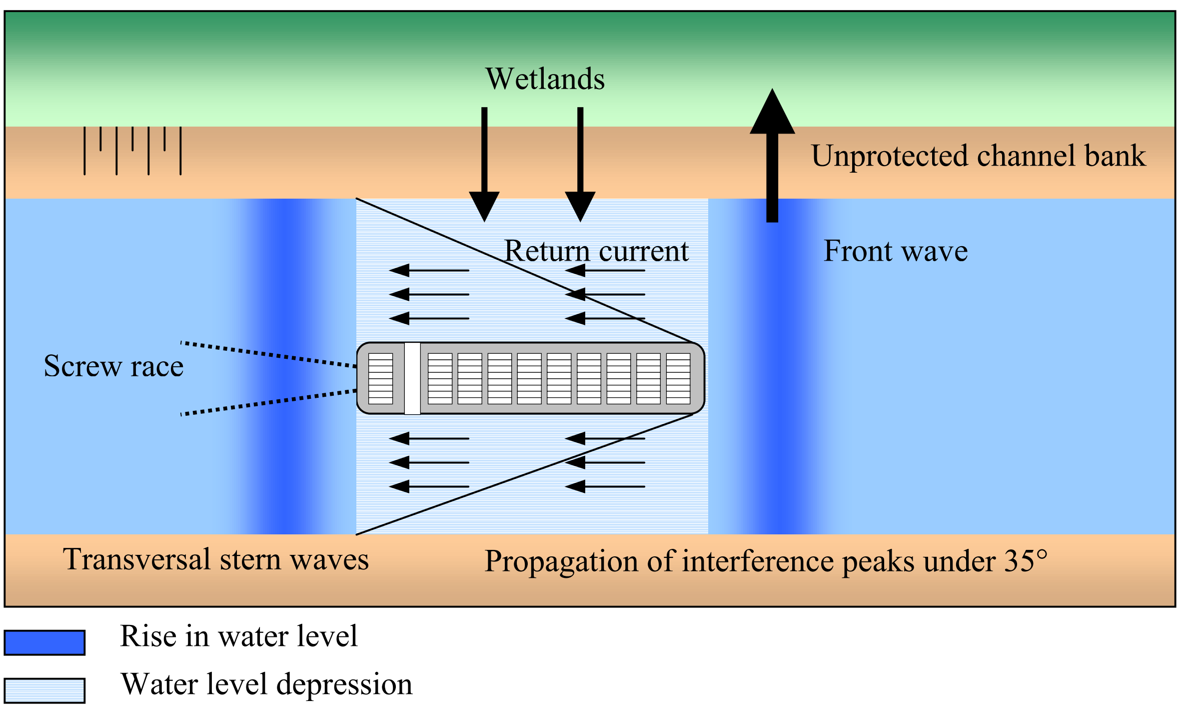


Figure 22-2 Ship-induced waves and currents

This maximum water level depression results in a maximum sailing speed for self propelled vessels. Moreover this water level depression sucks the water from the surrounding marshes back into the channel.

Secondary wave

The secondary wave system consists of transversal and divergent waves. The combination of the transversal and divergent waves results in interference peaks. In general the largest attack by interference peaks is caused by relative fast sailing unloaded vessel[8].

Screw race

The currents induced by the propulsion of a sailing vessel can result in erosion; especially currents by the bow screw can cause heavy hydraulic loads. However the hydraulic load induced by the primary and secondary wave-action is dominant over the hydraulic load induced by screw race. Figure 22-3 gives an overview of the different hydraulic loads on the unprotected channel banks.

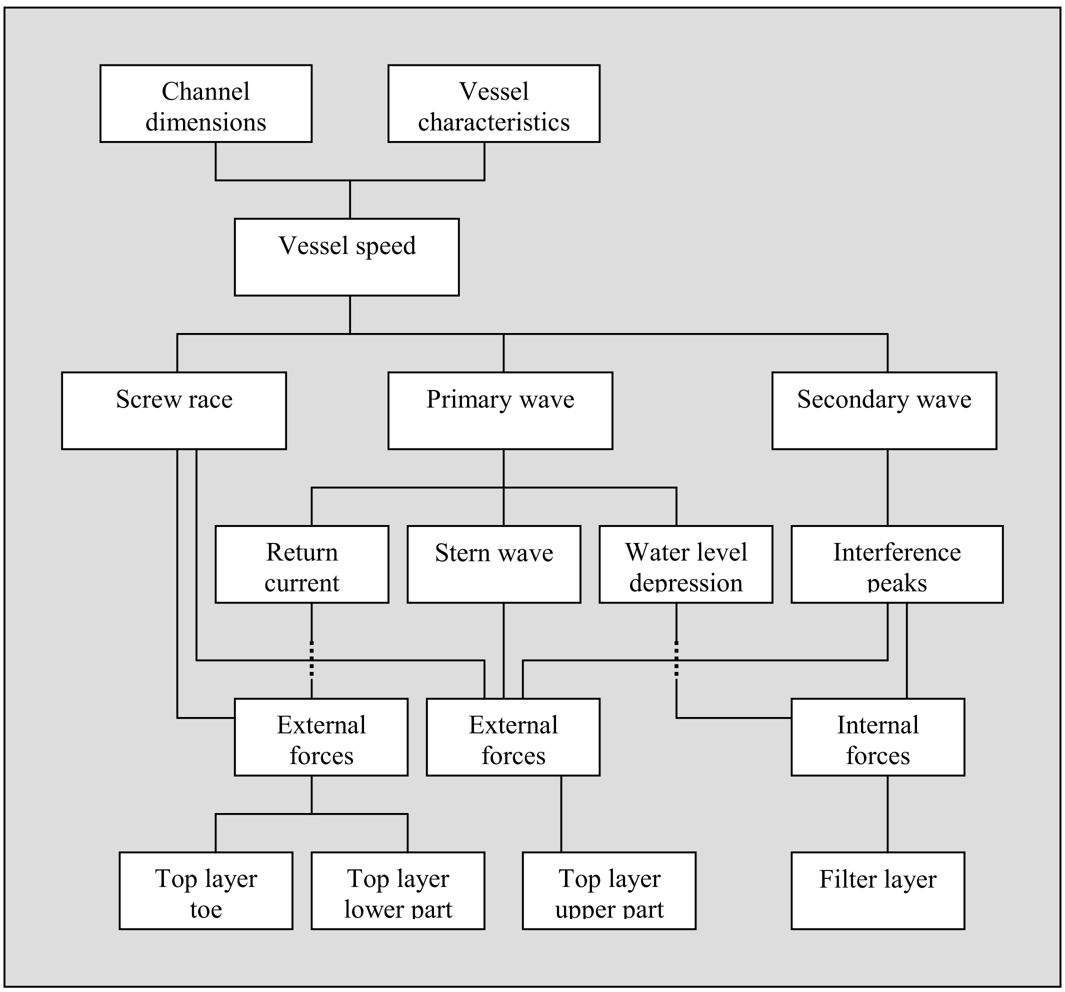


Figure 22-3 Hydraulic loads on the channel banks **(Structure of the figure COPIED from REF 40)**

[8] Fast sailing and unloaded vessel as: tug-boats and recreational vessel

Appendix 23 DIPRO

To calculate the most negative scenario the vessel speed has been chosen at 90% of the limit speed for a certain vessel on the MRGO.

The ship dimensions used in this calculation are not standard DIPRO ship dimensions; coefficients used in DIPRO might be slightly different for the used ship dimensions. Therefore the outcome should **NOT** be used in the design of the bank protection. The outcome from DIPRO is used to give an **INDICATION** of the relative dominance between the different hydraulic loads.

Container ship	
Length	225 m
Width	30 m
Draft	11 m

General cargo ship	
Length	140 m
Width	22 m
Draft	9 m

Recreational vessel [9]	
Length	12,5 m
Width	4,3 m
Draft	1,3 m

Fishing boat [10]	
Length	24
Width	6,7
Draft	3,8

Table 23-1 Vessel dimensions

[9] Dimensions of the “Grand Banks 42” REF 43
[10] Dimensions of the “HD 3 Nieuwediep” REF 44

Hydraulic loads

	Container ship	General cargo ship	Recreational vessel	Fishing boat
V_s	4,6 m/s	5,3 m/s	5,2 m/s	5,5 m/s
V_l	5,1 m/s	5,9 m/s	5,7 m/s	6,1 m/s
U_{rm}	1,4 m/s	1,1 m/s	0,07 m/s	0,2 m/s
U_{re}	1,4 m/s	1,1 m/s	0,07 m/s	0,2 m/s
D_{rm}	0,8 m	0,7 m	0,09 m	0,2 m
D_{re}	0,8 m	0,7 m	0,09m	0,2 m
Z_{max}	1,2 m	1,1 m	0,09 m	0,2 m
I_{gem}	0,09	0,054	0,044	0,071
H_i	0,99 m	1,35 m	0,11 m	0,55 m
H_t	Not dominant [11]	Not dominant	Not dominant	Not dominant
U_{max}	2,9 m/s	2,8 m/s	0,8 m/s	0,8 m/s

Table 23-2 Calculation of the hydraulic loads I

Symbol [12]	Explanation	unit
V_s	Vessel speed (relative to channel bank)	[m/s]
V_l	Limit speed	[m/s]
U_{rm}	Maximum return current	[m/s]
U_{re}	Average return current [13]	[m/s]
D_{rm}	Maximum water level depression	[m]
D_{re}	Average water level depression	[m]
Z_{max}	Stern[14] wave height	[m]
I_{gem}	Average wave-slope	[-]
H_i	Wave height interference peaks	[m]
H_t	Transversal wave height	[m]
U_{max}	Current velocity stern waves	[m/s]

Table 23-3 Calculation of the hydraulic loads II

[11] The transversal wave height is not dominant over the height of the interferences peaks and therefore not calculated in DIPRO. Appendix 21 gives a calculation of the transversal wave height.
[12] Symbols used in DIPRO
[13] between vessel and channel bank
[14] "haalgolf" in Dutch

Current attack

The characteristic stone diameter (D_{50}), required to withstand the hydraulic load by current attack, can be calculated with Shields [REF 71]:

$$D_{50-ur} > \frac{0{,}5 \cdot c_{fr} \cdot K_T \cdot u_r^2}{\psi_{u,s} \cdot \psi_c \cdot k \cdot g \cdot \Delta}$$

With:

$$k = \cos\alpha \left(\frac{1 - \tan^2 \alpha}{\tan^2 \varepsilon} \right)^{0{,}5}$$

$$c_{fr} = \left(2{,}87 + 1{,}58 \log \frac{x}{k_s} \right)^{-2{,}5}$$

$$x = \frac{\widehat{u}_r}{V_s + \widehat{u}_r} X$$

$$X = 0{,}15 L_s$$

With 10m ≤ X ≤ 20m

$$k_s = 2{,}0 \cdot D_{50}$$

Symbol [15]	Explanation	unit
c_{fr}	Shear stress coefficient	[-]
K_T	Turbulence factor (1,0)	[-]
u_r	Current velocity (return current)	[m/s]
$\psi_{u,s}$	Upgrading factor current attack (1,0)	[-]
ψ_c	Critical shear stress coefficient Shield	[-]
g	Gravity	[m/s^2]
Δ	Relative density	[-]
α	Angle channel bank	[º]
ε	Angle of internal friction (± 40º)	[º]
k_s	Bank roughness	[m]
x	Characteristic distance	[m]

Table 23-4 Current attack

[15] Symbols used in DIPRO

Stern wave

The characteristic stone diameter (D_{50}), required to withstand the hydraulic load by the stern wave, can be calculated with [REF 71]:

$$D_{50-zm} > \frac{z_{\max}}{\psi_{u,w} \cdot c \cdot (\cot \alpha)^{0,33} \cdot \Delta}$$

Symbol	Explanation	unit
z_{max}	Water level depression	[m]
D_{50}	characteristic stone diameter	[m]
$\psi_{u,w}$	Upgrading factor current attack (1,0)	[-]
Δ	Relative density	[-]
α	Angle channel bank	[º]
c	Coefficient depending on the vessel (1,4)	[-]

Table 23-5 Stern wave

Interference peaks

The characteristic stone diameter (D_{50}), required to withstand the hydraulic load by the Interference peaks, can be calculated with [REF 71]:

$$D_{50-Hi} > \frac{H_i \cdot (\cos \beta)^{0,5}}{\psi_{u,w} \cdot 1{,}6 \cdot (\cot \alpha)^{0,33} \cdot \Delta}$$

Symbol	Explanation	unit
H_i	Wave height interference peaks	[m]
D_{50}	characteristic stone diameter	[m]
$\psi_{u,w}$	Upgrading factor current attack (1,0)	[-]
Δ	Relative density	[-]
α	Angle channel bank	[º]

Table 23-6 Interference peaks

Required stone dimensions
To withstand the hydraulic loads a rip-rap bank revetment with the following D_{50} of the cover layer is required, Table 23-7

	Container ship	General cargo ship	Recreational vessel	Fishing boat
Current attack (return current)	0,023 m	0,014 m	-	-
Wave attack (interference peaks)	0,131 m	0,177 m	0,014 m	0,070 m
Wave attack (transversal waves)	0,180 m	0,143 m	0,019 m	0,033 m

Table 23-7 Required D_{50} bank revetment

(The ship dimensions used in this calculation are not standard DIPRO ship dimensions; coefficients used in DIPRO might be slightly different for the used ship dimensions. Therefore the outcome should **NOT** be used in the design of the bank protection. The outcome from DIPRO is used to give an **INDICATION** of the relative dominance between the different hydraulic loads.)

Conclusion
Both the current attack and wave attack cause erosion to the unprotected channel banks. A larger grain size is required to protect the channel bank against the wave attack compared to the current attack, Table 23-7. The conclusion can be drawn that the wave attack is dominant over the current attack.

Appendix 24 Causes of sedimentations

24.1 Erosion caused by hurricanes

Hurricanes can be responsible for enormous displacements of sediments (more information in paragraph 6.8) It is not clear to what extent hurricanes have been responsible for sedimentation and correlated additional maintenance dredging at the MRGO channel. A possible correlation could be found by calculating the average annual amount of maintenance dredging for hurricane years and none hurricane years

During the period 1965-2001 the following hurricanes have occurred in the coastal area of Louisiana [REF W29]:

Name	Date	Impact on MRGO[16]
Betsy	September 1965	Significant
Camille	August 1969	Significant
Edith	September 16th, 1971	Minor
Carmen	September 7-8th, 1974	Significant
Babe	September 1977	Significant
Bob	July 11th, 1979	Minor
Danny, Elena and Juan	1985	Minor
Florence	September 9th, 1988	Minor
Andrew	August 26th, 1992	Minor
Opal	October 4th, 1995	Minor
Josephine	October 5-8th, 1996	Minor
Danny	July 1997	Significant
George	September 1998	Significant

Table 24-1 Hurricanes in coastal Louisiana

Effect on sedimentation rate

To analyze if hurricanes are a major cause of sedimentation on the MRGO channel, the following steps were taken:

- First the average annual dredging costs were plotted for both hurricane years (all of the hurricanes listed in Table 24-1) and none hurricane yeas. These plots showed a nearly equal annual average amount of dredged materials.
- Secondly more data on the strength and alignment of the hurricanes was collected. The alignment and strength of the following hurricanes; Betsy, Camille, Carmen, Babe, Danny and George make impact on the dredging works plausible.
  (Selection is based on common sense, and REF W26, W28 and W29).
- Consequently the average annual dredging costs were plotted again for both hurricane years[17] and none hurricane yeas. This time only the hurricanes were included that traveled through the project area and had sufficient strength.

[16] The impact on the MRGO was estimated roughly based on the strength and the alignment of the hurricanes

The average annual amounts of dredged materials during hurricane years and non-hurricane years, over the period 1970 - 2001 are shown in Figure 24-1.

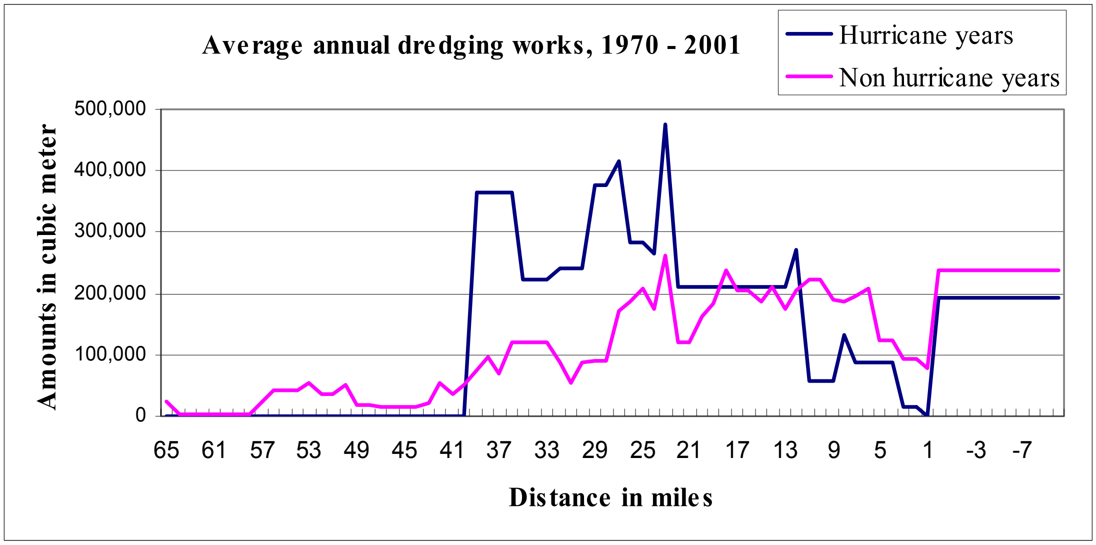


Figure 24-1 Average annual dredging works 1970-2001

Figure 24-1 shows that a hurricane, traveling through the project area, can result in significant higher maintenance dredging. Maintaining assumption of a correlation between the sedimentation rate and the amount of dredged materials, Figure 24-1 makes it plausible that the occurrence of a hurricane will result in above average sedimentation rates.

[17] The majority of the hurricanes occur during autumn, in the months September and October. The fiscal year for the USACE runs from oct-1 until sept-30. Therefore both the actual year of the hurricane and the consequent year are taken into account for the comparison.

The total amounts of dredged materials during hurricane years and non-hurricane years, over the period 1970 - 2001 are shown in Figure 24-2.

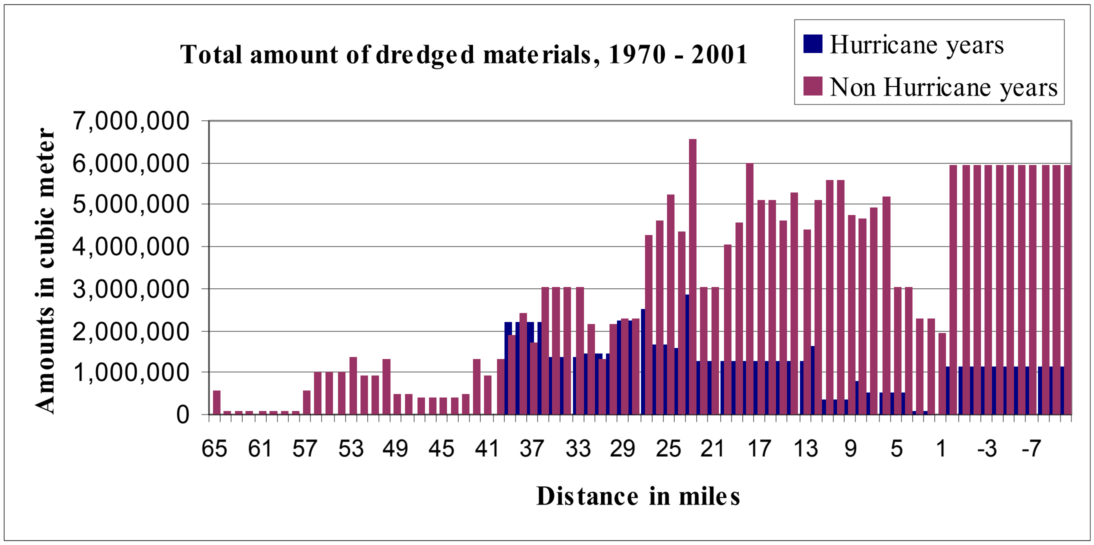


Figure 24-2 Total amount of dredged materials 1970-2001

Figure 24-1 and Figure 24-2 show that the seaward section of the Inland Reach (mile 20- 40) is especially vulnerable to hurricanes. For some locations the total amount of dredged materials during the hurricane years (6 years in total) is equivalent or even larger than the amount of materials during the non-hurricanes years (25 years in total).

The path of the hurricane and differences in soil-conditions can explain the difference in sedimentation rate along the MRGO. The hurricanes cause marshes to break and especially the soft marsh sections of the channel are most vulnerable. This will be further elaborated in paragraph 24.5.

Figure 24-1 shows a slightly lower annual dredging rate for hurricane years at the Breton Sound and the Bar Channel. “Emergency maintenance works” directly after a hurricane might postpone regular maintenance works due to a lack in available funding and equipment. “Emergency maintenance works” in the Inland Reach might have priority over the regular maintenance dredging works at the Breton Sound and the Bar Channel.

Conclusion
The average annual amount of dredged materials is significant higher for hurricane years than non-hurricane years. The conclusion can be drawn that hurricanes are a significant cause of sedimentation in the MRGO Channel, by moving sediments and intensifying bank erosion. Especially the Inland Reach is vulnerable to hurricanes.

24.2 Sediments carried by the Mississippi River

The Mississippi River carries enormous amounts of sedimentation. An average of about 200 million metric tons of suspended sediment is discharged in the Gulf of Mexico annually. (Only five rivers in the world exceed this sediment discharge [REF W30]).
The MRGO channel is connected directly to the Mississippi River only through the lock at Inner Harbor Navigation Channel. An indirect connection between the MRGO and the Mississippi is present through Bayou Dupre, through a fresh-water inlet. The fresh-water inlet between the Mississippi River and Bayou Dupre prevents sediments to enter the MRGO. Most likely the amount of sediments that passes the lock at the IHNC[18] and reaches the MRGO channel is insignificant.

Sediments from the Mississippi River reach the MRGO by a detour, as they are discharged in the Gulf of Mexico and subsequently carried by (tidal) currents to the outer parts of the MRGO channel, as explained in appendix 6.

Conclusion
The conclusion can be drawn that sediments carried by the Mississippi River play a negligible role in the sedimentation-processes in the Inland Reach of the channel.

[18] Inner Harbor Navigation Channel

Increased Tidal range

The construction of the MRGO channel made a direct connection between the Gulf of Mexico and the wetlands, allowing the tide to penetrate the wetlands. The effect of this larger tidal exchange is dual; the water velocities in the wetland area are larger than before the construction of the channel. The other effect is the increased salinity level caused by the salt-water flood current.

The increased water velocities will be described in this paragraph; paragraph 24.4 will deal with the increased salinity.

Tidal intrusion in the channel

The tide travels along the MRGO channel as a long wave. Convection, inertia and friction each have influence on the characteristics of the tide. Friction causes the amplitudes of the tide to decrease as the tide progresses along the channel.

The reduction over a certain distance, Δx, is equal to $e^{-\mu\Delta x}$. (in appendix 16 detailed information is given on the muting factor). Over a distance of 5 miles the amplitudes of the tide, water level and discharge, are equal to the amplitudes at the beginning of the channel multiplied by 0.92. (For an μ of $9.4 \cdot 10^{-6}$ m^{-1}, as calculated in appendix 16)

The reduction of the tidal amplitudes is shown in Figure 24-3.

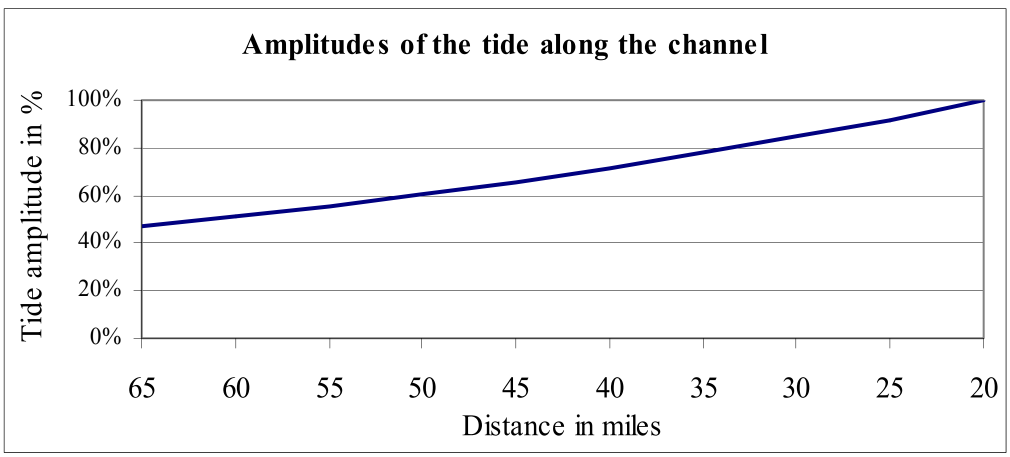


Figure 24-3 Amplitudes of the tide along the MRGO channel

The reduction of the tidal amplitudes per unit of length is relative small compared to other channels with similar dimensions. The diurnal character of the tide causes the influence of the tide to stretch relatively far into the MRGO channel.

However the current velocities of the tidal currents are negligible compared to the current velocity of the ship-induced return current[19].

Sediments from the tidal flats in the Breton Sound are transported along with the flood currents into the inland reach. However the ebb-currents transport the sediments in the opposite direction.

[19] The average tidal current velocity is 0.18 m/s (chapter 3.2.3.); the ship-induced return current can reach up to 1.4 m/s.

The amount of sediment transport mainly depends on the current velocity (for equal sediment characteristics).
The average current velocity is higher during ebb[20]. This would suggest that the net amount of sediment transported from the Breton Sound into the Inland Reach is relatively small.

[20] The decreasing water-level during ebb result in a decreasing flow-cross-section, and consequently an increasing current velocity.

24.3 Tidal intrusion in wetlands

The tidal currents that penetrate into the wetland, through small channels connected to the MRGO channel, carry sand and perished marshes into the channel. Subsequently the sand particles and the perished vegetation settle in the channel. Local increase in sedimentation rate can be expected around the intersection between the MRGO and the connecting channels, or bayous. Figure 24-4 shows the amounts of dredged materials relative to the locations of the bayous.

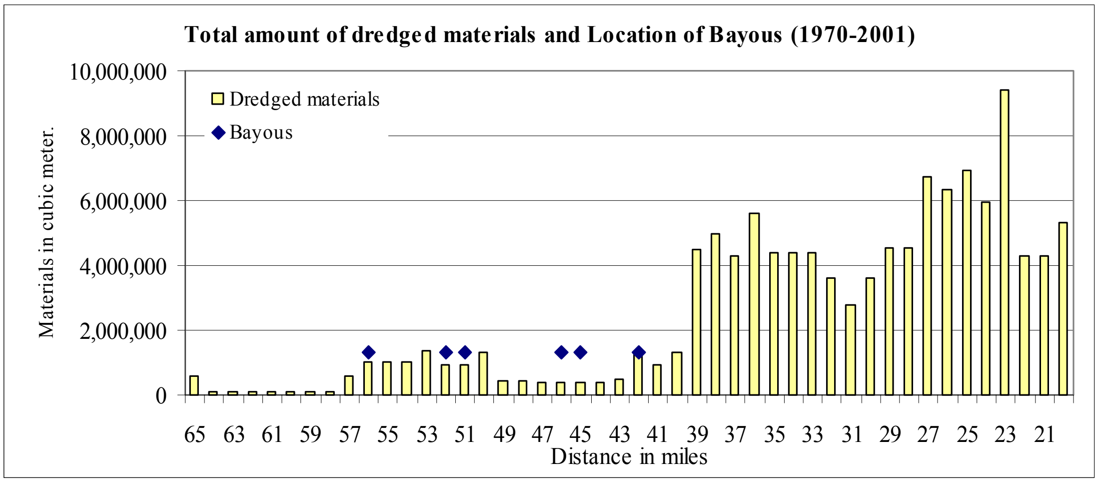


Figure 24-4 Dredged materials and location of bayous

The sedimentation rate shows a local increase at the intersection with some bayous, depending on the discharge of the different bayous. However the amount of sediments entering the channel through the bayous is negligible compared to the amount of eroded materials from the channel banks.

Conclusion

The tidal-current stretches relatively far into the MRGO channel. However the current velocities of the tidal currents are negligible compared to the current velocity of the ship-induced return current.

The tidal currents penetrate into the surrounding wetlands, through bayous connected to the MRGO channel, and carry sediments into the channel. However most likely this is not the dominant cause of sedimentation in the channel.

24.4 Variations in salinity level

Before the construction of the MRGO channel the wetland area was filled with fresh to brackish water. An equilibrium had been formed between the fresh water supply from the Mississippi River and the salt-water intrusion from the Gulf of Mexico. Since the construction of the channel the wetlands are directly connected to the Gulf of Mexico, and the fragile balance between fresh and salt water has been disturbed. The fresh/ brackish water area has changed to a brackish/salt water environment with all consequences for the vegetation. The salinity level in the project area varies at different locations, appendices 4 and 5.

Salt-water wedge

Besides sedimentation caused by perished marshes, the increased salinity level may cause direct sedimentation through a salt-water wedge.
The density of the salt water is higher than that of the fresh water. Consequently the fresh water "floats" over the salt water and density currents occur. Under certain conditions, depending on the fresh-and saltwater gradients, a salt-water wedge is formed.

At the MRGO the fresh water gradient is mainly formed by rainfall. Water from precipitation in the wetland area is drained into the channel resulting in a fresh water gradient. Fresh water from the Mississippi reaches the MRGO through the IHNC lock[21]. The relative fresh water from Lake Pontchartrain forms an additional fresh water gradient[22]. The salt water in the Gulf of Mexico induces a salt-water gradient, from the seaward direction.

The presence of a salt-water wedge would have a significant influence on the sedimentation pattern of the channel. The salt-water wedge could change the currents at the bottom of the channel significantly. At the inland side of the wedge, the bottom current is faced seaward and at seaside of the wedge the current has an opposite direction. In the tip of the wedge the velocity of the current is zero, causing sediment to settle, as can be seen in Figure 24-5.

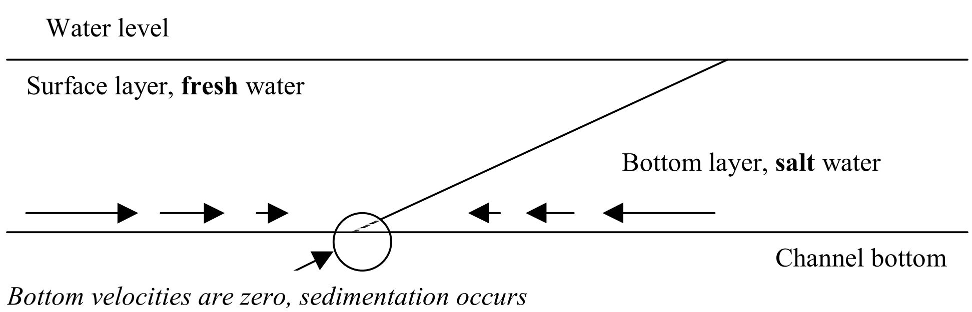


Figure 24-5 Saltwater wedge

Along with the tidal currents the salinity gradient varies in time. This results in a state of dynamic equilibrium and a mixing layer is formed between the fresh surface layer and the salt bottom layer. The tidal currents would cause a possible salt-water wedge to move back and forth in the

[21] The IHNC, Inner Harbor Navigation Canal, connects the MRGO channel with the Mississippi.
[22] The relative fresh water of Lake Pontchartrain reaches the MRGO through Lake Borgne and the Michoud Channel.

channel as a function of the tide. High sedimentation rates can be expected in the area in which the salt-water wedge moves back and forth.
The formation of a salt-water wedge depends, among others, on the fresh water discharge. Above a certain value for the fresh water discharge, salt-water intrusion is not possible. On the other hand, if the fresh water discharge is too small, the whole channel will be filled with salt-water and a salt-water wedge will not occur.
The other determining factor is the mixture between the salt and fresh water layer. This mixture requires energy, for example wave energy or energy from tidal currents.

A clear salt-water wedge cannot be observed at the MRGO channel[23]. However it remains possible that under certain conditions, e.g. extremely high rainfall, a salt-water wedge is formed. Even if a salt-water wedge would occur for a short duration, this would have an insignificant effect on the average sedimentation rate. After extreme conditions the prevailing currents would diminish the effect of a temporary salt-water wedge.

Flocculation
When the suspended sediments consist of clay and salinity differences are present, flocculation may occur. Suspended clay in fresh water consists of needle shaped particles having a maximum dimension less than a few micrometers. Due to their form, large surface area and the crystal structure of the clay minerals, the particles are negatively charged on the surface. Since the particles are so small, the electrostatic forces are dominant over the gravity forces, this keeps the particles separated and in suspension. When the fresh water meets the salt water, at the location of the salt- water wedge the positive ions (e.g. Na^+, $Mg2^+$, and Ca^{2+}) stick to the clay particles and neutralize the electrostatic forces. This causes the clay particles to flocculate and sedimentation occurs. In this process the critical salinity level is around 3 p.p.t.

Sediments in the channel consist of clay particles for about 20 -50% (chapter boundary conditions). At certain locations industrial waste-water and drainage water is pumped in the channel (paragraph **24.8**). This fresh water results in a local area of low salinity. The low salinity level causes the positive ions to release the clay particles. Consequently the clay particles remain separated and in suspension. As the salinity level increases at increasing distance from the fresh-water discharges flocculation occurs. This will result in a high local sedimentation rate.

Conclusion
The fresh water gradient is insufficient to create a clear salt-water wedge. However other phenomena involving salinity differences can occur. At certain locations industrial wastewater and drainage water is pumped in the channel. This fresh water results in a local area of low salinity. Flocculation might occur around these locations resulting in an increase local sedimentation rate.

[23] Measurements carried out REF 11, indicate a vertical mixed salinity level. Consequently the presence of a salt-water wedge is less likely.

24.5 Soil conditions

The soil conditions along the channel MRGO vary heavily at different locations.
In general the top layer, of about 3 m (10 ft.), consists of marsh and swamp deposits.
Soil layers below the marsh-layer mainly consists of (consolidated) clay and silt to a depth of 12 to 52 m (40 -170 ft.). Sand layers can be found at some locations but are uncommon in general.
Details on the soil conditions are given in chapter boundary conditions.

Bank erosion occurs only at the top layer. The channel banks below the top layer are stable and not exposed to wave action. Differences in soil type might explain local variations in the bank-erosion rate and consequently local variations in the sedimentation rate. Therefore the bank erosion is compared with the prevailing soil types.
To simplify the analysis of the bank erosion, the assumption is made that differences in bank erosion rate only depend on the prevailing soil-conditions. Off course the bank erosion depends mostly on the wave/current attack on the channel bank[24]. However, for this analysis, the wave/current attack is assumed constant over the channel length

Soil types

The soil types in the top layer can be categorized as followed:

- Firm Marsh
- Soft Marsh
- Swamp substrate

Marsh deposits consist of peat, other organic materials and clay and are mostly fibrous and black in color. Firm marshes are more cohesive than soft marshes, but both consist of the same materials. Swamp deposits contain wood fragments and are often brown, reddish-brown or black in color.

[24] Aspects as channel slope, perception rate will have an influence on the bank erosion rate, but are presumed constant over the channel length.

Figure 24-6 shows the bank erosion (from 1964 to 1996) for the different soil types. The "diamonds" give the average value of bank erosion for a specific soil type.

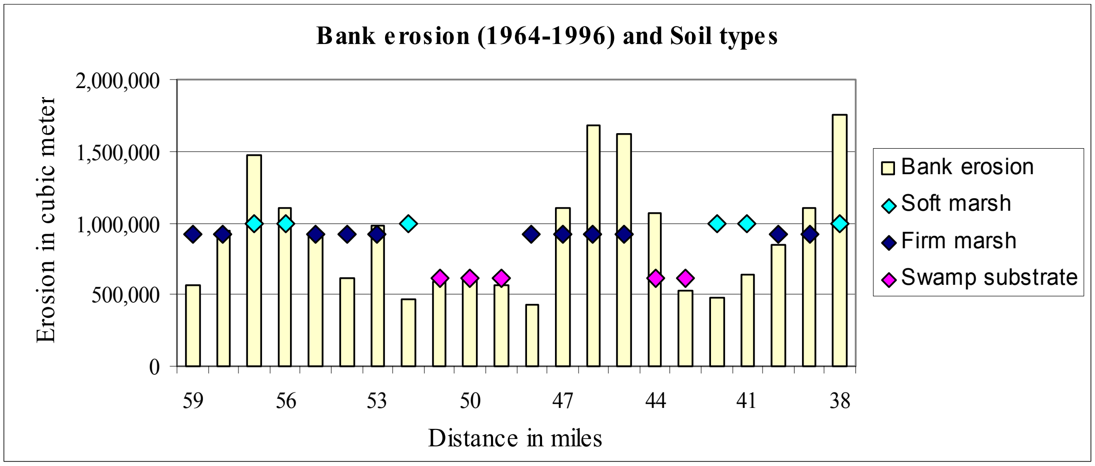


Figure 24-6 Bank erosion versus soil types

Figure 24-6 shows that locations with a top-layer of marsh materials are more vulnerable to bank erosions than locations with swamp-substrate. The average amount of bank erosion (1964 to 1996) per mile for soft marsh, firm marsh and swamp-substrate is 1,300,000, yard^3 1,200,000 yard^3 and 800,000 yard^3 respectively.

The bank erosion rate of the different soil types depends on the grain sizes and the cohesiveness of the materials. The particles of the swamp-substrate are smaller than those of the marshes making the swamp-substrate more vulnerable to erosion. However the swamp-substrate contains wood fragments of former vegetation and root systems. This keeps the soil composed and reduces the level of bank erosion.

An additional soil characteristic that might have an influence on the bank erosion is the clay percentage of the soil. However data on the clay-silt distribution is only available for the channel bottom and not for the top layer[25].
Based on the clay-silt percentage, appendix 38, a comparison is made between the clay percentage and the amount of dredged materials (1970-2001). Figure 24-7 shows that a higher amount of dredged materials for locations with a high clay percentage.
The clay particles remain in suspension for a longer period than the silt particles.

The water-content in fluid mud containing clay particles is therefore higher than mud containing silt particles. In general dredging in the Inland Reach is carried out with a cutterhead dredger, and the assumption is made that the water-content in the dredged materials is higher for higher clay percentages.

[25] A comparison between the clay percentage of the bottom materials and the channel bank erosion for a certain location would not be valid. Materials from bank erosion might settle at a different location than where the actual erosion toke place.

For an equal bank erosion rate this would result in higher rate of dredged materials for locations with a high clay percentage. The average amount of dredged materials for is 5,500,000 yard^3 for a clay percentage below 50% and 7,500,000 yard^3 for a clay percentage above 50%[26]. A higher clay percentage clearly results in higher amounts of dredged materials.

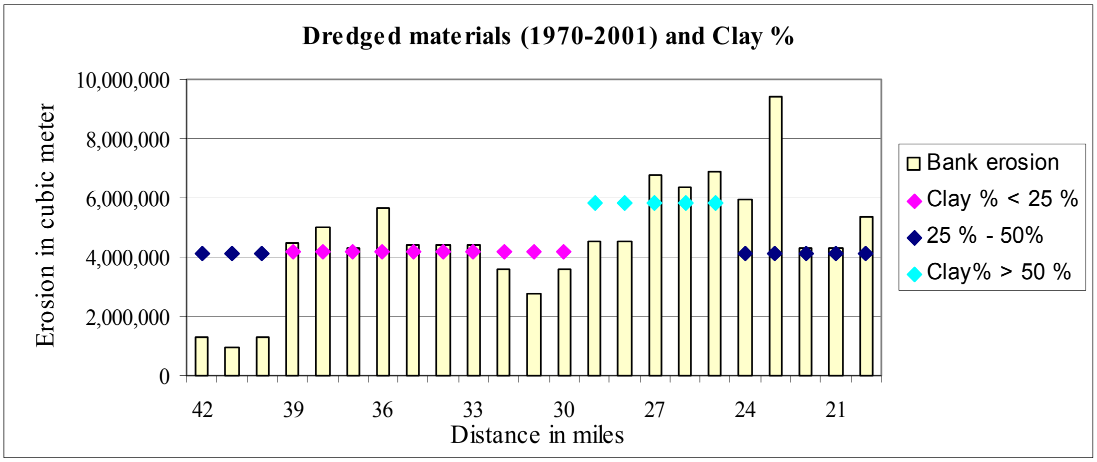


Figure 24-7 Dredged materials and clay percentage

Conclusion

The bank erosion has been compared with the prevailing soil types. The conclusion can be drawn that soil conditions have significant impact on the bank erosion rate (and consequently the sedimentation rate). Locations with a top-layer of marsh materials are more vulnerable to bank erosions than locations with swamp-substrate.

A higher clay percentage clearly results in higher amounts of dredged materials. The water-content in dredged materials is higher for an increasing clay percentage. Therefore a significant volume increase can be expected between eroded and dredged materials for locations with a high clay percentage.

[26] One could argue that this indicates a 35% increase in volume of eroded materials to dredged materials. However the erosion rate is not constant and other sedimentation factors play a role.

24.6 Change in geometry

The geometry of the channel has a large influence on the current velocity and consequently the sedimentation rate. An increase of the channel width will result in a decrease of the current velocity *(under a constant discharge)*. This decrease in current velocity allows the sediments to settle.

Lake Athanasio

In the Inland Reach, where the original dimensions of the channel are constant, a local increase in width only occurs at Lake Athanasio (Mile 27 - 24)[27]. The sedimentation rate is higher as the MRGO passes along the Southern boundary of the Lake.
(However the higher sedimentation rate is most likely caused by bank erosion due to wind-induced waves).

Bar Channel

Currents mainly cause sedimentation in the open water section. Density, longshore, tidal and wind-driven currents carry sediments from the surrounding flats to the channel, where settlement occurs. The sedimentation caused by these currents depends on the depth difference between the channel and the surrounding flats. In general, a deeper channel will incur more sedimentation by currents than a shallow channel. The velocity of the crosscurrent decreases when it crosses the channel, due to the increased depth, resulting in sedimentation. The channel depth of the MRGO increases from 11 m (Breton Sound) to 11.6 m at the Bar Channel, resulting in a relative higher sedimentation rate in the Bar Channel.

The bottom width of the MRGO increases from 152 m (Breton Sound) to 229 m at the Bar Channel. A significant larger area has to be dredged per channel mile, leading to larger amounts of dredged materials.
Figure 24-8 gives the amount of dredged materials per meter channel width for each mile along the channel.

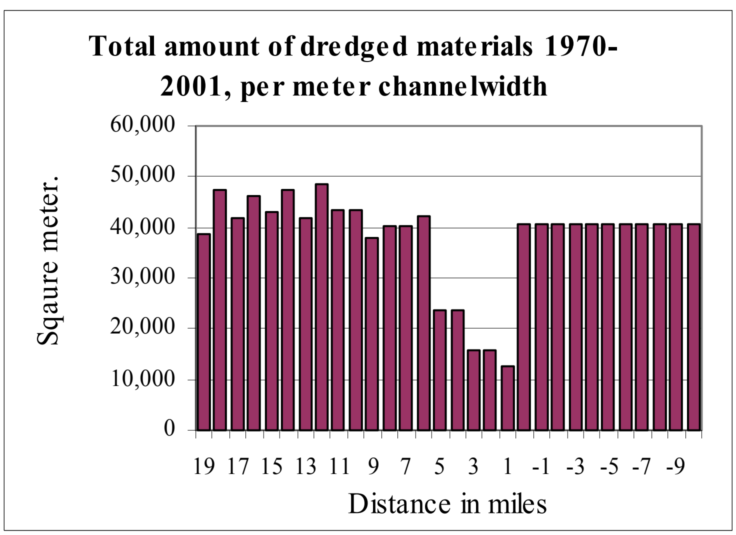


Figure 24-8 Total amounts of dredged materials per meter channel width

[27] When describing the channel in the direction New Orleans - Gulf of Mexico, mile 27 comes before mile 24.

24.7 Miscellaneous effects

Levee construction

A levee has been built, on the South Bank of the MRGO channel, to protect the populated hinterland against storm surge caused by hurricanes. Dredging works have been carried out in the MRGO channel to provide materials for the construction of the levee.

Between miles 65 -46 the channel was dredged to various depths, with an average depth of about 17 m (55 ft.) below M.S.L (Appendix 40 gives the average dredging depth per mile). At some particular locations (between mile 65 and 46) dredging was carried out up to a depth of 24 m (80 ft.) below M.S.L. [REF 46]

The dredging works for levee construction clearly had a large impact on the maintenance dredging frequencies. The amount of overdredging is large compared to the average annual sedimentation rate. On average a layer of 0.34 m (1.10 ft) is deposited in the Inland Reach every year[28] (The maximum sedimentation rate in the Inland Channel is 1.2 m (4.07 ft.) a year). Given this average sedimentation rate of 0.34 m a year and the average depth of 17 m below M.S.L, it can be concluded that the section, from mile 65 to 45, was not in need of maintenance dredging for a period of about 15 -20 years.

The low amounts of dredged materials from mile 65 -46 (figure 7-1) misrepresent the actual sedimentation rate. Clearly the direct relation between the maintenance dredging and the sedimentation rate doesn't hold for that part of the channel.

Jetties

Two jetties are present at both sides of the channel at the transition between the Inland Reach and the Breton Sound. These jetties limit the sedimentation by averting the crosscurrents.

Parallel jetties with an equal length might result in the formation of an ebb delta. The flow of the ebb-current is confined between the jetties and reduces in velocity as it enters the open water, resulting in sedimentation.

The jetties in the MRGO channel are not equal in length; a clear ebb delta is not formed. Logically the sedimentation rate increases at the end of the shortest jetty, as a result of a decrease in velocity and density currents.

[28] The average amount of dredged materials (over the period 1970 - 2001) is 107,105 cubic yards/mile per year in the Inland Reach. Given a bottom channel width of 152 m, this means an average sedimentation rate of 0.34 m a year.

24.8 Water discharge

The city of New Orleans has a rainfall sewer system that drains approximately 50,000 acres [REF 45]. With an average rainfall of 57 inches per annum, a large volume of water is discharged each year. The majority of this water is pumped into Lake Pontchartrain and a minor part is discharged at the MRGO channel. Table 24-2 indicates the maximum capacity of the discharge on the MRGO.

Pumping station	Discharge on MRGO through	Maximum capacity m^3/s	Maximum capacity cf/s[29]
Pumping station # 5	Bayou Bienvenue	66.8	2,360
Pumping station # 15	Michoud Channel	21.2	750

Table 24-2 Maximum fresh water discharge MRGO

Industrial wastewater is discharged on the MRGO by the NOPSI Michoud Plant through the Michoud Channel. The fresh waste and drainage water could have an effect on the local sedimentation rate. The first effect is that discharge of fresh water results in a local area of low salinity. Flocculation might occur around these locations resulting in a significant increase local sedimentation rate (paragraph 7.2.6.2.). The second effect is the presence of sediments in the drainage water. The drainage water might contain high concentrations of sediments. Bayou Bienvenue and the Michoud channel intersect the MRGO around mile 59. The sedimentation rate doesn’t show a local increase around mile 59 (figure 7-1) therefore the impact of the water discharge on the sedimentation rate of the MRGO is negligible.

[29] Cf/s; cubic foot per second

Appendix 25 Bank line retreat and bank erosion per mile

Bank line retreat
Table 25-1 gives the amount of bank-line retreat for the period 1964-1996. A survey has been carried out by the USACE in 1996 to address the bank-line retreat for each “STA”. Table 25-1 gives the amount of bank-line retreat averaged over each mile, based on data from the survey by the USACE. (The relation between “STA” and miles is given in appendix 30).

The average annual amount of bank-line retreat (over the period 1964-1996) is:

- South bank: **3,6m** (12.0 ft.)
- North bank: **5,5m** (18.1 ft.)

Location	**South Bank**		**North Bank**	
	Avg. retreat/yr.	Avg. retreat	Avg. retreat/yr.	Avg. retreat
Mile	In ft.	In ft.	In ft.	In ft.
65.0	6.8	217.4	18.5	592.0
64.0	3.9	126.0	1.6	51.2
63.0	6.7	214.4	1.3	41.6
62.0	7.0	225.0	2.7	85.3
61.0	7.4	237.4	0.5	17.3
60.0	7.9	251.3	1.2	39.7
59.0	6.7	214.6	12.6	404.3
58.0	12.3	394.6	15.7	502.4
57.0	14.8	474.0	43.9	1404.8
56.0	18.0	577.3	17.4	556.2
55.0	15.3	488.5	13.6	434.1
54.0	8.7	279.7	9.7	309.8
53.0	9.4	299.4	15.0	480.0
52.0	8.7	278.9	2.5	79.5
51.0	10.0	320.4	4.4	140.0
50.0	7.6	243.3	11.2	358.4
49.0	7.2	229.3	9.2	292.8
48.0	4.7	151.2	10.8	346.9
47.0	12.5	401.1	29.6	948.3
46.0	23.7	757.8	34.9	1115.5
45.0	25.5	814.7	27.4	876.2
44.0	19.6	628.5	11.5	368.0
43.0	5.4	172.6	11.5	366.9
42.0	4.8	155.1	10.5	335.4
41.0	6.6	211.2	18.5	592.6
40.0	12.5	401.4	15.7	503.0
39.0	16.4	523.7	16.5	527.5
38.0	16.0	511.4	44.6	1427.8
37.0	13.1	420.3	25.5	816.5
36.0	7.5	240.0	4.7	151.0

(Continued on next page)

Location	South Bank		North Bank	
	Avg. retreat/yr.	Avg. retreat	Avg. retreat/yr.	Avg. retreat
Mile	In ft.	In ft.	In ft.	In ft.
35.0	12.4	398.1	11.5	368.6
34.0	19.7	629.8	23.5	752.0
33.0	24.9	796.8	21.7	692.8
32.0	21.2	678.4	24.6	788.5
31.0	23.4	747.5	41.8	1338.2
30.0	26.4	844.8	31.2	999.0
29.0	23.2	742.9	48.0	1536.5
28.0	10.6	337.9	18.1	579.8
27.0	13.3	426.2	37.9	1214.1
26.0	14.1	450.7	5.2	164.8
25.0	9.0	288.2	41.0	1312.0
24.0	12.6	404.4	49.2	1574.4
23.0	14.9	476.3	27.0	864.0
22.0	0.0	0.0	2.7	87.7
21.0	0.1	1.9	3.6	116.5
20.0	0.0	0.0	3.7	119.0
Average	**12.0**	**384.4**	**18.1**	**579.8**

Table 25-1 Average annual bankline retreat

Bank erosion per mile
The amount of bank erosion has been calculated by multiplying the average bankline retreat per mile (data listed in appendix 24) and the average decrease in bank-level per mile. The average decrease in bank-level is calculated using the present water depth level and the original level of the channel bank.
The amount of bank erosion per mile is given in Table 25-2.

Bank erosion per mile (1964 -1996)			
	South Bank	North Bank	Total
Mile	(m^3/mile)	(m^3/mile)	(m^3/mile)
65	650,044	885,118	1,535,162
64	376,821	76,551	453,372
63	641,113	62,198	703,310
62	672,849	127,585	800,434
61	710,009	25,836	735,844
60	751,346	59,327	810,673
59	641,591	483,546	1,125,137
58	1,298,033	600,924	1,898,957
57	1,275,776	1,680,290	2,956,066
56	1,553,598	665,226	2,218,824
55	1,314,760	519,269	1,834,029
54	752,686	463,132	1,215,818
53	805,793	1,148,262	1,954,054
52	750,676	190,101	940,777
51	958,081	209,319	1,167,399
50	727,615	535,855	1,263,471
49	685,767	437,775	1,123,542
48	452,032	414,905	866,938
47	1,079,366	1,134,227	2,213,593
46	2,039,313	1,334,280	3,373,593
45	2,192,606	1,047,980	3,240,586
44	1,691,390	440,167	2,131,557
43	516,080	548,614	1,064,694
42	463,898	501,408	965,305
41	568,390	708,860	1,277,250
40	1,080,285	601,689	1,681,974
39	1,566,101	630,906	2,197,007
38	1,376,192	2,134,810	3,511,002
37	1,256,868	1,464,991	2,721,859
36	789,430	225,825	1,015,255
35	1,190,365	440,933	1,631,297

(Continued on next page)

Bank erosion per mile (1964 -1996)			
Mile	South Bank (m^3/mile)	North Bank (m^3/mile)	Total (m^3/mile)
34	1,694,834	1,349,208	3,044,042
33	2,144,379	1,242,993	3,387,372
32	2,028,596	1,178,882	3,207,478
31	2,235,283	1,200,508	3,435,791
30	2,526,176	896,218	3,422,394
29	1,999,411	1,378,393	3,377,803
28	909,423	520,163	1,429,586
27	1,147,113	1,089,126	2,236,240
26	1,212,851	197,118	1,409,970
25	861,770	1,569,291	2,431,061
24	1,088,380	1,883,149	2,971,529
23	1,281,747	1,291,794	2,573,542
22	0	104,875	104,875
21	3,445	243,814	247,259
20	0	142,384	142,384

Table 25-2 Amount of bank erosion per mile (1964-1996)

Appendix 26 Unit rate analysis

The unit rate of the maintenance dredging costs is: dredging costs per cubic yard dredged material. In the following paragraphs the relation between unit rates and the following aspects will be discussed:

- Time
- Project size
- Location

Unit rates over time

The nominal costs per cubic yard have shown an upward trend over the period 1979-2001. This upward trend can mainly be ascribed to inflation. Figure 26-1 shows the average maintenance dredging costs adjusted for inflation[30]. The nominal costs have been converted to prices of 2002 according to the actual average Consumer Price Indexes (USA) over the period 1965-2002 [REF 39]. (Inflation rates are given in appendix 28). The average unit rate for the MRGO is $ 1.46 per cubic meter over the period 1970-2001.

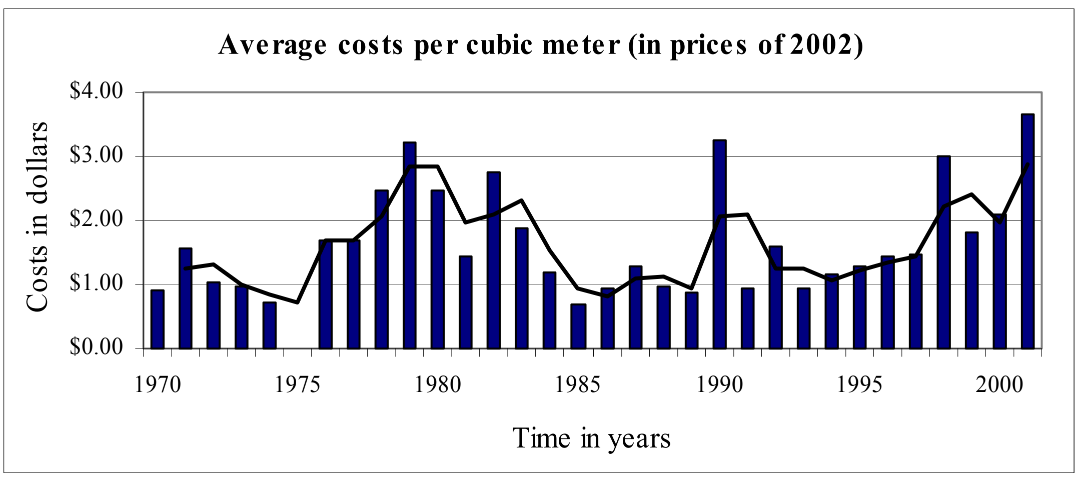


Figure 26-1 Average costs per cubic yard

After 1988[31] dredged materials removed from the Inland Reach have been used for the creation of new wetland areas. This significantly increased the distance to the disposal area, however this effect had a negligible influence on the unit rates (even for the specific unit rate of the inland reach).

Around 1995 the shipping industries increased their demands on the navigability of the MRGO. This resulted in a need for increased accuracy of the dredging works. The result is an upward trend of the unit rates from 1995 to 2000.

[30] All costs in this report have been adjusted for inflation (converted to prices of 2002) unless specifically mentioned otherwise.
[31] Prior to and including the fiscal year 1988 dredged materials were placed on the South Bank of the channel.

Factors as competition, the use of new efficient equipment, environmental restriction and fuel prices also have their influence on the costs per cubic yard.

Unit rates related to project size
Economy-of-scale advantages make larger works relatively less expensive. In general, the costs per cubic yard are lower for larger dredging works (with comparable conditions). The relative high mobilization costs can be divided over a larger number of cubic yards resulting in lower costs per cubic yard. Moreover the use of more efficient large-scale equipment can reduce the unit rates. Large projects, with a long time span, increase the utilization- rate of the contractors' equipment. Part of the contractors' annual expenses for overhead and amortization are fixed. The more materials are dredged by the contractor the lower the fixed expensed per cubic yard for the contractor, which in turn should result in lower costs per cubic yard for the client.

In Figure 26-2 the costs per cubic yard are given in relation to the project size. If the theory of economy of scales would hold for the MRGO channel a descending trend should be seen.

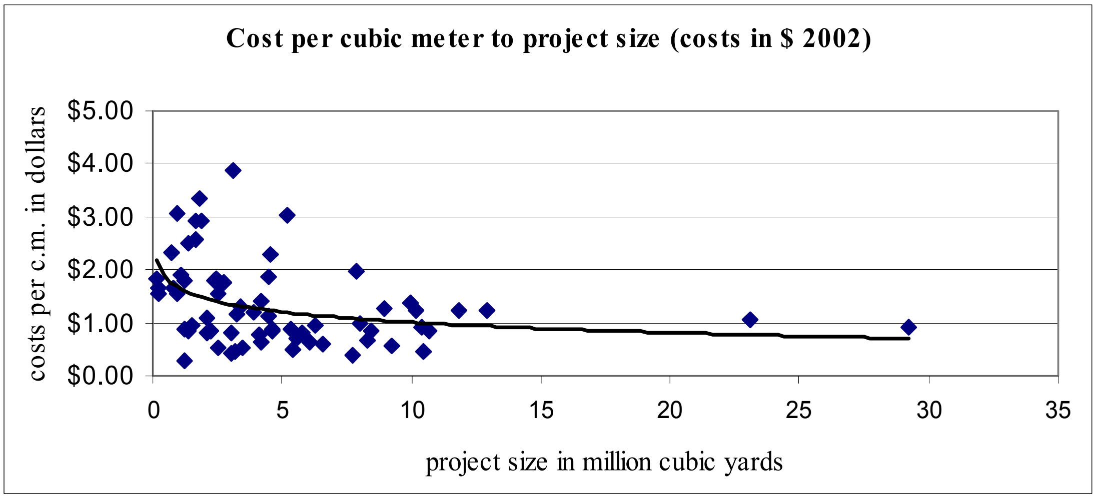


Figure 26-2 Costs per cubic yard to project size

No direct relation between the size of the project and the costs per cubic yard can be given, however a descending trend can be identified. The theory of economy of scales seems to hold for the dredging works at the MRGO channel[32].

[32] Nevertheless, Figure 26-2 should only be used to explain differences in the maintenance dredging costs. The figure should **not** be used to estimate costs of any future projects.

Unit rates per locations

The average costs per cubic yard vary along the different sections of the MRGO channel. Figure 26-3 shows[33] the costs per cubic yards for the different sections of the channel for the period 1970 - 2001.

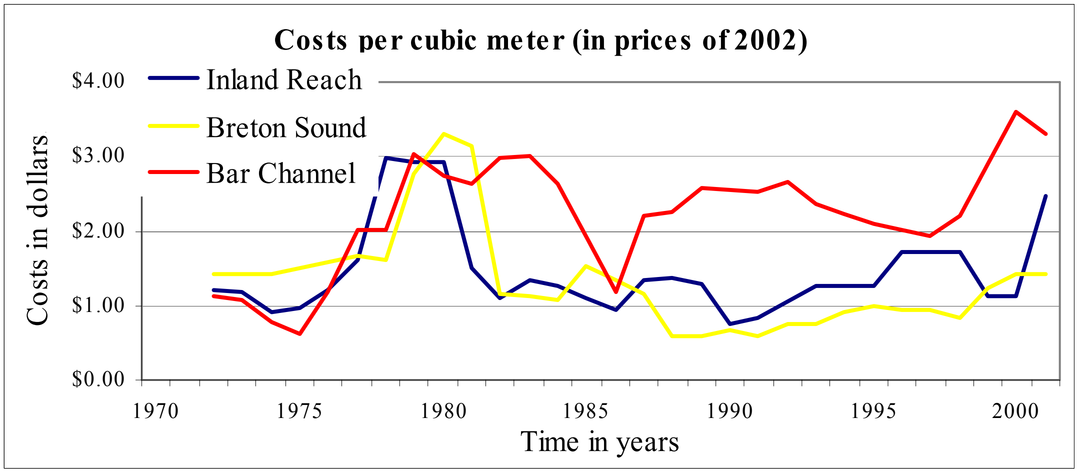


Figure 26-3 Costs per cubic yard

Table 26-1 gives the average costs per cubic yard over the period 1970-2001 for each section of the channel.

Section	Average costs (in $ 2002)	
	Per cubic meter	Per cubic yard
Inland Reach	$ 1.35	$ 1.03
Breton Sound	$ 1.18	$ 0.90
Bar Channel	$ 2.03	$ 1.55
All sections	$ 1.46	$ 1.12

Table 26-1 Average costs per cubic yard

The characteristics of the maintenance works are the most determining factors in the costs per cubic yard. The following aspects might explain differences in costs per cubic yard for the different sections:

- Execution method
- Distance to disposal area
- Characteristics of dredged materials
- Size of the maintenance works

[33] The three-years-average costs per cubic yard are shown for the period 1974 - 2001.

Execution method

The execution method depends, among others, on:

- Characteristics of materials to be dredged
- Sea conditions
- Waterdepth, at dredging location and disposal area
- Required accuracy
- Distance to disposal area

These factors are similar for all sections of the MRGO channel, except for the sea conditions. The wind and wave condition are more severe in the open section of the channel, Breton Sound and the Bar Channel, than in the Inland Reach. The Chandeleur and Breton Islands rim protects the open section and the wave climate is mild. However the conditions at the Bar Channel are not suitable for the small-middle range cutter-head dredgers used in the Inland Reach and the Breton Sound. Suction hopper dredgers are used in the Bar Channel section.
The productivity of suction hopper dredgers decrease as the distance to the disposal area increases. (The dredging cycle takes longer, since more time is spent on sailing from and to the disposal area). Consequently the production rate is relatively[34] lower, resulting in higher costs per cubic yard. In general, the use of hopper dredgers results in higher dredging costs per cubic yard, even for a similar production rate. This explains the higher costs per cubic yard for the Bar Channel.

Distance to disposal area

The dredging costs depend clearly on the distance to the disposal area. As mentioned above; the production rate of the hopper dredger depends on the sailing time to the disposal (which is related to the distance to the disposal area). A larger distance to the disposal area results in higher the costs per cubic yard. Another possible execution method is the combination of a cutter dredger with horizontal transport through a pipeline. As the distance between the channel and the disposal area increase more engine power is needed to pump the dredged materials through the pipeline. This results in higher costs per cubic yard.

Independent from the execution method, the costs per cubic yard will always be higher if the distance to the disposal area is larger.

Section	Disposal area	Distance to disposal area
Inland Reach	Wetland creation areas	0.5 – 6 miles [35]
Breton Sound	South of the channel	± 0.5 miles
Bar Channel	South of the channel	± 0.5 miles

Table 26-2 Disposal areas of dredged materials

The distance to the disposal areas is equal for the Breton Sound and the Bar Channel, Table 26-2. The larger distance to the disposal for the Inland Reach explains the higher costs per cubic yard compared to the Breton Sound.

[34] For a comparable pump capacity between the hopper dredger and the cutter dredger and remaining all other factors influencing the production rate constant
[35] Prior to and including the fiscal year 1988 dredged materials were placed on the South Bank of the channel.

Characteristics of dredged materials
Large differences in costs per cubic yard can occur as a result of different characteristics of the materials to be dredged. When hard rock is dredged production rates are low and wear is large. When dredging mud with a water content, the production rates are high and the wear is relatively small.
The dredged materials have similar characteristics in the different sections. However the clay percentage and the water content in the **unconsolidated**[36] clay in the Inland Reach is higher than the Breton Sound and the Bar Channel.

Size of the maintenance works
As explained in above, the dredging costs per cubic yard decrease when the amount of dredged materials increases (ceteris paribus). The average amount of dredged materials for the Inland Reach, Breton Sound and Bar Channel is 4.7 million m^3, 4.8 million m^3 and 2.4 million m^3 respectively. The relative small maintenance works could explain the relative higher dredging costs per cubic yard at the Bar Channel.

[36] Unit prices would increase significantly if consolidated layers of clay would be dredged.

Appendix 27 Constructed and proposed bank protections

Table 27-1 gives the list of constructed and proposed bank protections [REF USACE].

Location	Status	Channel Bank
58.9-56.6	Proposed	North bank
49.0 -48.5	Scheduled	North bank
45.0 -43.1	Scheduled	North bank
40.9-38.9	Scheduled	North bank
38.9-38.5	Scheduled	South bank
37.2-36.5	Constructed	North bank
36.2-35.6	Constructed	North bank
33.9-32.6	Constructed	North bank
31.8-30.1	Proposed	North bank
30.1-29.3	Proposed	South bank
29.9-29.2	Proposed	North bank
27.8 -27.3	Proposed	North bank
23.2-20.2	Constructed	North bank
23.2-15.0	Constructed	South bank

Table 27-1 Constructed and proposed bank protections

Proposed : the location has been identified as a potential location for bank protection.
Scheduled : the construction of a bank protection has been scheduled.
Constructed : a bank protection has been constructed.

Appendix 28 Multi Criteria Evaluation explanation

The Multi Criteria Evaluation (MCE) is used as a tool to make choice between different alternatives [REF 13]. Different alternatives will be subjected to different criteria. Each combination of criterion and alternative is given a score, scaled from 1 (most negative influence) to 5 (most positive influence). All these scores are multiplied by the weight-factor. The weight-factor represents the importance of each criterion. Finally the products of the weight factors and the scores are summed.

The following table is an example of an MCE-table.

Criteria	Weight-factor	Alternative 1	Alternative 2	Alternative 3
Criterion 1	A	2	3	4
Criterion 2	B	4	1	5
Criterion 3	C	3	2	4
Total		Sum I	Sum II	Sum III

Table 28-1 Explanation of the multi-criteria-evaluation

Sum I = 2A + 4B + 3C
Sum II = 3A + B + 2C
Sum III = 4A + 5B + 4C

The different sums represent the value of each alternative. The alternative with the highest total score (sum) is the alternative with the highest value.

The scores are not exactly quantified, they only give an indication. Moreover the weight factors are subjective. To reduce the subjectivity of the weight factors, different scenarios are proposed in a sensitivity analysis with different weight factors.

Appendix 29 Criteria and components

Criteria	Component
Navigability & safety	Number of bends
	Number of shoals
	Channel dimensions, width and draft
	Shelter against winds, (cross)-currents and waves
Sailing time (Gulf – New Orleans)	Channel length
	Vessel speed
Wetland creation	Area of wetland created after 20 years
Ecological impact	Salinity level
	Spawn areas
	Vegetation
Durability	Expected lifespan
Predictability of the alternative	Chance of successful implementation
Hurricane resistance	Resistance against hurricanes
Recreation & fishery	Wave height reflection
	Obstacles for recreational ships
Storm surge protection	Protection against storm surge

Table 29-1 Criteria Multi Criteria Evaluation

Appendix 30 Alternatives

General alternatives

30.1 Do nothing

When evaluating alternatives a comparison should be made with the alternative of doing nothing. This should be done in order to guarantee an improvement of the present situation.
Without countermeasures the channel banks at the Inland Reach would most likely continue to erode. The amount of erosion would slowly decrease in time and eventually an equilibrium slope would be reached. Figure 30-1 shows a slightly downward trend in the annual amount of dredged materials at the Inland Reach over time (Figure 30-1, blue line). This might indicate that the channel-banks have become more stable and bank erosion is indeed decreasing in time.

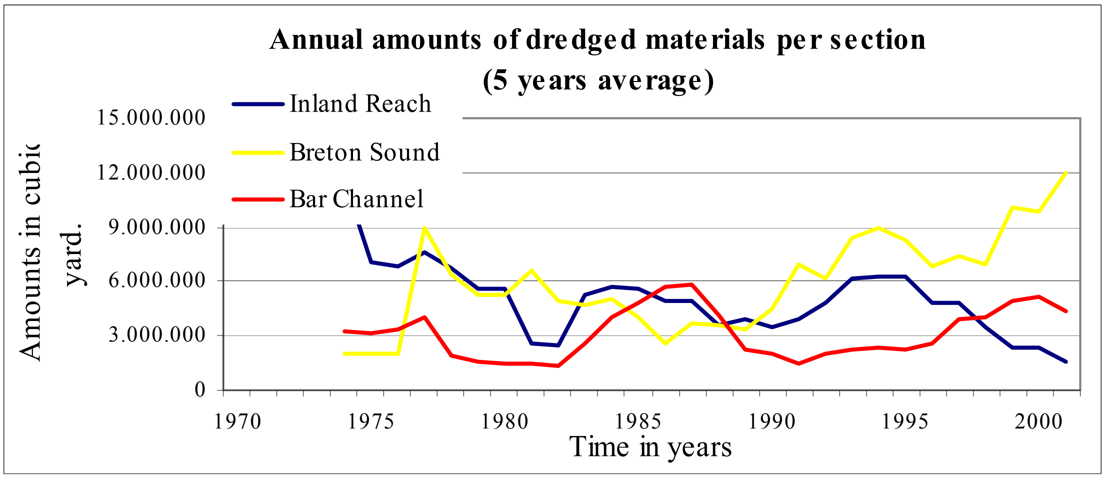


Figure 30-1 Annual amounts of dredged materials per section

The do-nothing alternative is described qualitatively according to the criteria presented in paragraph 10.2

Navigability & Safety
The present navigability & safety on the MRGO is excellent, no additional measures would have to be taken.

Sailing time
The typical sailing time on the MRGO is in the order of 6 hours for a deep-draft vessel, Table 30-1.

Section	Length	Velocity [37]	Sailing time
Inland Reach	46 miles	± 10 kn.	± 4 hr.[38]
Breton Sound + Bar Channel	30 miles	± 13 kn.	± 2 hr.

Table 30-1 Sailing time MRGO

[37] Assumption of the average vessel velocity
[38] 10 knots = 11.5 miles/hr, length Inland Reach 46 mile, 46/11.5 = 4

Wetland creation
Without countermeasures Valuable wetland area will be lost as a consequence of bank erosion. The average bankline retreat was 9,1m per mile per year (3,6m/yr South and 5,5m/yr North bank) over the last 32 years (more details on the bank line retreat are given in appendices 24 and 25). The bankline retreat is assumed constant over the last 32 years and future bank erosion is assumed to be in the same order of magnitude[39].
Therefore an area of roughly 3,300 acres[40] , surrounding the MRGO-channel, would be lost if no measurements were taken over the period 2005-2025[41]

Ecological impact
At present the increase in salinity level has most likely stabilized. In the do-nothing alternative an increase in salinity level is not expected. However the transformation from fresh-brackish marsh to salt-water-marsh is expected to continue[42].
Moreover the maintenance dredging works have a negative impact on the ecosystem when bottom dwelling organisms (as oysters and clams) die in the dredging process.

Durability
Maintenance dredging works remain necessary to meet the navigational requirements.
Under the present maintenance dredging works the lifespan of the MRGO channel would exceed the required lifespan.

Predictability of implementation
The maintenance dredging costs can be estimated, with reasonable accuracy, using historical data from maintenance dredging works.

Hurricane resistance, **recreational** attractiveness and **storm surge protection** remain unchanged under the do-nothing alternative.

[39] This is a conservative assumption on the amount of bank-erosion. The actual bank-erosion will most likely be less since a slightly downward trend can be identified in the amounts of dredged materials in the Inland Reach.
[40] 45 miles, 30 feet, 20 years $45 \cdot 1{,}609 \cdot 30 \cdot 0.3048 \cdot 20 = 1324$ ha or 3272 acres
[41] In comparison; the total loss of the wetland area in Louisiana continues with a rate of 25 to 35 square miles a year [REF W2] (16,000 to 22,400 acres a year).
[42] Vegetation requires significant amounts of time to adapt to the new salinity level

Costs

Figure 30-2 shows the average annual maintenance dredging costs, adjusted for inflation. The average annual dredging costs show a stable[43] pattern with an average of $ 12 Million a year for the period 1970-2001.

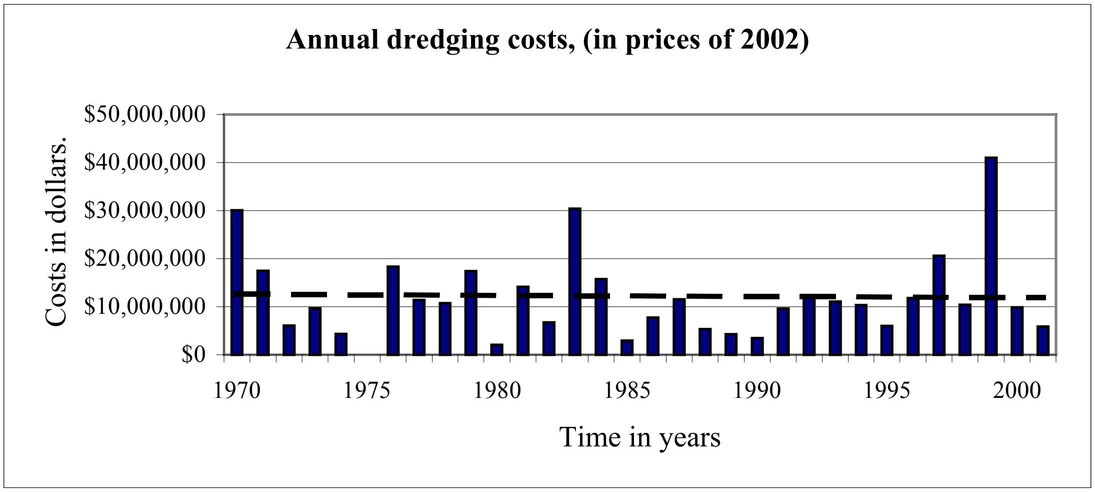


Figure 30-2 Annual dredging costs over the period 1970-2001

Although the future annual dredging costs are hard to estimate, Figure 30-2 can be used to give a rough estimate. The trend of the average annual dredging costs over the period 2005-2025 is assumed linear (as the actual trend over the period 1970-2001)
Consequently the average annual maintenance dredging costs over the period 2005-2025, are estimated at about $ 12 million (in prices of 2002).

The total costs of the do-nothing alternative are roughly estimated in the order of $ 100-300 million for the period 2005-2025[44] for the MRGO. Table 30-2 gives the estimated annual costs per mile for all sections.

Section	Length miles	Average annual costs per mile (in $ 2002) [45]	Estimated annual costs per mile
Inland Reach	19 [46]	$ 210,000	$ 100,000 – $ 300,000
Breton Sound	20	$ 185,000	$ 100,000 – $ 300,000
Bar Channel	10	$ 415,000	$ 300,000 – $ 550,000

Table 30-2 Estimated annual costs per mile

[43] The dotted line in Figure 30-2 is the linear trend line of the annual dredging costs over the period 1970-2001.
[44] $12 million a year over 20 years = $240 million
[45] over the period 1970-2001
[46] The length of the Inland Reach is **46** miles. However over 90% of the dredged materials have been dredged over mile 38-20 (19 miles). Therefore the average costs are calculated over the area where the costs have been incurred.

30.2 Closure of the MRGO channel

Different levels of closure can be suggested for the MRGO channel, ranging from a complete closure for all ships, to a closure for ships with a certain draft class.

Complete closure

A complete closure of the MRGO could be simply executed by the construction of a dam at the seaward entrance of the channel. The direct connection between the wetlands and the Gulf of Mexico would be completely sealed of (an indirect connection would remain intact through lake Borgne). The dam could be constructed by sand since the current velocities in the channel are low. The actual closure of should take place around slack water when the tidal currents are minimal, which makes the capital costs of a dam relatively low.
Closing the MRGO channel could have large benefits for the surrounding wetlands.
Tidal intrusion into the wetland area would now be prevented and wetland loss due to ship-induced waves would be stopped. However the salinity in the wetlands would remain around the same level. When water in the wetland area is evaporated, the salt particles remain in the ecosystem.
Constructing a dam in different phases could solve this problem. First a sill, with corresponding bottom protection works could be constructed. This would reduce the intrusion of the dense salt water from the Gulf of Mexico significantly. Fresh water from rainfall would flush the wetlands. Salt particles would dissolve in this fresh water and be carried to the Gulf. Flushing the MRGO channel with fresh water from the Mississippi could accelerate this process.
The ongoing increase in salinity-level at Lake Borgne and Lake Pontchartrain would be stopped. However the process of salinity reduction could take a significant amount of time.
Closure of the MRGO channel would have a dramatic impact on the local economy. The deep-draft ships would not be able to reach the Port of New Orleans. Appendix 8 gives an overview of the economic impact the MRGO channel has on the local and statewide economy. Plans are made to construct a new IHNC-lock to allow deep-draft ships to reach the Port of New Orleans through the Mississippi River. However it would take a considerable amount of time before the lock is operational.

Partial closure

To limit the salt water intrusion a large sill could be constructed at the entrance of the channel. Only ships with a certain draft would be allowed to sail the channel. The height of the sill would depend on this draft limit.
The closure for a certain category of ships would have a positive impact on the environment.

Closure of MRGO with transfer terminal

If the MRGO channel were closed without compensating measurements for the navigation, this would have a large negative impact on the economy of New Orleans.

A transfer terminal could be constructed at the mouth of the Mississippi River to compensate the navigational requirements. The construction of a transfer terminal could create a balance between the economic requirements and the environmental needs.
Deep draft container vessels can berth at the transfer terminal. Loading and unloading at the transfer terminal instead of the port of New Orleans would save costly time. Container ships

would not have to sail to New Orleans over the MRGO channel or the Mississippi river, with an unprofitable speed.
This would bring a competitive advantage to the Port of New Orleans.

The transfer terminal should be located at the transition between deep and shallow water. This would allow deep draft container ships to reach the transfer terminal without the need of an approach channel. Since the sedimentation rate in the Mississippi Delta is high the maintenance dredging costs of an approach channel would be high. On the other hand should the location be close to shallow water to limit the costs of land reclamation. An optimum should be found, in which the balance of cut and fill[47] should be strived after.
The commodities handled at the transfer terminal should be limited to containers; the other commodities will be (un)loaded at their present berths in New Orleans.

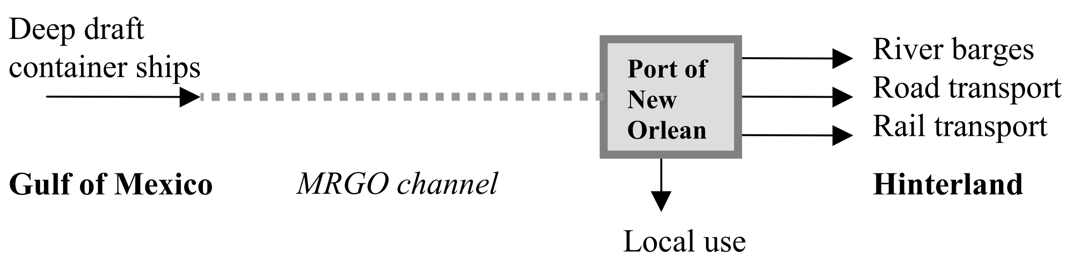


Figure 30-3 Present shipment of containers

River barges would transport the containers to New Orleans for local use or transfer on rail or truck. An other part of the containers would be shipped to the hinterland directly.

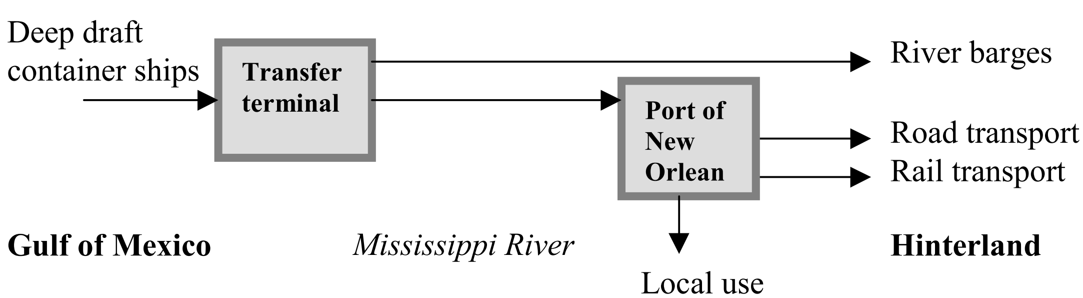


Figure 30-4 Shipment of containers with a transfer terminal

However the barges and other ships would have to use the IHNC-lock to sail from the Mississippi River to most berths of the Port of New Orleans. The present capacity of the IHNC-lock would not allow this alternative.

[47] The amount of dredged materials dredged for the construction of the approach channel should be of the same magnitude as the amount of dredged materials needed for the land reclamation.

Conclusion

The closure of the MRGO channel is a serious alternative in the strategies to restore the wetlands in Louisiana. Closing the channel could have a positive ecological impact on the wetlands. However the closure of the channel without meeting the navigation requirements would have a dramatic impact on the economy of New Orleans. The construction of a transfer terminal would have positive impacts on the environment and the navigation. However all alternatives involving the closure of the MRGO require the construction of the proposed new IHNC-lock. The construction of the new IHNC-lock has still to be approved and it would take at least 15 to 20 years before the lock would be operational. Therefore all alternatives involving the closure of the MRGO have been **rejected** in the design process.

30.3 Stepped bottom

To achieve a one time reduction of the amount of dredged materials an alternative cross-section could be implemented. Based on the requirements of the channel dimensions (discussed in paragraph 5.3) the stepped bottom alternative has been designed. The alternative is a combination of a one-way lane for the container ships with a draft of 11 m and a double lane for the general cargo ships with a draft of 9 m, as can be seen in Figure 30-5. To allow a passage between a container ship and a general cargo ship the bottom width would have to be increased to 182 m. The stepped bottom alternative could be implemented in combination with other alternatives.

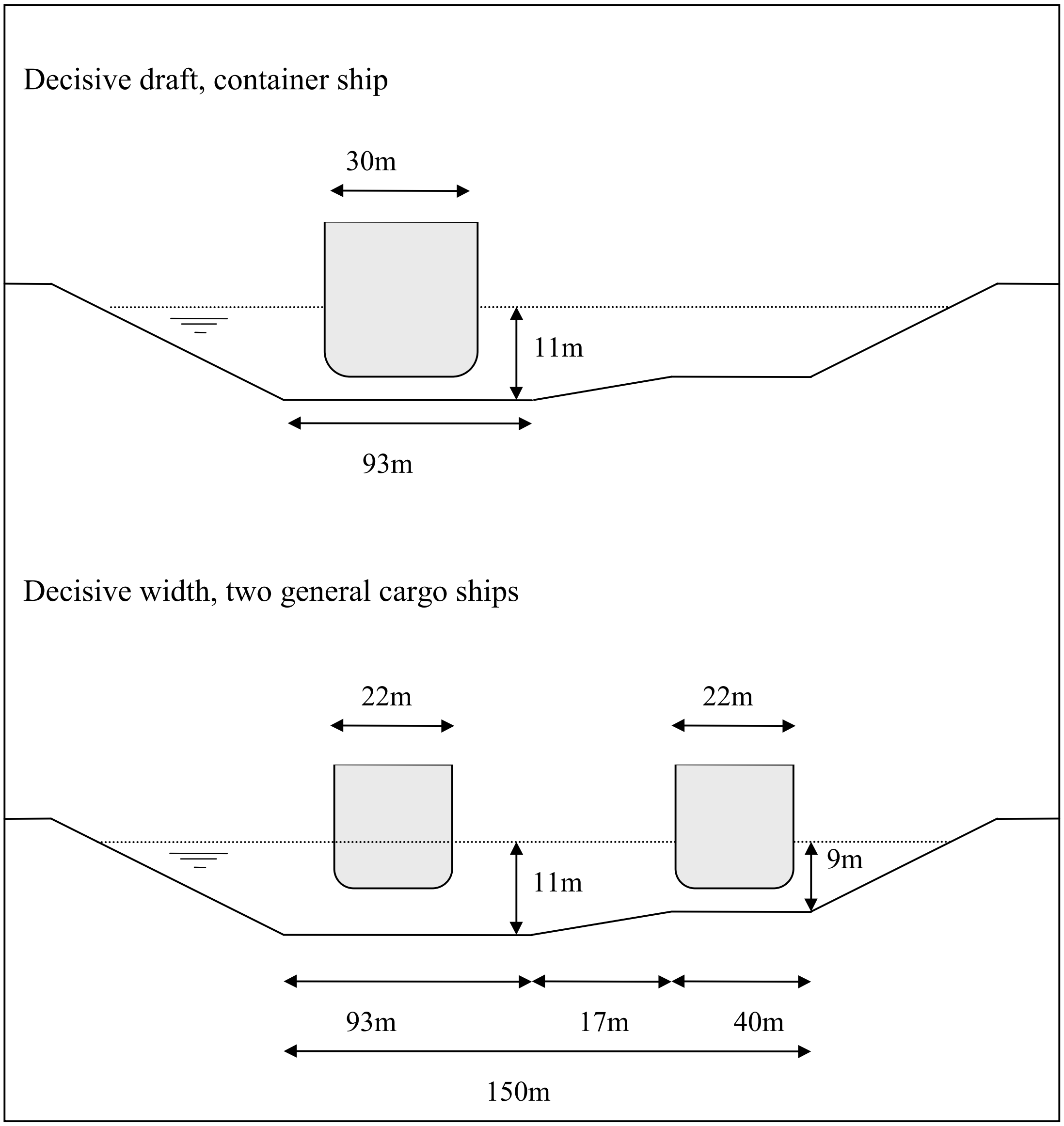


Figure 30-5 stepped bottom cross section

Navigability & Safety
One of the channel lanes (in Figure 30-5, starboard) has a gentle slope perpendicular to the sailing direction of the ships. Ships sailing over a bottom with a perpendicular slope might get problems in maneuvering in case the clearance between the bottom of the ship and the channel bottom would be small. The water resistance at the shallow side is much higher and this might cause the ship to drift. However for small-draft vessels this effect will be negligible. The navigability of the standard cross section (do-nothing alternative) is superior over stepped bottom alternative.
In a standard cross section channel ships will sail on the starboard side of the channel only to change lane when passing other vessels. When implying the alternative cross section the deep-draft ships will sail in the deep lane both upstream as well as downstream, in other words one time on the starboard side of the channel and one time on the larboard side.

In the latter case, when a deep-draft ship is sailing on the larboard side of the channel, unsafe situations might occur. Sufficient guidance is required to prevent collisions. The safety of the standard cross section is superior over the alternative cross section.

Sailing time
The capacity of the standard cross section is superior over the stepped bottom alternative. However both cross sections meet the capacity requirements. If navigation on the channel MRGO would significantly increase the sailing time of the stepped bottom alternative might increase due to waiting time.

Ecological impact
It is likely that a smaller cross section of the channel will result in a smaller discharge of the flood current. A smaller discharge of the flood current would have a positive effect on the salinity level. (The salinity level could be lowered to its' more natural level). The alternative cross section has a smaller area than that of the standard cross section. However this difference is that small that the difference in salinity level will be negligible.

Maintenance dredging costs
The amount of dredged materials could be reduced significant, in case one side of the channel is dredged to 30 ft. instead of 36 ft. In the Inland Reach reduction of the future amounts of dredged materials is limited, since the sedimentation rate in the Inland Reach depends on the bank erosion and not on the channel depth[48]. However the sedimentation rate in the open water section will most likely reduce in case the depth of one side of the channel is reduced. Applying the stepped bottom alternative compared to the standard cross section would certainly reduce the dredging costs.

An amount in the order of 150,000 cubic yard[49] could be saved per mile. This would be a one time costs reduction of about 14 million[50] on the total MRGO maintenance costs. Most likely the

[48] Neglecting local differences in sedimentation rate due to depth differences
[49] $6 \cdot 110 + \frac{1}{2} \cdot 6 \cdot 60 = 840$ square feet = 93.3 square yard, 1 mile= 1760 yard, $93.3 \cdot 1760 = 164{,}280$
[50] Average cost per cubic yard = \$1.12 (chapter 8), length MRGO = 76 mile, reduction per mile 164,280, $1.12 \cdot 76 \cdot 164{,}280 = \$\ 13{,}983{,}514$.

annual maintenance dredging costs in the Bar Channel and the Breton Sound would be reduced when the stepped bottom alternative is realized. Further research should be carried out to estimate this costs reduction.

Closure of small connected channels

The closure of small connected channels or bayous could help to reduce the sedimentation rate in the channel. Some of the bayous and channels are used by navigation and should remain open; other channels are less important for navigation and could be closed. The closure of small channels will reduce the salinity intrusion and will have a positive effect on the quality of the wetlands. However the effect of closing certain channels will not have a dramatic impact on the sedimentation rate (paragraph 7.2.5.2). Moreover certain channels are privately owned and it would be expensive to close them. Further study is recommended to address which bayous and channels could be closed.

Amount of materials reduction
The maintenance dredging costs can be reduced if the amounts of dredged materials could be limited. According to the causes of sedimentation (chapter 7) alternatives have been generated to reduce the sedimentation rate in the channel. As concluded in chapter 7 the bank erosion is the most dominant cause of sedimentation in the Inland Reach. On the open water section the cross-currents, driven by tidal and wind activity, cause sedimentation.

Figure 30-6 and Figure 30-7 give an impression of the cross section of the Inland reach and the Open water section respectively (figures are not in scale and dimensions can deviate along different locations with each section).

Inland reach

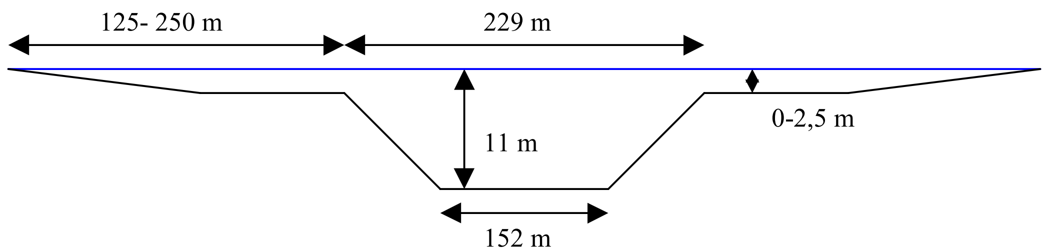


Figure 30-6 Impression cross-section Inland Reach

Open water section

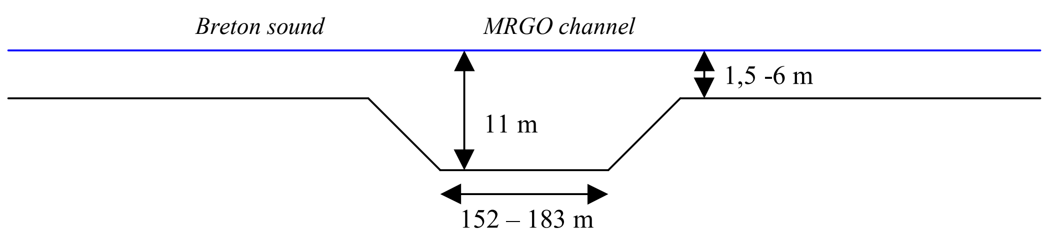


Figure 30-7 Impression cross-section open water section MRGO

The alternatives reducing the amount of dredged materials can be categorized in:
Reduction of bank erosion
Increase strength → bank revetments
Reduce loads → wave-height reduction
Reduction of sedimentation in the open water section

Reduction of bank erosion

Figure 30-8 shows the different alternatives that reduce the amount of bank erosion. A division is made between alternatives that reduce the loads and alternatives that increase the strength.

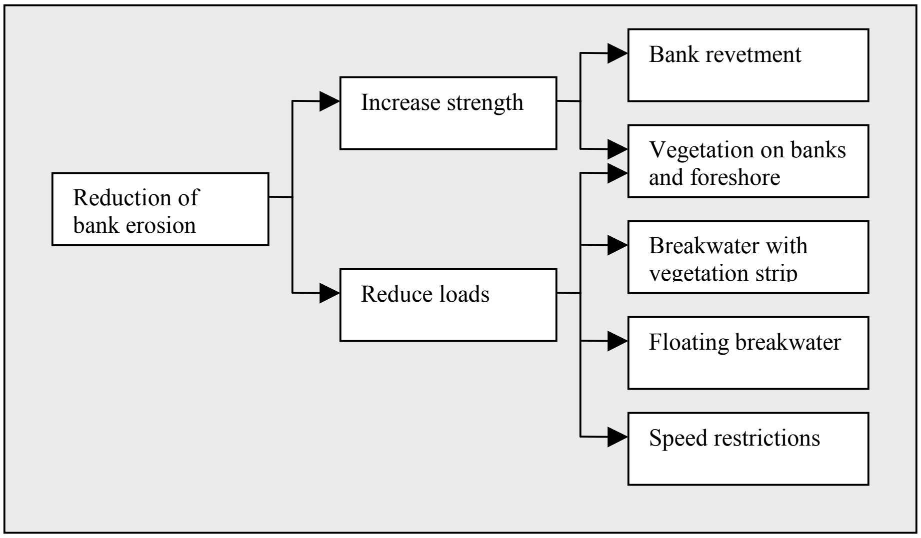
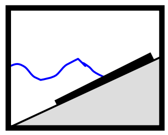


Figure 30-8 Alternatives for the reduction of bank erosion

30.4 Bank revetments



A bank revetment will protect a channel bank against the attacks from waves and currents and prevent erosion. The **strength** of the channel bank is increased. Consequently the amount of materials that settle in the centre of the channel is reduced drastically resulting in a reduction of the maintenance dredging costs.

Soil conditions
The unconsolidated clay layers have insufficient strength to support most of the bank revetments. If a revetment would be constructed without soil improvements the revetment would sink in the soft subsoil at a high settlement rate. Additional materials would have to be placed to maintain the desirable crest level.

Materials
Bank revetments can be constructed with numerous materials. The most promising materials are listed below:

Rip-rap
The most commonly used material for bank protection is rock. The use of randomly placed rocks is called rip-rap. The cover-layer should be placed on a filter layer (geo-textile or rock) to prevent erosion of the subsoil. The stability of a bank protection with a rip-rap cover-layer depends on the shape of the stones, their size, their weight and their degradation.
It is important that the stones are placed within their layer thickness. For example larger stones from the cover layer could cause damage to the filter-layer if placed incorrectly.
A large advantage of the rip-rap cover is the high flexibility compared to other materials. When the cover layer settles, due to the unstable soil conditions at the MRGO, the stones will resettle to a certain extent resulting in an additional safety factor. The failure process is gradual and clearly visible, making the maintenance planning easier. The bank protection can be divided in the following parts:

- Toe
- Lower revetment
- Upper revetment

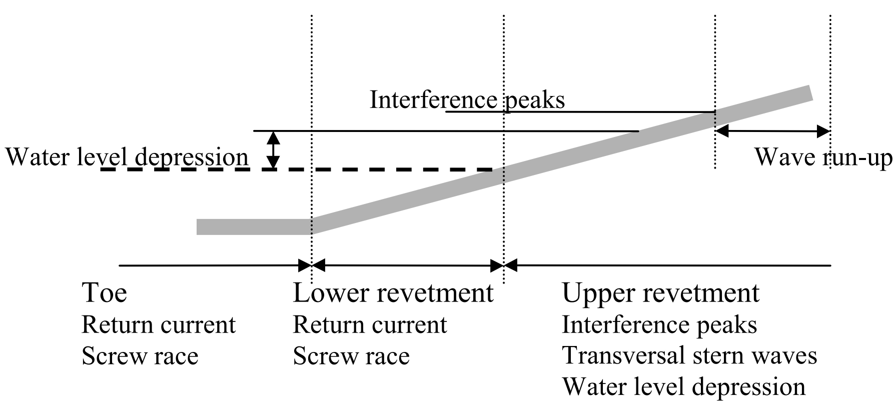


Figure 30-9 Channel bank with different attacks of waves and currents

The toe and the foreshore of the bank have to be protected in order to prevent the transport of sediments from the foreshore to the center of the channel.
The low bearing capacity of the soft subsoil makes the use of rip-rap without additional measures infeasible.

Stone mattresses
To increase the strength of the channel bank a fascine mattress can be used. The weight of the mattress is divided over a large surface making it suitable for the soft subsoil of the MRGO banks.

In case only one layer of stones is placed vegetation can grow on the channel banks, through the stone layer. When the plants are fully grown their root system increases the strength of the bank. Before that a filter, such as a degradable geotextile, is needed.
As an alternative to a stone layer a revetment of open asphalt (e.g. Fixtone® by Bitumarin) can be used. The high strength and density of the open asphalt layer make it possible to construct the revetment with a thin layer.

Sheet piles
When a steep slope is desired, due to limited available space, sheet piles are the most promising alternative. At the MRGO space is not limited and a gentle slope is preferred to allow crossing possibilities for animals. Recreational vessel could endure hindrance from reflecting waves against the sheet piles. Moreover the reflecting waves would lead to erosion in front of the sheet piles resulting in sedimentation in the channel.
Sheet piles have fewer problems with the bearing capacity of the soft subsoil, however sheet piles with a considerable length are required to ensure stability.
The light-weight plastic[51] sheet piles would be a promising alternative compared to the concrete[52] or steel[53] sheet piles. The minimum length of the sheet piles should be 2·h with anchorage and 3·h without anchorage. The chosen h depends on the expected erosion in front of the sheet piles, the decisive wave- height and the bearing capacity of the subsoil.

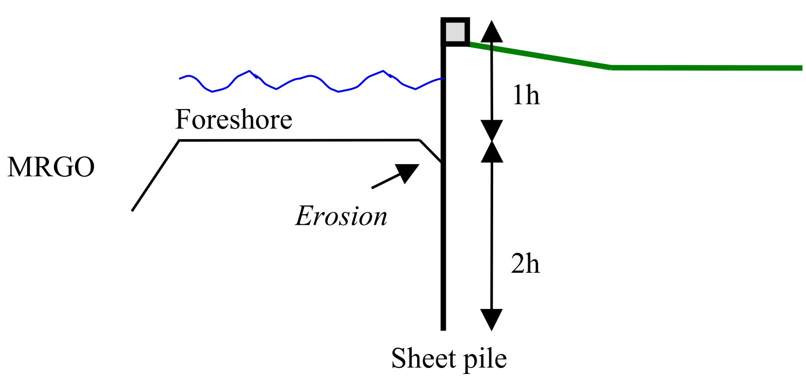


Figure 30-10 The sheet pile alternative

[51] Density PP = 920 kg/m^3 (57.4 lb/ft^3), density PVC = 1,450 kg/m^3 (90.5 lb/ft^3)
[52] Density concrete = 2,300 -2,450 kg/m^3 (144 - 153 lb/ft^3)
[53] Density steel = 7,850 kg/m^3 (490 lb/ft^3)

Vegetation
A bank protection composed of vegetation would be favorable for both the reduction of the dredging costs as well as the recovery of the environmental surrounding.
When the plants are fully grown their root system increases the strength of the bank.
The choice of the vegetation depends on the following aspects: erosion, water quality, min and max pH value, salinity level, wave-height, current velocities, water level fluctuations, bank slope, grazing by animals and maintenance. Only limited species of vegetation are suitable for the boundary conditions of the MRGO. Salt meadow cordgrass (Spartina patens) and oystergrass (Spartina alterniflora) are the most promising plants, to survive on the channel banks. However the plants are not able to withstand the ship-induced waves and currents from deep draft ships.

Navigability & safety
A bank revetment will have an insignificant impact on the navigability and the safety compared to the do-nothing alternative. When using sheet-piles as the bank protection the navigability and safety for smaller vessel reduce due to wave reflection and the accompanying interferences peaks.

Sailing time
A bank revetment will have no impact on the sailing time compared to the do-nothing alternative.

Wetland creation
A bank revetment will fix the location of the channel bank; consequently the loss of wetland is prevented[54]. However a bank revetment will not enhance the creation of new wetland areas.

Ecological impact
Banks form the transition from water to land and are an essential part of the ecosystem. Fish use shallow parts to spawn or hide from predators. Insects live on aquatic plants, birds look for food or rest while mammals come to feed and drink. [REF 2] Environmental friendly alternatives that use vegetation on the channel banks are less promising due to the severe attack of ship-induced waves and currents.
The other alternatives that can withstand the wave and current attack are less environmental friendly. Sheet piles are particularly environmental unfriendly.

[54] The loss of wetlands directly surrounding the MRGO

Durability
The durability of the bank revetment depends on the choice of materials. A rip-rap bank protection exceeds the required lifespan when maintained properly. Steel sheet piles are vulnerable to corrosion (especially in salt water) and require a coating.
(Appendix 31 gives an indication of failure of construction materials in bank revetments).

Predictability of the alternative
A bank revetment will be subjected to settlement due to the weak soil conditions at the MRGO. Soil conditions vary heavily along different locations. If the settlement is not proper dealt with in the final design failure of the bank revetment might occur.

Bank erosion is prevented by a bank revetment; however the sedimentation transport from the foreshore to the centre of the channel is not prevented. Therefore the sedimentation rate reduction is hard to estimate.

Hurricane resistance
A sheet pile revetment is relatively invulnerable to hurricanes. A rip-rap revetment most likely requires some maintenance works after a hurricane.

Recreation & fishery
When using sheet-piles as the bank protection the navigability and safety for smaller vessel reduces due to the wave reflection and the accompanying interferences peaks, this would have a large negative impact on the recreational value of the MRGO.

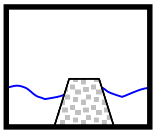
Storm surge protection
A revetment could provide protection against storm surge, depending on the crest height. However a storm protection levee should be constructed to obtain the required crest height.

Capital costs
A sheet pile of 20 ft. is used to give an initial estimation of the capital costs.
The capital costs of a sheet pile construction, at both sides of the channel, are in the order of $ 2-3 million per mile [REF 41 and 55].
Capital costs of a rip-rap revetment, at both sides of the channel, are estimated about $ 1- 2 million per mile.

Maintenance costs
Bank erosion is prevented by a bank revetment; however the sedimentation transport from the foreshore to the centre of the channel is not prevented. Therefore the possible sedimentation reduction is hard to estimate. The assumption is made that the annual maintenance costs reduction will be about 30-70%. The future average annual maintenance dredging costs are estimated at $ 30,000- $ 210,000 [55] per mile.

[55] The estimated average annual dredging costs of the do-nothing alternative for the Inland Reach are $100,000-$300,000. A costs reduction of 30-70% over this amount would give: $30,000- $210,000

30.5 Breakwater



A (submerged) breakwater close to the bank-line could reduce the **loads**, the wave attack, on the channel banks significantly. A lower wave height would result in a reduced amount of bank erosion. Moreover the (submerged) breakwater would prevent sediment transport from the channel-bank to the centre of the channel. This would reduce the amount of materials to be dredged.

Vegetation strip
Between the breakwater and the bankline vegetation can be placed. The vegetation will help to reduce the amount of bank-erosion. Moreover new wetland area is created.

Crest height
The transmitted wave height depends on the height of the breakwater. The higher the crest of the breakwater the more effective the breakwater is in reducing the maintenance dredging costs[56]. However the capital costs of the breakwater increase drastically with an increasing crest height[57]. More materials are needed for a higher crest. Moreover a heavy construction would result in expensive measures to prevent settlement. An economic optimum of the crest height can be found between the capital costs and the expected maintenance costs[58].

Materials
A (submerged) breakwater can be constructed with different materials, lose rock, gabions or sand sacks are the most promising materials.

Rubble-mound breakwater
The breakwater is composed of rock material. Quarry stone is dumped or placed on top of a filter (a filter is required to prevent wash-out of the smaller particles). The rubble mound breakwater is the most conventional system to construct a breakwater. Therefore much (practical) information is available on the stability requirements.
Quarry stone is not available in Louisiana and rock materials should be transported over significant distances (from e.g. Tennessee or Kentucky).

[56] A crest height reduces the amount of sedimentation in the channel (reduced bank-erosion and transport from bank to channel centre) and consequently the amount of dredged materials and the maintenance dredging costs.
[57] The "trapezium"-shape, of the breakwater, results in a more than linear relation between the crest height and the construction costs.
[58]Further research should indicate the optimal crest height.

Gabions
Gabions are rectangular baskets or mattresses fabricated from steel wire, galvanised or in some cases PVC coated. Nominal mesh sizes range from 50 to 100mm and are hexagonal of shape. Gabions can be constructed without heavy equipment and can be refilled if necessary. Moreover gabions are flexible and can maintain their function even if the foundation settles.

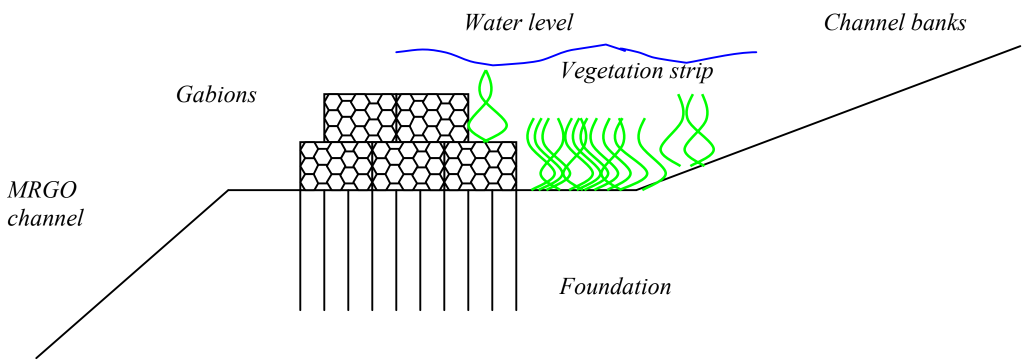


Figure 30-11 The (gabion) breakwater alternative with vegetation strip

A disadvantage is the fact that the structural performance depends on the condition of the steel wire. Corrosion can lead to failure of the whole system and therefore periodic-inspections and maintenance are required.

Foundation
Both the gabions as the rubble mound breakwater form a heavy load on the unstable subsoil. The unconsolidated clay layers have insufficient strength to support the breakwater. If a breakwater would be constructed without soil improvements the breakwater would sink in the soft subsoil at a high settlement rate. Additional materials would have to be placed to maintain the desired crest height. Experience gained from similar projects suggests heavy maintenance works after 3 and 7 years.

A solution for this problem is to improve soil conditions locally. Different techniques can be suggested to improve the bearing capacity of the subsoil [REF USACE]:

- Near surface grouting
  Grouting significantly increases the strength of the soil and grouting should decrease settlement to less than half of the non-grouting scenario [REF USACE].
- Dry-Mix options
  The soft soils are mixed with cement or lime by special injecting equipment. This increases the strength of the soil significantly.
- Sand base
  The soft mud can be replaced by sand to limit settlement. However the heavier sand will increase the load on the soft subsoil, resulting in settlement of deeper soils.
- Buoyancy methods
  The extra load on the soils by the breakwater can be compensated by buoyancy. Buoyancy can be achieved by low weight concrete or foam panels.

Grouting and Dry-mix methods have proven to increase the strength of the soil significantly on land based projects. The improvement of soils below the water-level is technically possible but results in higher capital costs compared to land based soil improvement.

Navigability & safety
The top width of the channel will be reduced, due to the construction of a breakwater. Small recreational boats, such as airboats, can no longer sail directly next to the channel banks. However the fairway width remains sufficient. a breakwater will have a negligible impact on the navigability and the safety.

Sailing time
A breakwater will have no impact on the sailing time compared to the do-nothing alternative.

Wetland creation
New wetland area is created when vegetation is placed between the breakwater and the bankline. Depending on the location along the channel the amount of wetland creation can be significant.

Ecological impact
The gentle unprotected channel bank in combination with a vegetation strip could play an important part of the ecosystem. Fish could use shallow parts to spawn or hide from predators. Insects live on aquatic plants, birds look for food or rest while mammals come to feed and drink. [REF 2]

If the optimal crest height of the breakwater lies above the waterline, measurements have to be taken to guarantee water quality between the breakwater and the shoreline. To refresh the water in the strip, exchange in water between the strip and the channel should be possible. The water-level depression of a passing ship can be used to increase the exchange between water in the strip and the channel.

Durability
The lifetime of a rubble mound breakwater and a gabion breakwater exceed the required lifespan if proper maintenance works are taken.

Predictability of the alternative
The implementation of the breakwater and the estimation of the sedimentation reduction can be estimated with reasonable accuracy.

Hurricane resistance
A breakwater most likely requires some maintenance works after a hurricane.

Recreation & fishery
A breakwater will have no impact on the recreational value compared to the do-nothing alternative.

Storm surge protection
A permeable breakwater does not provide sufficient protection against storm surge.

Costs

The capital costs of a conventional rubble mound breakwater, without soil improvements, are in the order of $ 300 per channel foot[59].

The capital costs are in the order of $ 1.5 million[60] per mile. The heavy maintenance works costs $ 130 and $ 100 per foot[61] for maintenance works after 3 and 7 years respectively. If breakwaters would be constructed at both sides of the channel the total costs would be in the order of $ 4-6 million[62] per mile (including vegetation).

The construction of soil improvements below water level is not very common and consequently the execution costs are high. Capital costs of ground improvement are estimated at $ 560 per channel foot [REF USACE].

Maintenance costs

Bank erosion is prevented by a breakwater; moreover the sedimentation transport from the foreshore to the centre of the channel is prevented. The assumption is made that the annual maintenance costs reduction will be about 75-95%. The future average annual maintenance dredging costs are estimated at $ 5,000- $ 75,000 [63] per mile.

[59] Estimated breakwater dimensions; height 6.5 ft, crest width 3 ft. width 21 ft. (volume per foot = 68 cubic foot = 2.5 cubic yard)

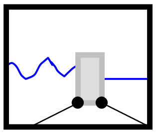
[60] 1 mile = 5280 foot, costs per foot = $300, cost per mile = $ 1,584,000

[61] $109 (2008) and $74 (2012) in prices of 2002

[62] 1 mile = 5280 foot, costs per foot = $483 (300+109+74), cost per mile = $ 2,550,240, breakwaters on both channel banks costs x2.

[63] The estimated average annual dredging costs of the do-nothing alternative for the Inland Reach are $100,000-$300,000. A costs reduction of 75-95% over this amount would give: $5,000- $75,000

30.6 Floating breakwater



A floating object can effectively block wave energy depending on the shape of the structure. This would reduce the **load**, the wave attack, on the channel bank, resulting in less bank erosion and consequently lower dredging costs. In general a floating breakwater is only effective when the length of the breakwater in the wave direction is larger than the wavelength. [REF 2]
The forces on the anchorage system may become extremely high, resulting in high capital costs. The floating breakwater would be placed on the relative shallow fore shore. Currents caused by the drawdown of the passing vessels would cause high current velocities under the floating breakwater, Figure 30-12. This would increase the amount of sedimentation in the channel, making the floating breakwater alternative less effective. The conclusion can be drawn from appendices 22 and 23 that the ship-induced-wave attack on the channel banks is dominant over ship-induced-current attack. This would make it plausible that a floating breakwater could reduce the bank-erosion, and consequently the maintenance dredging costs.
The floating objects could cause hindrance to navigation, especially when the anchorage system would fail.

Vegetation Islands
A floating breakwater could be planted with vegetation to improve the quality of the ecosystem. Small (water) animals could climb on the islands to feed or seek shelter.

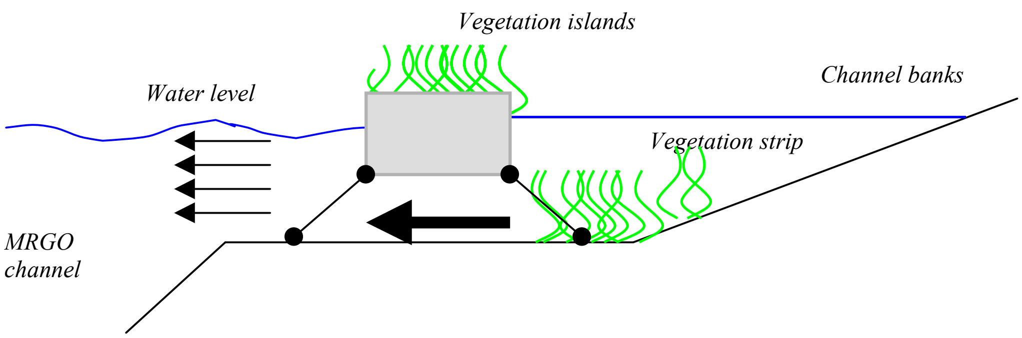


Figure 30-12 The Vegetation island alternative

The same disadvantages of the floating breakwater apply for the vegetation islands.
The high anchorage costs and the extreme current velocities under the islands make this alternative less effective.

Navigability & safety
In case the anchorage system would fail the floating breakwater might float in the fairway. This could cause hindrance to navigation and create unsafe situations especially for small recreational vessels.

Sailing time
A floating breakwater will have no impact on the sailing time compared to the do-nothing alternative.

Wetland creation
New wetland area is created when vegetation is placed between the floating breakwater and the bankline. Depending on the location along the channel the amount of wetland creation can be significant.

Ecological impact
The gentle unprotected channel bank in combination with a vegetation strip could play an important part in the ecosystem, like a conventional breakwater paragraph 30.5. Water in the strip, between the breakwater and the bank line, is refreshed easily since water flows beneath the floating breakwater. Moreover fish can reach the vegetation strip easily.

Durability
The lifetime of a floating breakwater and a vegetation island exceed the required lifespan. Every 2-3 years the vegetation on the vegetation islands should be mowed.

Predictability of the alternative
The reduction of the sedimentation rate is hard to estimate. The bank erosion is reduced significantly; however currents underneath the floating breakwater could transport sediments from the foreshore to the centre of the channel.

Hurricane resistance
Floating breakwaters are particularly vulnerable to hurricanes. Especially the anchorage system is vulnerable.

Recreation & fishery
A floating breakwater will have no impact on the recreational value compared to the do-nothing alternative. However measurements should be taken to prevent people from entering the islands.

Storm surge protection
A floating breakwater does not provide any protection against storm surge.

Capital costs
Vegetation islands costs about $ 1600, - per island[64] (triangle 3x3x3 m). Per mile 1074 islands[65] would be needed to provide a connected rim of islands on both sides of the channel. The total capital costs per mile would be in the order of $ 2 million (including costs of placement).

[64] Information based on product information provided by Bitumarin, Opijnen, The Netherlands.
[65] 1 mile = 1609.35 m, length of 1 island = 3m, per mile 1609.35/3= 537 islands, for both sides of the channel 537·2 = 1074 islands

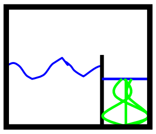
Maintenance costs

The amount of bank erosion will be reduced by a floating breakwater; however the sedimentation transport from the foreshore to the centre of the channel is not prevented. Therefore the possible sedimentation reduction is hard to estimate. The assumption is made that the annual maintenance costs reduction will be about 20-70%. The future average annual maintenance dredging costs are estimated at \$ 30,000- \$ 240,000 [66] per mile.

[66] The estimated average annual dredging costs of the do-nothing alternative for the Inland Reach are \$100,000-\$300,000. A costs reduction of 20-70% over this amount would give: \$30,000- \$240,000

30.7 Pile screens with vegetation strip

Vegetation on foreshore



If vegetation is placed on the foreshore it will reduce the hydraulic **load** on the banks. Both the wave height and the current velocities can be reduced significantly. The stiffer the stalks of the vegetation the more effective they are in wave reduction. Stalks bending in the wave direction are less effective, but still reduce wave energy through vibrations perpendicular to the wave direction. Part of the wave energy is reduced by friction between the stalks.
Only limited species of vegetation are suitable for the boundary conditions[67] of the MRGO. Salt meadow cordgrass (Spartina patens) and oystergrass (Spartina alterniflora) are the most promising plants, to survive on the channel banks. However the plants are not able to withstand the ship-induced waves and currents from deep draft ships. Therefore the use of vegetation without a wave height reduction is rejected.

Pile screens

A row of vertical piles, made of wood, can be used to reduce the wave height and provide sufficient shelter for plants to grow on the foreshore. The wave height reduction depends on the distance between the piles. In general, the smaller the distance between the piles the higher the wave height reduction.

Bottom protection is necessary in order to prevent erosion around the piles. The relative light weight of the wood limits settlement. However the construction should be designed to cope with some settlement. Horizontal movement should be limited by the construction of a horizontal construction.

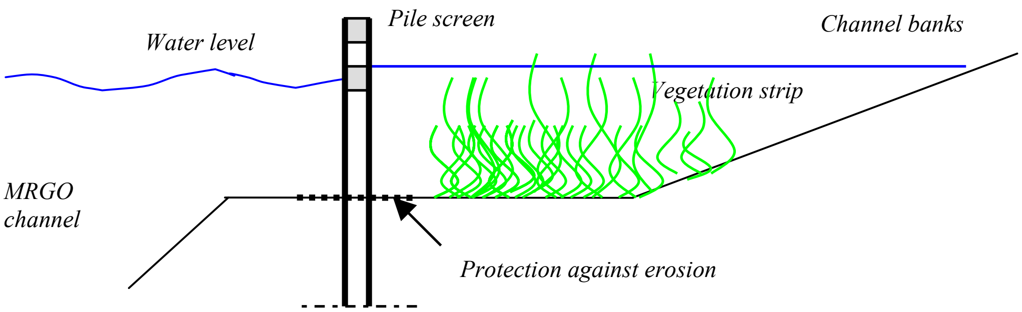


Figure 30-13 The pile screen alternative

Navigability & safety

A pile screen will have an insignificant impact on the navigability and the safety.

Sailing time

A pile screen will have no impact on the sailing time compared to the do-nothing alternative.

[67] Boundary conditions as: water quality, min and max pH value, wave-height, current velocities, water level fluctuations, bank slope.

Wetland creation
New wetland area is created when vegetation is placed between the pile screen and the bankline. Depending on the location along the channel the amount of wetland creation can be significant.

Ecological impact
The gentle unprotected channel bank in combination with a vegetation strip could play an important part of the ecosystem. Water in the strip, between the breakwater and the bank line, is refreshed easily since water flows between the piles. Moreover fishes can swim between the piles and reach the vegetation strip easily.

Durability
The lifetime of a pile screen exceed the required lifespan, if the wood is prepared properly before construction.

Predictability of the alternative
The estimation of the sedimentation reduction is hard to estimate. The bank erosion is reduced significantly; however currents between the pile screen could transport sediment from the foreshore to the centre of the channel.

Hurricane resistance
A pile screen construction is relatively invulnerable to hurricanes.

Recreation & fishery
A pile screen construction will have no impact on the recreational value compared to the do-nothing alternative. Some waves might be reflected by the pile screen, however this effect will be limited, since some wave energy progresses behind the pile screen.

Storm surge protection
A pile screen construction does not provide protection against storm surge.

Capital costs
The capital costs of a pile screen construction, at both sides of the channel, are in the order of $ 1.0- 1.5 million[68] per mile.

Maintenance costs
The amount of bank erosion will be reduced by a pile screen; however the sedimentation transport from the foreshore to the centre of the channel is reduced but not prevented. Therefore the possible sedimentation reduction is hard to estimate. The assumption is made that the annual maintenance costs reduction will be about 40-70%. The future average annual maintenance dredging costs are estimated at $ 30,000- $ 180,000 [69] per mile.

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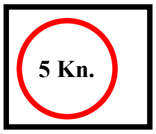
[68] About $200 per pile, piles every 50 cm.
[69] The estimated average annual dredging costs of the do-nothing alternative for the Inland Reach are $100,000- $300,000. A costs reduction of 40-70% over this amount would give: $30,000- $180,000

30.8 Speed limits on the MRGO Channel



The speed of the oceangoing vessels sailing the Inland Reach is about 10 knots [REF Cresernt Pilots]. This speed is in line with the calculated limit speed of about 12 knots (appendix 20). The bank erosion depends on the ship-induced wave heights. Ship-induced wave heights in turn depend on the speed of a sailing vessel. In general the faster the speed of a vessel the higher the wave heights, providing the ship is sailing below its critical velocity (more details are given in appendix 20). If a speed limit would be implied the loads on the channel banks, the ship-induced wave heights, would be reduced significantly. The effect on the sedimentation rate will be even larger since currents, that transport sediments from the channel banks to the centre of the channel, are smaller for a lower vessel speed.

The strength of the vegetation on the bank-line varies with the seasons. Depending on the vegetation a season-dependable speed limit could be imposed on the MRGO Channel. Further research should suggest when a speed limit should be imposed

Navigability & safety
The probability of a ship collision depends, among other aspects, on the speed of the sailing vessels. The probability of a ship collision decreases with increasing ship speed. (Appendix 32) Therefore probability of a ship collision would increase under a speed limit. However the impact of a ship collision is smaller for lower vessel speeds.
The effects on the navigability and the safety should be further studied on.

Sailing time
The ship-induced wave height can only be reduced to a certain extent. Ocean going vessel need a certain speed to maintain control over steerage. Moreover economic considerations should be taken into account. The longer it takes the vessel to sail the channel the higher the shipping expenses. For example the current sailing time of the Inland Reach is about 4 hours[70] with a speed limit of 5 knots the sailing time will be doubled to 8 hours. For a ship sailing the MRGO back and forth the loss will be 8 hours.
It will be in the interest of the competitiveness of the Port of New Orleans not to impose a speed limit.

Wetland creation
When the bank erosion could be reduced due to a speed limit the loss of wetland will decrease. Some vegetation might start to grow on the foreshore and the channel banks depending on the implied speed limit. However the amount of wetland created in this manner will be negligible.

Ecological impact
A speed limit will most likely have a positive impact on the surrounding ecosystem.

Durability
The speed limit alternative exceeds the required lifespan.

[70] 10 knots = 11.5 miles/hr, length Inland Reach 46 mile, 46/11.5 = 4

Predictability of the alternative
At present a speed limit is imposed for the section between mile 48 and mile 41. However the effects on the sedimentation rate can not be identified.

The exact amount of sedimentation reduction gained from a speed limit is hard to estimate. When the ship-induced wave height is reduced other phenomena become dominant in the process of bank erosion. Most likely Wind-induced waves could become the dominant cause of erosion, if a speed limit would be implied.

Hurricane resistance
The speed limit alternative is not vulnerable to hurricanes.

Recreation & fishery
The hindrance of deep-draft vessels to recreation would be reduced. However the recreational vessels and fishing boats would have to obey the speed limit as well. This could decrease the recreational attraction of the channel and have negative impact on the fishing companies.

Storm surge protection
The speed limit alternative does not provide protection against storm surge.

Costs
Compensation to the shipping companies for the additional sailing time is necessary in order to maintain the competitiveness of the Port of New Orleans.

Maintenance costs
The amount of bank erosion will be reduced by a speed limit. When the ship-induced wave height is reduced other phenomena become dominant in the process of bank erosion. Most likely Wind-induced waves could become the dominant cause of erosion, if a speed limit would be implied. Therefore the possible sedimentation reduction is hard to estimate. The assumption is that the annual maintenance costs reduction will be about 20-70%. The future average annual maintenance dredging costs are estimated at $ 30,000- $ 240,000 [71] per mile.

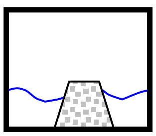
The shipping companies should be compensated for the increased sailing time in order to remain the current level of competitiveness of the Port of New Orleans. These compensation costs should be added to the annual maintenance costs calculated above, to make a fair judgment among the different alternatives. Further research is needed to calculate an optimal sailing speed.

[71] The estimated average annual dredging costs of the do-nothing alternative for the Inland Reach are $100,000-$300,000. A costs reduction of 20-70% over this amount would give: $30,000- $240,000

Trench sedimentation reduction
The amounts of materials dredged from the Breton Sound and the Bar Channel are large. Sedimentation in these sections is caused by cross-currents induced by tide and wave action. The maintenance dredging costs could be reduced significantly if the sedimentation rate in the open water section could be reduced.

All strategies described below serve the same objective (reduction of sediment transport by cross-currents) and are therefore variants.
Not all criteria used to describe the alternatives of the Inland Reach apply to the open water section. The following criteria are NOT used to describe the open water variants: sailing time, wetland creation and storm surge protection.
The following criteria are used: navigability & safety, ecological impact, durability, predictability implementation, hurricane resistance and recreation & fishery.

30.9 Jetty extension



At the transition between the Inland Reach and Breton Sound two jetties have been constructed to reduce the shoaling rate in this area. Both jetties (North and South) were constructed with an initial length of 3 miles[72]. The jetties were constructed of rubble mound without any foundation. Since soil conditions are very poor in the area the placed rocks "sunk" in the mud; additional rock was placed to compensate the sinking. This construction method resulted in a total need of 856,000 m^3 (1,120,000 yd^3) stone. The extension of the jetties would minimize the dredging costs in the open water section.

The breakwater will be perforated at certain locations to allow small vessels (such as fishing boats and recreational vessels) to cross the MRGO. However sedimentation will occur around these crossing points

Length of the breakwater
The length of the breakwater has significant impact on the capital costs and the maintenance dredging costs. The waterdepth in the Breton Sound increases gradually towards the Gulf of Mexico. Therefore the amount of materials needed to construct the breakwater increases drastically as the waterdepth increases[73]. However the reduction in maintenance dredging costs reduces for an increasing waterdepth. With increasing capital costs and decreasing costs reduction as the waterdepth gradually increases a point will be reached where it will not be economical feasible to construct a breakwater[74].

Navigability & safety
The extension of the jetties would take away the cross currents and increase the navigability. However the increase in navigability is small since the present current velocities are low. The

[72] Afterwards the South jetty was enlarged to a total length of 8 miles; the North jetty was not extended.
[73] The "trapezium"-shape, of the breakwater, results in a more than linear relation between the crest height and the construction costs.
[74] This method might even result in a length of zero, in other words it might not be economic feasible to construct a breakwater for a period of 20 years.

safety of the deep draft vessel sailing the channel will remain unchanged compared to the do-nothing alternative[75].

Ecological impact
The construction of a breakwater will have a large impact on the tidal currents. This will have a negative impact on the ecosystem. Moreover the tidal basin would be cut in two pieces decreasing the quality of the ecosystem.

Durability
The expected lifespan of the breakwater would exceed the required lifespan.

Predictability implementation
The implementation of the breakwater and the estimation of the sedimentation reduction can be estimated with reasonable accuracy.

Hurricane resistance
The impact of a hurricane on the breakwater would be relative insignificant. However some additional maintenance works might be required.

Recreation & fishery
The extension of the jetties will have a negative impact on the recreation and fishery since only limited possibilities will be present to cross the MRGO.

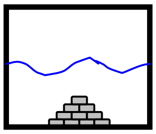
Costs
The original construction method resulted in a stone volume of about 1000 cubic foot per foot channel length[76] (90 m^3 per meter channel length).
Using a unit rate of $ 0.025 [77]per kg [REF 41] the costs per foot channel length can be estimated at $ 750 ($ 2,250 per meter length). If breakwaters would be constructed at both sides of the channel the total costs would be in the order of $ 6-10 million[78] per mile. This costs estimation is made for a breakwater in a waterdepth of about 8 foot, the construction of a breakwater in a larger waterdepth will be significant higher.

Maintenance costs
The amount of bank erosion will be reduced to a minimum by the extension of the jetties. The assumption is made that the annual maintenance costs reduction will be about 75-95%. The future average annual maintenance dredging costs are estimated at $ 5,000- $ 75,000 [79] per mile (Breton Sound).

[75] Deep draft vessels would ground on the shallow banks before collision with the breakwater.

[76] 1,120,000 cubic yard for 6 miles; 186,667 cubic yard (5 million cubic foot) per mile; about 1000 cubic foot per foot.(90 cubic meter per meter channel length)
[77] For a stone gradation of 40-200kg.
[78] 1 mile = 5280 foot, costs per foot = $750, cost per mile about $4 million, breakwaters on both channel banks costs, about $8 million.
[79] The estimated average annual dredging costs of the do-nothing alternative for the Breton Sound are $100,000-$300,000. A costs reduction of 75-95% over this amount would give: $5,000- $75,000

30.10 Submerged breakwater with geotextile systems



A submerged breakwater could be constructed parallel to the MRGO channel to reduce the transversal erosion (caused by density currents). For the following variants the breakwater will be constructed with Geotextile systems. Geotextile systems utilize high strength synthetic fabric as a form for casting large units with sand or a sand-cement mixture.

Sand sacks

Sand filled breakwaters are constructed of stacked sacks a staggered pattern and can be ideal for the construction submerged breakwater. However in general the sand-filled structures are used as temporary structures to learn the natural responses, or as permanent structures at locations with relatively low wave attack. (Wave-height below 1.5m). The lifespan of the fabric is affected by chemical deterioration under the action of ultraviolet light.

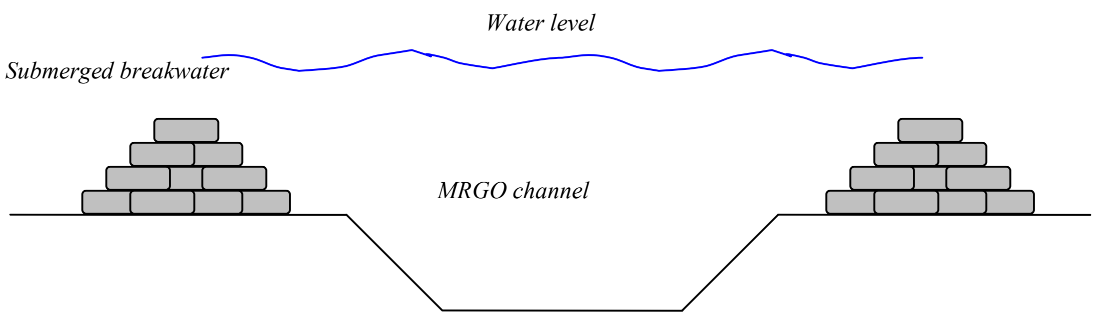


Figure 30-14 A submerged breakwater constructed with sand bags

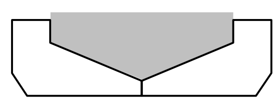
The experience learned that woven acrylic and nylon bags survive the exposure to sunlight best, and under ideal conditions may have a lifespan of about eighth years. If the geotextile is protected by a layer of rocks or by other means not exposed to ultraviolet light, the lifespan can reach 30 years or even more. Sacks filled with mortar are more durable than sand sacks only their use should be limited to areas of low wave activity, since their inter-module bonding is vulnerable for settlement.

Geo Nicbag®

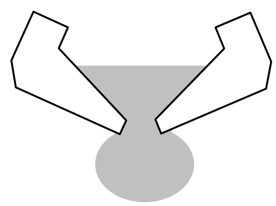
As an variant for small sand sacks larger bags can be used as for example the Geo Nicbag® produced and distributed by KEMEX. The bags have a limited lifespan due to ultraviolet light, at the MRGO the lifespan without further protection would be less than one year. When sprayed with bitumen the lifespan can be extended to a maximum of 10 years. A maximum lifespan of 30 years is possible in seawater when the bags are covered (and thereby not exposed to ultraviolet light). The Nicbags, composed of polypropylene are vulnerable to scratches.

Geotube systems
The geotube systems are sausage shaped bags constructed from permeable but soil-tight geotextile and with sand. The tube can either be filled hydraulically or constructed in a split-dumping barge. Using the first technique, **hydraulically filling** [REF 53], the geotextile is put in place by a roller system placed on a pontoon. After the tube is positioned on the sea bottom, a layer of quarry stone is dumped at both sides in order to keep the tube fixed on the location. The tube is filled for 80% from one side and afterwards completely filled from the other side. A number of filling holes are open during the filling in order to prevent the pressure in the geotube from becoming too great. The possible length of the submerged breakwater is unlimited because the different tubes can be sewn together. The length of the tubes itself depends on the required diameter.
The second technique of filling the geotube is with the use of a **split-dumping barge**.

I. First the geotextile will be placed on the bottom of the split-dumping barge. Afterwards sand is pumped in the split-dumping barge over the geotextile. The geotextile is sewn together to achieve a closed tube (The geotubes can not be sewn together under water; therefore a small overlap is required.)



II. At the location where the submerged should be located the barge will open and the geotube will drop in prepared bed. At the shoals surrounding the MRGO the water depth and the draught of the vessel will limit the diameter of the tube.



III. After the geotube is placed on the sea bottom quarry stone will be dumped at both sides to keep the geotube fixed on its position.

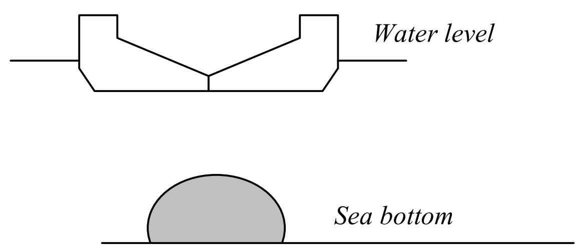


Figure 30-15 The placement of a geotube-submerged breakwater

Navigability & safety
The construction of a submerged breakwater would take away the cross currents and increase the navigability. However the increase in navigability is insignificant since the present current velocities are low.

Ecological impact
The construction of a submerged breakwater will have a relative small impact on the ecosystem.

Durability
The textile materials have a limited lifespan due to ultraviolet light, at the MRGO the lifespan without further protection would be less than one year. When sprayed with bitumen the lifespan can be extended to a maximum of 10 years. A maximum lifespan of 30 years is possible in seawater when the bags are covered (with a stone layer).
Small vessels or fishing nets could cause damage to the submerged breakwater.

Predictability implementation
The implementation of the submerged breakwater and the estimation of the sedimentation reduction can only be estimated roughly.

Hurricane resistance
The impact of a hurricane on the submerged breakwater would be relative insignificant.

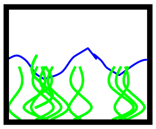
Recreation & fishery
Depending on the crest height some small vessels will not be able to sail over the submerged breakwater. This will cause hindrance to small vessels and decrease the recreational attraction of the MRGO.

Costs
If submerged geotube breakwaters would be constructed at both sides of the channel the capital costs would be in the order of $ 2-5 million per mile.

Maintenance costs
Depending on the crest height of the submerged breakwater the maintenance costs could be reduced significantly. Further studies are required to estimate the amount of maintenance costs reduction. The assumption is made that the annual maintenance costs reduction will be about 10-40%. The future average annual maintenance dredging costs are estimated at $ 60,000- $ 270,000 [80] per mile.

[80] The estimated average annual dredging costs of the do-nothing alternative for the Breton Sound are $100,000-$300,000. A costs reduction of 10-40% over this amount would give: $60,000- $270,000

30.11 Artificial seaweed



In some coastal areas natural seaweed plays an important role in retaining sand along the coastlines due to the reduction of the shear stresses exerted by currents and waves on the seabed. This has led to the concept of applying artificial seaweed for erosion control.

The experience gained in the past indicates that artificial seaweed can be successfully applied for scour prevention around the legs of offshore platforms and around offshore pipelines when the anchorage is designed properly. One of the main engineering problems was the anchorage of the seaweed on the bottom. Other studies have indicated that continuous screens of seaweed, perpendicular to the current were more effective than bunches of seaweed at intervals.

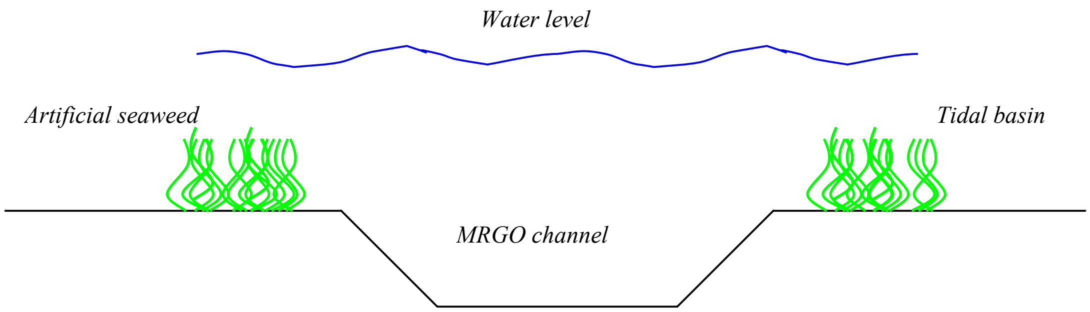


Figure 30-16 The artificial seaweed variant

The artificial seaweed might reduce the sediment transport by absorbing part of turbulent shear stress with its stalks. The reduced shear stress transferred to the bottom sediments resulted in reduced bed load. A similar reduction in turbulent vertical mixing within the boundary layer established by the seaweed reduced suspended sediment transport as well.

Navigability & safety

The construction of artificial seaweed could reduce the cross currents and increase the navigability in the MRGO channel. However the increase in navigability is insignificant since the present current velocities are low.

In case the anchorage system of the artificial seaweed would fail the stalks might cause hindrance to navigation.

Ecological impact

The artificial seaweed could provide shelter for smaller fish and act as a spawning area.

However in case the anchorage system of the artificial seaweed would fail the stalks might have a negative impact on the ecosystem.

Durability

The materials of the artificial seaweed will have a limited lifetime. Ultraviolet light, wave- and current attack and seawater will shorten the lifetime of the materials.

Depending on the height of the stalks (of the artificial seaweed) some small vessel will not be able to sail over the artificial seaweed.

Damage could occur when small vessels would sail through the seaweed. Clear guidance system should be constructed to prevent small ships sailing through the seaweed.

Predictability implementation
Artificial seaweed has successfully been used for scour prevention around the legs of offshore platforms and around offshore pipelines. Artificial seaweed has been unsuccessful for the prevention of beach erosion.
The application of artificial seaweed to reduce sedimentation induced by cross-currents has not been tested yet. The variant is innovative and the predictability of this variant is low.

Hurricane resistance
The impact of a hurricane on the artificial seaweed is hard to predict, since the system has not been used yet. Most likely the artificial seaweed will not be extremely vulnerable to a hurricane since the leaves of the artificial seaweed will reach the water level (Figure 30-16).

Recreation & fishery
Depending on the height of the stalks (of the artificial seaweed) some small vessel will not be able to sail over the artificial seaweed. Clear guidance system should be constructed to prevent small ships sailing through the seaweed. This will have a negative impact on the recreational attraction of the MRGO and a negative impact on the fishing companies.

Costs
Further studies are required to estimate the capital costs of the artificial seaweed. (More details on the artificial seaweed are given in section IV).

Maintenance costs
Depending on the height and the number of stalks the maintenance costs could be reduced significantly. Further studies are required to estimate the amount of maintenance costs reduction. The assumption is made that the annual maintenance costs reduction will be about 30-80%. The future average annual maintenance dredging costs are estimated at $ 20,000- $ 210,000 [81] per mile.

[81] The estimated average annual dredging costs of the do-nothing alternative for the Breton Sound are $100,000-$300,000. A costs reduction of 30-80% over this amount would give: $20,000- $210,000

Unit rate reduction alternatives
30.12 Optimization of the Maintenance dredging works

Dredging policy
The lower the required depth of the MRGO the lower the amount of dredged materials, the lower the dredging costs. However overdredging (advanced maintenance dredging) can be economical feasible under certain circumstances.
The main advances of maintenance dredging are:

- Less frequent dredging would reduce overall dredging costs[82].
- Hindrance to navigation caused by maintenance dredging works is reduced.

The sedimentation rate at the MRGO is influenced by extreme weather conditions (as storm and hurricanes). After these extreme conditions relative expensive maintenance dredging is required. By overdredging the channel the frequency and quantity of maintenance dredging can be reduced.

Equipment and execution method
The unit rate of maintenance dredging is highly determined by equipment used and the execution method. The execution method and the equipment used are already optimized for the local boundary conditions. Therefore a further costs reduction at this aspect can not be realized.

Disposal area
Smaller distances between the location of dredging and the disposal areas will result in a lower unit rate. This aspect will be significant in the allocation of new disposal areas and places for the creation of new wetlands.

Sediment traps
The location where sediments settle can be controlled by a sediment trap. A local increase in depth will result in a decrease in current velocity and consequently sedimentation in the sediment trap. Sediment traps do not catch all the sediment moving in the area. Therefore dredging cannot be completely avoided but the frequency and quantity of the maintenance dredging works can be significantly reduced. The sediment trap itself must be emptied periodically to keep it functional.
The main advantages of a sediment trap at the MRGO would be:

- Less frequent dredging would reduce overall dredging costs.
- Hindrance to navigation caused by maintenance dredging works is reduced.
- The sediment trap can be located close to dredged material disposal areas.

However sediment traps at the MRGO would be less effective. In general the distance between the location of bank erosion and the location of sedimentation is small. Therefore large amounts of sediments traps should be constructed at the MRGO reducing the advantages of a sediment trap. Therefore the use of sediment traps at the MRGO is discouraged.

[82] The amount of dredged materials would be larger for each maintenance work resulting in a lower unit price.

Environmental alternatives
The alternatives in this paragraph do not reduce the maintenance dredging costs but could be suggested as an additional alternative to improve the environmental conditions of the wetlands surrounding the MRGO.

30.13 Use of dredged materials for the creation of wetlands
Materials from maintenance dredging works have been used for the creation of new wetland areas, starting in the fiscal year 1988. Abandoned channels and shallow water areas close to the MRGO channel are suitable for the creation of new wetland areas.

Especially the breakwater-alternative is promising in the creation of new wetland area. After the construction of the breakwater dredged materials could be pumped between the breakwater and the channel bank. Consequently vegetation should be placed in this shallow water strip.

The sediments dredged from the MRGO have a low concentration of nutrients. The growth of new vegetation could be enhanced by adding nutrients to the dredged sediments. The use of nutrient rich sewage materials should be considered.
However additional research should be carried out on the environmental impact of sewage materials for the creation of wetlands.

30.14 Salinity level reduction
Decrease cross-section at entrance
A decrease in the entrance cross-section (the transition between Breton Sound and the Inland Reach) could reduce the salt-water gradient from the Gulf of Mexico. However most likely the decrease in salinity level will be small. More drastic countermeasures like the construction of a sluice would be necessary to reduce the salinity to its original level. Under the current ship movements the construction of a deep-draft sluice would be highly economical unfeasible. Moreover a sluice would increase the sailing time on the MRGO. Therefore the construction of a sluice like construction is rejected.

Fresh water from the Mississippi River
Fresh water from the Mississippi could be pumped or discharged in the wetlands surrounding the MRGO resulting in a reduction of the salinity level. This method increases the environmental quality of the wetlands and is currently practiced at Bayou Dupre[83].

[83] Bayou Dupre is connected to the MRGO at mile 52.7

Certain alternatives (as the closure of the MRGO) were not suitable for the prevailing boundary conditions or didn't meet the requirements and have been rejected in the design process. The most promising alternatives are summarized in Figure 30-17.

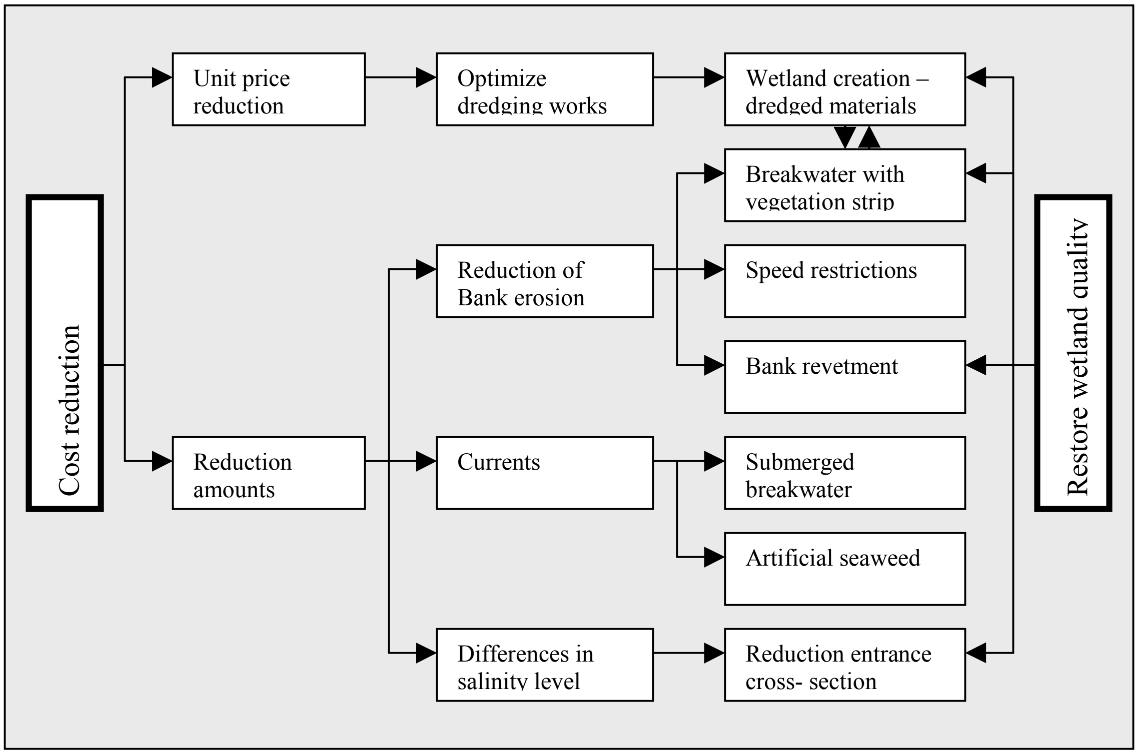


Figure 30-17 Relation between objectives and alternatives

Appendix 31 Materials in bank revetments

A study carried out by L.G. Mouchel and Partners (1985) REF PIANC indicates the use of different cover materials used (world-wide) in revetments. (Data copied from ref 40).

Category	Total placed area (10^3 m^2)	Percentage
Rip-Rap	18,648	69.0 %
Fabric/ other containers	3,500	13.0 %
Concrete blocks	1,949	7.2 %
Other systems	1,671	6.2 %
Bituminous systems	1,240	4.6 %
Total	27,008	100.0 %

Table 31-1 Materials in bank revetments I

Category	Total placed area (10^3 m^2)	Number of failures	Number of failures per 10^3 m^2
Rip-Rap	18,648	53	2.8
Bituminous systems	1,240	5	4.0
Fabric/ other containers	3,500	34	9.7
Other systems	1,671	22	13.2
Concrete blocks	1,949	26	13.3

Table 31-2 Materials in bank revetments II

Appendix 32 Probability of ship collision

To calculate the probability of a collision, it is necessary to obtain sufficient data and experience from shippers familiar with the channel. When adequate data are lacking, data and experience from other similar shipping areas can be used. Estimations on the probability of a collision can also be calculated by using an analytical approach.

To give a rough estimate of the probability of collision on the MRGO channel the analytical model from R.R. Solem [REF 56] is used[84].

$P = (P_{(C)} \cdot P_{(E)} \cdot 3 \cdot 10^{-8} \cdot L \cdot n_1 \cdot (v_1 + v_2)(b_1 + b_2))/(v_1 \cdot v_2 \cdot B)$

	Explanation	Dimension	Value
P	Incident per movement	-	
$P_{(C)}$	Probability of avoidance when on a collision course	-	$2 \cdot 10^{-4}$
$P_{(E)}$	Probability of external control when on a collision course	-	1.0
L	Length of fairway considered	m	122,000
n_1	Number of movements per year of parallel traffic	-	1,000
v_1	Speed of vessel taken under consideration	Knots	10
v_2	Speed of other vessels in the area	Knots	10
b_1	Beam of the vessel taken under consideration (70 ft.)	m	20
b_2	Beam of other vessel in the area	m	20
B	Width of the fairway (500 ft.)	m	150

Table 32-1 Probability of ship collision

To do a fair calculation, the probability of collision of all vessel categories should be summed. However if all vessel movements should be divided into smaller segments, the probabilistic calculations become less accurate.

Assumptions
To give a rough estimation of the probability of collision the actual situation has been simplified significantly. In the order of 1000 ship movements occur per year. The average beam of the vessels is assumed 20 m and the average vessel speed is assumed 10 knots.

When using these assumptions the probability of a collision can be roughly estimated at:
$P = 3.9 \cdot 10^{-5}$

[84] The analytical model used does not consider special problem areas such as bends, traffic junctions etc.

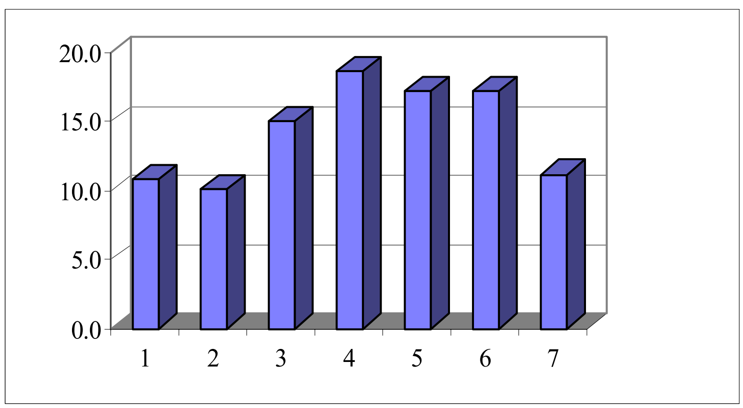
Appendix 33 Sensitivity analysis

Emphasis environmental aspects

Value		Do-nothing	Sheet piles	Rip-rap revetment	Breakwater	Floating breakwater	Pile screen	Speed limit
Criteria	Weight							
Navigability & safety	5	5	2	5	5	1	5	4
Sailing time	5	5	5	5	5	5	5	1
Wetland creation	**35**	1	3	3	5	5	4	2
Ecological impact	**30**	2	1	3	4	5	5	3
Durability	5	5	3	4	4	1	2	5
Predictability impl.	5	5	4	4	5	1	2	3
Hurricane resistance	5	5	4	3	3	1	4	5
Recreation	5	5	1	5	5	5	3	1
Storm surge protection	5	1	1	5	1	1	1	1
Total score	**100**	**250**	**235**	**350**	**435**	**400**	**400**	**260**

Table 33-1 MCE emphasis environmental aspects

1 Do-nothing
2 Sheet piles
3 Rip-rap revetment
4 **Breakwater**
5 Floating breakwater
6 Pile screen
7 Speed limit

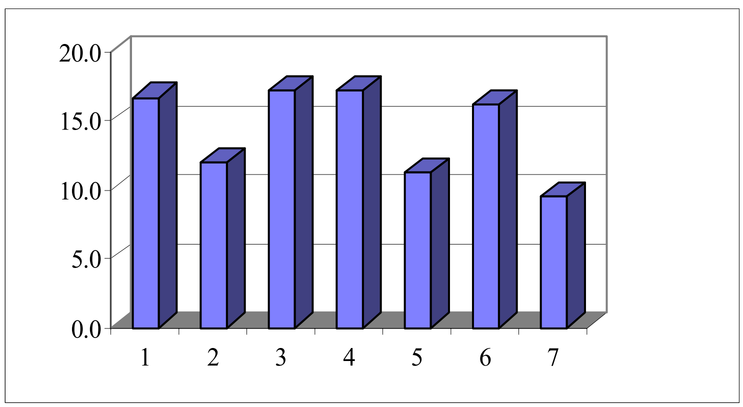


Emphasis deep-draft navigation

Value		Do-nothing	Sheet piles	Rip-rap revetment	Breakwater	Floating breakwater	Pile screen	Speed limit
Criteria	Weight							
Navigability & safety	**30**	5	2	5	5	1	5	4
Sailing time	**35**	5	5	5	5	5	5	1
Wetland creation	5	1	3	3	5	5	4	2
Ecological impact	5	2	1	3	4	5	5	3
Durability	5	5	3	4	4	1	2	5
Predictability impl.	5	5	4	4	5	1	2	3
Hurricane resistance	5	5	4	3	3	1	4	5
Recreation	5	5	1	5	5	5	3	1
Storm surge protection	5	1	1	5	1	1	1	1
Total score	**100**	**445**	**320**	**460**	**460**	**300**	**430**	**255**

Table 33-2 MCE emphasis deep-draft navigation

1 Do-nothing
2 Sheet piles
3 **Rip-rap revetment**
4 **Breakwater**
5 Floating breakwater
6 Pile screen
7 Speed limit

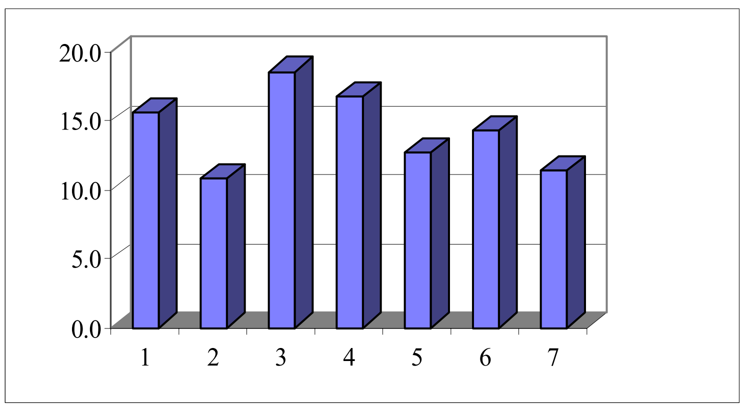


Emphasis on concerns local residents

Value		Do-nothing	Sheet piles	Rip-rap revetment	Breakwater	Floating breakwater	Pile screen	Speed limit
Criteria	Weight							
Navigability & safety	5	5	2	5	5	1	5	4
Sailing time	5	5	5	5	5	5	5	1
Wetland creation	**15**	1	3	3	5	5	4	2
Ecological impact	5	2	1	3	4	5	5	3
Durability	5	5	3	4	4	1	2	5
Predictability impl.	5	5	4	4	5	1	2	3
Hurricane resistance	**20**	5	4	3	3	1	4	5
Recreation	**20**	5	1	5	5	5	3	1
Storm surge protection	**20**	1	1	5	1	1	1	1
Total score	**100**	**345**	**240**	**410**	**370**	**280**	**315**	**250**

Table 33-3 MCE emphasis on concerns local residents

1 Do-nothing
2 Sheet piles
3 **Rip-rap revetment**
4 Breakwater
5 Floating breakwater
6 Pile screen
7 Speed limit

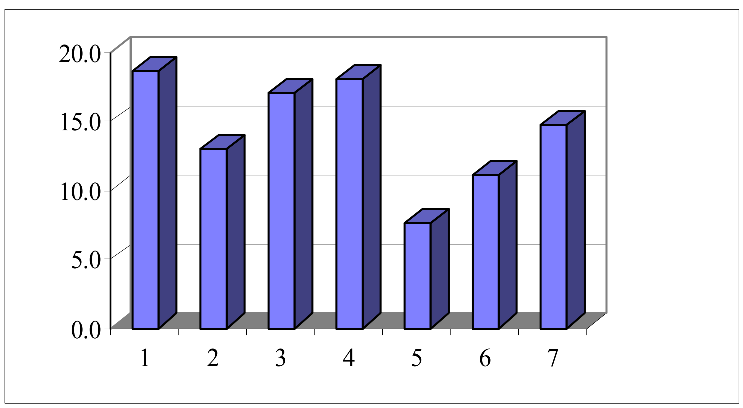


Emphasis on functionality

Value		Do-nothing	Sheet piles	Rip-rap revetment	Breakwater	Floating breakwater	Pile screen	Speed limit
Criteria	Weight							
Navigability & safety	5	5	2	5	5	1	5	4
Sailing time	5	5	5	5	5	5	5	1
Wetland creation	5	1	3	3	5	5	4	2
Ecological impact	5	2	1	3	4	5	5	3
Durability	**35**	5	3	4	4	1	2	5
Predictability impl.	**30**	5	4	4	5	1	2	3
Hurricane resistance	5	5	4	3	3	1	4	5
Recreation	5	5	1	5	5	5	3	1
Storm surge protection	5	1	1	5	1	1	1	1
Total score	**100**	**445**	**310**	**405**	**430**	**180**	**265**	**350**

Table 33-4 MCE emphasis on functionality

1 **Do-nothing**
2 Sheet piles
3 Rip-rap revetment
4 Breakwater
5 Floating breakwater
6 Pile screen
7 Speed limit



Appendix 34 Maintenance cost reduction

Alternative	Total cost per mile 2005-2025
Do-nothing	$ 1.4 - 4.4 million
Breakwater - one bank	$ 2.8 - 5.8 million
Breakwater - two banks	$ 4.1 - 7.1 million
Pile screen - one bank	$ 1.4 - 4.3 million
Pile screen - two banks	$ 1.5 - 4.1 million

Table 34-1 Total costs per mile over the period 2005-2025

Alternative	Cost reduction per mile 2005-2025
Breakwater - one bank	$ -(1.4) million
Breakwater - two banks	$ -(2.7) million
Pile screen - one bank	$ 0 - 0.1 million
Pile screen - two banks	$ -(0.1) - 0.3 million

Table 34-2 Costs reduction per mile over the period 2005-2025

Priority	Location	Length[85]	Bank[86]	Alternative	Cost reduction[87]
1	66.0- -10.0	76	N/A	Stepped bottom	$14.0 million
2	24.2- 23.2	1.0	N + S	Pile screen	$ 0.2 million
3	38.9- 38.0	0.9	N	Pile screen	$ 0.1 million
4	27.9- 25.0	2.9	S	Pile screen	$ 0.3 million
5	31.8- 28.0	3.8	N	Breakwater	$ -(5.3) million
6	28.6- 28.3	0.3	S	Breakwater	$ -(0.4) million
7	48.3- 45.2	3.1	N	Pile screen	$ 0.3 million
8	58.9- 57.3	1.6	N	Pile screen	$ 0.2 million
9	42.8- 42.4	0.4	N	Breakwater	$ -(0.6) million
10	42.8- 42.4	0.4	S	Pile screen	$ 0 million
11	53.6- 53.2	0.4	N	Pile screen	$ 0 million
12	34.4- 33.9	0.5	N	Pile screen	$ 0.1 million
13	59.9- 54.4	5.5	N	Breakwater	$ -(7.7) million
Total maintenance cost reduction[88]					$ 1.8 million

Table 34-3 Overview costs reduction strategies

[85] Length in miles
[86] N: North side of the channel, S: South side of the channel
[87] Compared to the do-nothing alternative over the period 2005-2025
[88] The total reduction of maintenance dredging costs for the fiscal years 2005-2025, total reduction of maintenance costs is reduction minus the construction costs of the alternative.

Appendix 35 Wetland creation

The channel-banks will most likely continue to erode unless measurements are taken. This would result in the loss of valuable wetland area. The average bankline retreat was 30 feet per mile per year (12ft/yr South and 18 ft/yr North bank) over the last 32 years; (appendix 24). The bankline retreat is assumed constant over the last 32 years and future bank erosion is assumed constant as well[89].

Assumptions

- Wetland loss do-nothing South bank : 12ft/yr
- Wetland loss do-nothing North bank : 18 ft/yr
- Wetland loss pile screen[90] South bank : 6 ft/yr
- Wetland loss pile screen North bank : 9 ft/yr
- Wetland creation vegetation strip : 300 ft.

Alternative	Wetland creation per mile
Do-nothing - south bank	29 acre [91]
Do-nothing - north bank	44 acre
Do-nothing - two banks	63 acre
Breakwater - south bank	36 acre [92]
Breakwater - north bank	36 acre
Breakwater - two banks	36 acre
Pile screen - south bank	14 acre
Pile screen - north bank	22 acre
Pile screen - two banks	36 acre

Table 35-1 Wetland creation per mile

[89] This is a conservative assumption on the amount of bank-erosion. The actual bank-erosion will most likely be less since a slightly downward trend can be identified in the amounts of dredged materials in the Inland Reach.

[90] A pile screen is assumed to reduce the bank erosion by at least 50%

[91] 1 mile = 5280 foot, 12 foot/yr, 20 years; $5,280 \cdot 12 \cdot 20 = 1,267,200$ square foot or 29 acres

[92] 1 mile = 5280 foot, 300 foot; $5,280 \cdot 300 = 1,584,000$ square foot or 36 acres

Priority	Location	Length[93]	Bank[94]	Alternative	Created wetland
1	66.0- -10.0	76	N/A	Stepped bottom	0
2	24.2-23.2	1.0	N + S	Pile screen	36 acre
3	38.9-38.0	0.9	N	Pile screen	20 acre
4	27.9-25.0	2.9	S	Pile screen	41 acre
5	31.8-28.0	3.8	N	Breakwater	137 acre
6	28.6-28.3	0.3	S	Breakwater	11 acre
7	48.3-45.2	3.1	N	Pile screen	68 acre
8	58.9-57.3	1.6	N	Pile screen	35 acre
9	42.8-42.4	0.4	N	Breakwater	14 acre
10	42.8-42.4	0.4	S	Pile screen	6 acre
11	53.6-53.2	0.4	N	Pile screen	9 acre
12	34.4-33.9	0.5	N	Pile screen	11 acre
13	59.9-54.4	5.5	N	Breakwater[95]	1056 acre
created wetland area					1444 acre
Wetland loss at other locations MRGO					2394 acre
Total increase in wetland area					-(950) acre

Table 35-2 Overview strategies wetland creation

Total wetland loss MRGO 2005-2025

South bank	Alternative	Length
	Bank protection	4.6 mile
	Do-nothing	40.4 mile

At the South bank a total of 40.4·29 =1172 acre of wetland area would be lost, over the period 2005-2025.

North bank	Alternative	Length
	Bank protection	17.2 mile
	Do-nothing	27.8 mile

At the North bank a total of 27.8·44 =1223 acre of wetland area would be lost, over the period 2005-2025.

A total loss of 1223+1171= 2394 acre of wetland would be lost at other locations than where the breakwater and pile screen would be constructed.

[93] Length in miles
[94] N: North side of the channel, S: South side of the channel
[95] The average width of the vegetation strip between mile 59.9-54.4 is 1600 ft.

Appendix 36 Calculation of h_s

The h_s, the intrusion depth of the logarithmical velocity distribution in the vegetation, can be calculated with the following approach: **(APPROACH COPIED FROM REF 65)**

$$h_s = g\frac{1+\sqrt{1+\dfrac{4\cdot E^2\cdot\kappa^2(h-k)}{g}}}{2\cdot E^2\cdot\kappa^2}$$

With;

$$E = \frac{\sqrt{2\cdot A}\cdot(-C_1\cdot e^{-k\cdot\sqrt{2\cdot A}}+C_2\cdot e^{k\cdot\sqrt{2\cdot A}})}{2\cdot\sqrt{C_1\cdot e^{-k\cdot\sqrt{2\cdot A}}+C_2\cdot e^{k\cdot\sqrt{2\cdot A}}+u_{s0}{}^2}}$$

$$A = \frac{m\cdot d\cdot C_d}{2\cdot\alpha}$$

$$\alpha = 0.0144\cdot\sqrt{h\cdot k}$$

$$u_{s0} = \sqrt{\frac{2\cdot g\cdot i}{C_d\cdot d\cdot m}}$$

$$C_1 = \frac{2\cdot B\cdot(h-k)}{\sqrt{2\cdot A}\cdot(e^{k\cdot\sqrt{2\cdot A}}+e^{-k\cdot\sqrt{2\cdot A}})}$$

$$C_2 = \frac{-2\cdot B\cdot(h-k)}{\sqrt{2\cdot A}\cdot(e^{k\cdot\sqrt{2\cdot A}}+e^{-k\cdot\sqrt{2\cdot A}})}$$

Appendix 37 Relative dominance ship- and wind-induced waves

According to ref 41 (CUR manuals 200 and 201) the bank-line retreat caused by ship- and wind-induced waves can be calculated.
The theoretical bank-line retreat can **NOT** be calculated with accuracy due to limited data on the local soil characteristics and ship-induced wave height. However it gives an **INDICATION** on the relative dominance between the ship- and wind-induced wave attacks.

$$h_s = 0{,}22 \cdot N^{0{,}07} \cdot H_s \cdot \left(\frac{H_s}{L_z} \right)^{-0{,}3}$$

For conditions of: $H_0 T_0 > 300 \cot \alpha$ and $\cot \alpha \leq 5$

$$l_s = \left(\frac{h_s}{p} \right)^{1{,}28}$$

$$b = 0{,}5\left(l_s - h_s \cot \alpha \right)$$

Symbol	Explanation	Unit
b	Bank line retreat at water level	[m]
N	Number of waves (with a minimum of 500)	-
H_0	Dimensionless wave height $H_0 = H_s/\Delta \cdot D_n$	-
H_s	Significant wave height	[m]
T_0	Dimensionless wave period $T_0 = (g/D_n)^{0,5} \cdot Tz$	-
T_z	Wave period deep water	[s]
L_z	Wave length deep water $L_z = (g \cdot T_z)^2/2 \cdot \pi$	[m]
D_n	Nominal sediment diameter	[m]
α	Angle of channel bank at water level	[º]
p	Parameter depending on the D_{50}	-
h_s	Parameter in calculating the bankline retreat	-
l_s	Parameter in calculating the bankline retreat	-

Table 37-1 Calculation of the bank line retreat

Bankline retreat wind-induced waves, Table 37-2.

Symbol	Value	Unit	Reference
hs	0.18	-	Calculated
N	100000	-	Assumption based on par 3.2.3.3.
Hs	0.15	[m]	Table 3.3 chapter 3.2.3.3.
Lz	2.97	[m]	Calculated
Tz	1.38	[s]	Table 3.3 chapter 3.2.3.3.
D_{50}	0.01	[m]	Assumption based on
p	0.05	-	Figure 18 CUR manual 201
ls	5.19	-	Calculated
α	20.00	-	Assumption
cotα	0,45	-	Cotα ≤ 5 holds
300cotα	134.10	-	Calculated
H_0T_0	392935.17	-	H_0T_0 > 300cotα holds
b	**2.55**	[m]	Calculated

Table 37-2 Calculation of the bank line retreat wind-induced waves

Bankline retreat ship-induced waves, Table 37-3.

Symbol	Value	Unit	Reference
hs	0.67	-	Calculated
N	500	-	500 ship movements
Hs	1.20	[m]	Assumption ref USACE
Lz	6.25	[m]	Calculated
Tz	2.00	[s]	Assumption1
D_{50}	0.01	[m]	Assumption based on
p	0.05	-	Figure 18 CUR manual 201
ls	27.67	-	Calculated
α	20.00	-	Assumption
cotα	0.45	-	Cotα ≤ 5 holds
300cotα	134.10	-	Calculated
H_0T_0	4555770.11	-	H_0T_0 > 300cotα holds
b	**13,68**	[m]	Calculated

Table 37-3 Calculation of the bank line retreat ship-induced waves

Conclusion

The bankline retreat over the considered period (of one year) is significant higher for a ship-induced wave attack than for a purely wind-induced wave attack. This leads to the conclusion that the ship-induced wave attack in dominant over the wind-induced wave attack.

Appendix 38 Silt-clay distribution MRGO

The Corps of Engineers has performed a geotechnical study in 1976 [REF 45]. Samples were collected from mile 20 to mile 60 from the channel bottom at both sides of the channel and in the centerline. The samples show an absence of sand particles and consisted completely of clay and silt. (Data copied from REF 45).

Mile	location	Silt	Clay
20	Center	54.8%	45.2%
	North Bank	62.6%	37.4%
	South Bank	60.4%	39.6%
	Average distribution	59.3%	40.7%
25	Center	48.0%	52.0%
	North Bank	47.6%	52.4%
	South Bank	48.0%	52.0%
	Average distribution	47.9%	52.1%
30	Center	-	-
	North Bank	88.2%	11.8%
	South Bank	72.8%	27.2%
	Average distribution	80.5%	19.5%
35	Center	58.0%	42.0%
	North Bank	87.6%	12.4%
	South Bank	94.2%	5.8%
	Average distribution	79.9%	20.1%
40	Center	42.0%	58.0%
	North Bank	75.7%	24.3%
	South Bank	84.3%	15.7%
	Average distribution	67.3%	32.7%
45	Center	33.4%	66.6%
	North Bank	64.5%	35.5%
	South Bank	-	-
	Average distribution	49.0%	51.1%
50	Center	66.6%	33.4%
	North Bank	50.4%	49.6%
	South Bank	-	-
	Average distribution	58.5%	41.5%
55	Center	80.8%	19.2%
	North Bank	43.4%	56.6%
	South Bank	45.2%	54.8%
	Average distribution	56.5%	43.5%
60	Center	77.6%	22.4%
	North Bank	67.4%	32.6%
	South Bank	42.7%	57.3%
	Average distribution	62.6%	37.4%

Table 38-1 Silt-clay distribution MRGO

Appendix 39 Amounts of dredged materials (1970-2001)

Data are available on all maintenance dredging works on the MRGO over the period 1970-2001. This data has been categorized to year and location. Table 39-1 gives the total amount of dredged materials per mile over the period 1970 -2001.

Mile	Materials dredged (1970-2001)	
	(m^3/mile)	(cubic yard/mile)
65	583,939	763,763
64	80,320	105,054
63	80,320	105,054
62	80,320	105,054
61	80,320	105,054
60	80,320	105,054
59	80,320	105,054
58	80,320	105,054
57	592,339	774,750
56	1,032,942	1,351,037
55	1,032,942	1,351,037
54	1,032,942	1,351,037
53	1,359,934	1,778,727
52	919,332	1,202,440
51	919,332	1,202,440
50	1,301,609	1,702,440
49	462,597	605,054
48	462,597	605,054
47	382,278	500,000
46	382,278	500,000
45	382,278	500,000
44	382,278	500,000
43	501,050	655,348
42	1,323,141	1,730,603
41	940,864	1,230,603
40	1,303,600	1,705,044
39	4,491,954	5,875,253
38	4,999,676	6,539,328
37	4,299,402	5,623,405
36	5,628,353	7,361,607
35	4,382,770	5,732,446
34	4,382,770	5,732,446
33	4,382,770	5,732,446
32	3,599,351	4,707,773
31	2,774,019	3,628,280
30	3,615,776	4,729,255

Mile	Materials dredged (1970-2001)	
	(m^3/mile)	(cubic yard/mile)
29	4,530,181	5,925,252
28	4,530,181	5,925,252
27	6,752,085	8,831,393
26	6,330,146	8,279,516
25	6,908,942	9,036,554
24	5,935,713	7,763,618
23	9,429,703	12,333,584
22	4,302,958	5,628,055
21	4,302,958	5,628,055
20	5,331,421	6,973,234
19	5,868,178	7,675,286
18	7,249,010	9,481,345
17	6,367,926	8,328,931
16	7,050,339	9,221,494
15	6,586,753	8,615,147
14	7,226,902	9,452,430
13	6,355,089	8,312,141
12	7,387,330	9,662,261
11	6,608,284	8,643,308
10	6,608,284	8,643,308
9	5,773,692	7,551,702
8	6,133,218	8,021,944
7	6,141,310	8,032,529
6	6,411,586	8,386,037
5	3,582,625	4,685,896
4	3,582,625	4,685,896
3	2,387,641	3,122,916
2	2,387,641	3,122,916
1	1,948,194	2,548,142
0	7,407,565	9,688,728
-1	7,407,565	9,688,728
-2	7,407,565	9,688,728
-3	7,407,565	9,688,728
-4	7,407,565	9,688,728
-5	7,407,565	9,688,728
-6	7,407,565	9,688,728
-7	7,407,565	9,688,728
-8	7,407,565	9,688,728
-9	7,407,565	9,688,728
-10	7,407,565	9,688,728

Table 39-1 Amounts of dredged materials (1970-2001)

Appendix 40 Dredging works hurricane protection levee

A hurricane protection levee has been constructed on the South Bank of the MRGO from mile 65 to mile 45. Table 40-1 gives the depth to which the dredging has been carried out (the dredging for the hurricane protection levee is not included in the maintenance dredging works).
(Data based on historic dredging contracts USACE).

Mile	Dredging depth	
	in meter	in feet
65	13.7	45
64	13.7	45
63	18.3	60
62	18.3	60
61	16.8	55
60	18.3	60
59	18.3	60
58	18.3	60
57	16.8	55
56	18.3	60
55	16.8	55
54	15.2	50
53	not available	not available
52	not available	not available
51	15.2	50
50	15.2	50
49	15.2	50
48	15.2	50
47	18.3	60
46	18.3	60
45	15.2	50

Table 40-1 Dredging works hurricane protection levee

Appendix 41 Annual amounts and costs maintenance dredging 1970-2001

Data are available on all maintenance dredging works on the MRGO over the period 1970-2001. This data has been categorized to year and location. Table 41-1 gives the amount of dredged materials per mile per year. The costs of the maintenance dredging works have been converted to the price level of 2002, using the inflation rates calculated in appendix 28.

	Inland reach		Breton Sound		Bar channel		Total	
	cubic meter	Costs (in $ 2002)	cubic meter	Costs (in $ 2002)	cubic meter	Costs (in $ 2002)	cubic meter	Costs (in $ 2002)
1970	22,346,952	$26,912,898			4,130,563	$3,146,432	25,504,994	$30,059,330
1971	9,903,050	$16,002,480			1,159,830	$1,432,106	11,062,880	$17,434,586
1972	3,223,164	$2,649,456	1,577,153	$2,242,512	1,029,473	$1,160,352	5,829,790	$6,052,320
1973	3,542,598	$4,024,823			6,344,238	$5,633,694	9,886,835	$9,658,517
1974	4,996,076	$3,987,088			917,466	$321,125	5,913,542	$4,308,213
1975							0	
1976	9,023,626	$14,482,674			1,908,329	$3,850,344	10,931,955	$18,333,018
1977			6,824,134	$11,431,578			6,824,134	$11,431,578
1978	1,399,876	$6,118,099	2,954,833	$4,612,327			4,354,709	$10,730,426
1979	2,470,461	$3,702,879	2,371,671	$11,998,812	558,458	$1,689,216	5,400,590	$17,390,907
1980					836,038	$2,066,451	836,038	$2,066,451
1981			7,939,245	$9,676,331	1,850,959	$4,457,600	9,790,204	$14,133,931
1982	1,697,235	$1,868,045	1,697,235	$1,868,045	744,336	$2,992,000	2,441,571	$6,728,090
1983	7,801,236	$12,521,830	2,302,273	$2,417,921	6,033,967	$15,486,165	16,137,476	$30,425,915
1984	3,530,637	$3,856,420	3,530,637	$3,856,420	6,118,875	$8,024,764	13,180,148	$15,737,604
1985	4,138,396	$2,650,200	126,934	$306,096			4,265,330	$2,956,296
1986	1,615,606	$1,736,460	2,326,938	$1,283,700	4,418,541	$4,739,625	8,361,085	$7,759,785
1987	1,827,271	$4,265,970	5,915,180	$2,951,040	1,289,947	$4,307,310	9,032,398	$11,524,320
1988	2,656,137	$1,799,892	1,941,538	$1,323,450	938,943	$2,222,325	5,536,618	$5,345,667
1989	4,621,734	$3,858,780			192,464	$390,988	4,814,198	$4,249,768
1990					1,058,646	$3,446,688	1,058,646	$3,446,688
1991			8,014,866	$4,830,028	2,074,521	$4,748,161	10,089,387	$9,578,189
1992			4,237,386	$3,827,430	3,398,622	$8,242,883	7,636,008	$12,070,313
1993	4,808,029	$6,050,436	7,040,951	$5,028,674			11,848,979	$11,079,110
1994			8,174,935	$8,854,378	728,616	$1,485,005	8,903,551	$10,339,383
1995			4,099,678	$4,687,875	596,676	$1,287,580	4,696,355	$5,975,455
1996	2,612,501	$4,467,218	2,453,188	$1,426,982	3,207,548	$5,908,002	8,273,237	$11,802,202
1997			6,458,825	$7,073,862	7,593,823	$13,541,432	14,052,648	$20,615,294
1998					3,468,109	$10,379,724	3,468,109	$10,379,724
1999	953,252	$1,078,056	17,634,403	$24,269,247	3,965,306	$15,648,709	22,552,960	$40,996,012
2000			3,411,990	$4,952,268	1,289,627	$4,923,860	4,701,616	$9,876,128
2001	1,446,666	$5,510,847			162,995	$354,321	1,609,661	$5,865,168
Total	94,614,502	$127,544,550	101,033,991	$118,918,977	65,044,396	$131,886,862	258,995,655	$378,350,389

Table 41-1 Amounts and costs of dredged materials (1970-2001)

Appendix 42 Relation “STA” and miles

To specify a location at the MRGO miles and “STA” are used. Certain Maintenance Dredging works and surveys are noted in “STA”. Table 42-1 shows how miles and STA are related [REF USACE].

Mile	STA
66.0	0.00
65.0	52.80
64.0	105.60
63.0	158.40
62.0	211.20
61.0	264.00
60.0	316.80
59.0	369.60
58.0	422.40
57.0	475.20
56.0	528.00
55.0	580.80
54.0	633.60
53.0	686.40
52.0	739.20
51.0	792.00
50.0	844.80
49.0	897.60
48.0	950.40
47.0	1,003.20
46.0	1,056.00
45.0	1,108.80
44.0	1,161.60
43.0	1,214.40
42.0	1,267.20
41.0	1,320.00
40.0	1,372.80
39.0	1,425.60
38.0	1,478.40
37.0	1,531.20
36.0	1,584.00
35.0	1,636.80
34.0	1,689.60
33.0	1,742.40
32.0	1,795.20
31.0	1,848.00
30.0	1,900.80
29.0	1,953.60
28.0	2,006.40
27.0	2,059.20
26.0	2,112.00
25.0	2,164.80
24.0	2,217.60
23.0	2,270.40
22.0	2,323.20
21.0	2,376.00
20.0	2,428.80
19.0	2,481.60
18.0	2,534.40
17.0	2,587.20
16.0	2,640.00
15.0	2,692.80
14.0	2,745.60
13.0	2,798.40
12.0	2,851.20
11.0	2,904.00
10.0	2,956.80
9.0	3,009.60
8.0	3,062.40
7.0	3,115.20
6.0	3,168.00
5.0	3,220.80
4.0	3,273.60
3.0	3,326.40
2.0	3,379.20
1.0	3,432.00
0.0	3,484.80
-1.0	3,537.60
-2.0	3,590.40
-3.0	3,643.20
-4.0	3,696.00
-5.0	3,748.80
-6.0	3,801.60
-7.0	3,854.40
-8.0	3,907.20
-9.0	3,960.00
-10.0	4,012.80

Table 42-1 Relation “STA” and miles

Appendix 43 Inflation rates

Table 43-1 gives the purchasing power of historical dollars in a particular year in dollars of 2002. Data on the purchasing power has been copied from W39. Consequently the inflation rate has been calculated according to the annual percentage change in purchasing power.

Year	Purchasing power in dollars 2002	Inflation rate
1965	$ 5.74	2.87%
1966	$ 5.58	3.14%
1967	$ 5.41	4.24%
1968	$ 5.19	5.49%
1969	$ 4.92	5.58%
1970	$ 4.66	4.48%
1971	$ 4.46	3.24%
1972	$ 4.32	6.14%
1973	$ 4.07	10.90%
1974	$ 3.67	9.23%
1975	$ 3.36	5.66%
1976	$ 3.18	6.71%
1977	$ 2.98	7.58%
1978	$ 2.77	11.24%
1979	$ 2.49	13.70%
1980	$ 2.19	10.05%
1981	$ 1.99	6.42%
1982	$ 1.87	3.31%
1983	$ 1.81	4.02%
1984	$ 1.74	3.57%
1985	$ 1.68	1.82%
1986	$ 1.65	3.77%
1987	$ 1.59	3.92%
1988	$ 1.53	4.79%
1989	$ 1.46	5.80%
1990	$ 1.38	3.76%
1991	$ 1.33	3.10%
1992	$ 1.29	3.20%
1993	$ 1.25	2.46%
1994	$ 1.22	2.52%
1995	$ 1.19	3.48%
1996	$ 1.15	1.77%
1997	$ 1.13	1.80%
1998	$ 1.11	2.78%
1999	$ 1.08	2.86%
2000	$ 1.05	2.94%
2001	$ 1.02	2.00%
2002	$ 1.00	

Table 43-1 Inflation rates 1965-2002

Inflation rate
The inflation rate has been calculated using the percentage difference in purchasing power between two consecutive years. For example:

Inflation rate 1994 = (pp(1994)- pp(1993))/ pp(1993)·100% = (1,22-1,19)/1,19·100% = 2.52%
(pp = purchasing power)

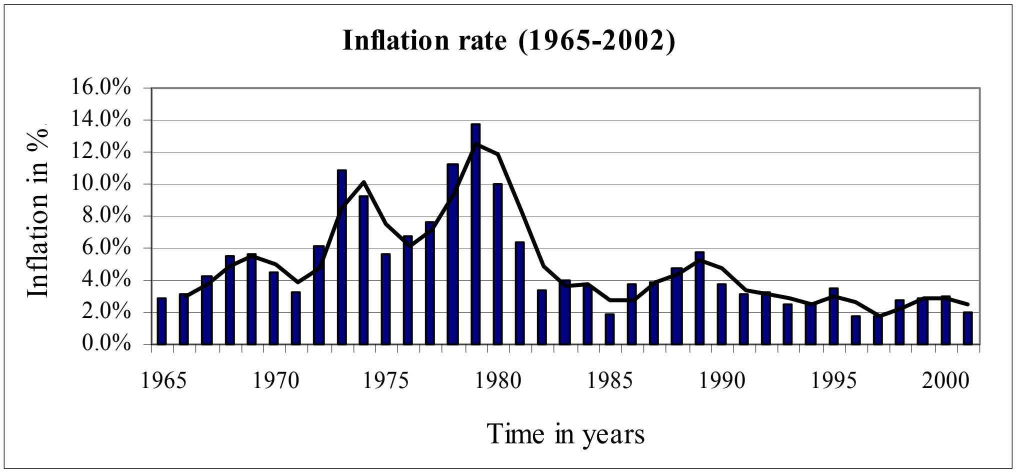


Figure 43-1 Annual inflation rate over time

Purchasing power in time
Figure 43-2 gives the purchasing power of historical dollar prices concerted to dollars of 2002. For example $1 in 1978 would buy the same product x as $2.77 would buy in 2002.

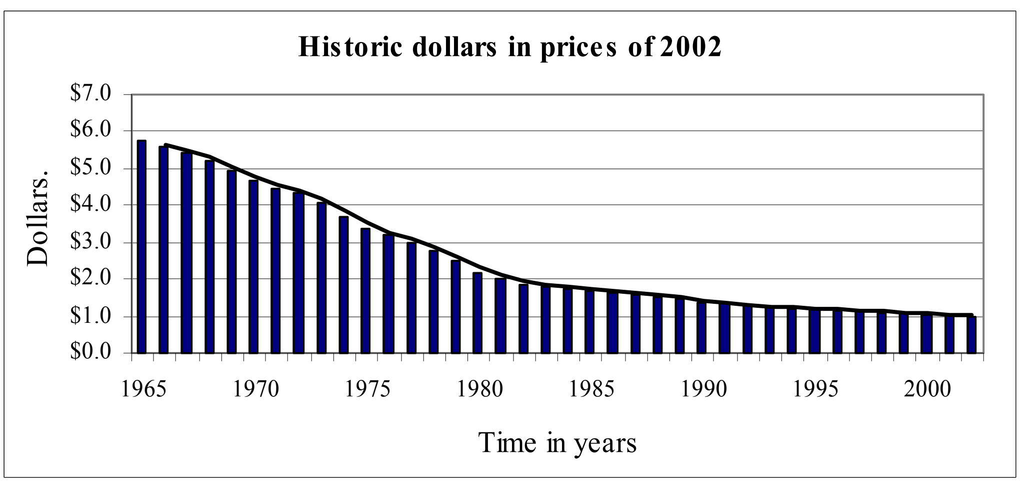


Figure 43-2 Historic dollars in prices of 2002

Appendix 44 Gained experience with artificial seaweed

The Netherlands
(Based on experience gained in Lith (1978 and 1979), Ameland and Texel (1974 and 1975) by Delft Hydraulics, Rijkswaterstaat, Bitumarin B.V. and Nicolon B.V.) [REF 74 and 75]

Test sections with artificial seaweed in Texel and Ameland showed an initial accumulation of sediments within the artificial seaweed field [REF 74 and 75]. However after certain years the sand accumulation reduced significantly and erosion became dominant. Studies (by Rijkswaterstaat) showed an increase in density of the artificial seaweed. The initial density of the seaweed of 200 kg/m^3 was increased to 1000 -1100 kg/m^3 by water-suction and the growth of natural vegetation on the artificial vegetation. The increase in density resulted in sinkage of the artificial seaweed. Consequently the required reduction of current velocity and shear stress could not be accomplished.

Appendix 45 1-DV model

APPENDIX 43 IS BASED ON AND (PARTLY) COPIED FROM THE MANUAL OF THE 1-DP MODEL.
WL| Delft Hydraulics, R.Uittenboogaard, J. van Kester and G. Stelling.

With the 1-DV model a velocity distribution can be calculated for a flow over and through vertical cylinders. (1- DV unsteady models resolve the time- and depth-dependency of the velocity and concentration fields)

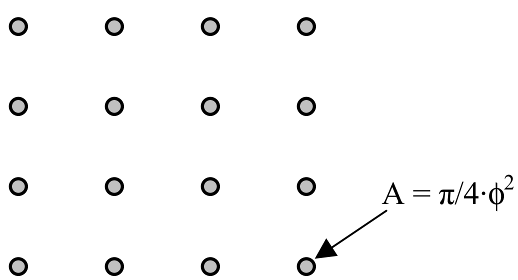
Table 46-3 gives the most relevant coefficient used in the 1-DV model and in the equations of appendix 43.

1-DV notation	explanation	symbol	Unit
CDPLNT	drag coefficient	C_D	
BRANCH	typical leaf diameter	ϕ	[m]
NCROSS	number of leaves per m^2 horizontal surface	n	[m^{-2}]

Table 45-1 Main coefficients 1-DV model

In the initial calculations the dimensions of the artificial seaweed are assumed constant over the depth.
The specific plant area A_p is defined per m^2 horizontal cross section:

$$A_p(z) = \frac{\pi}{4}\phi^2(z)n(z) \tag{1}$$



The depth-averaged horizontal velocity U is defined by the user. Consequently the current U is interpreted as flow rate and the computation satisfies:

$$U = \frac{1}{d+\varsigma}\int_{-d}^{\varsigma}\{1 - A_p(z)\}u(z)dz \tag{2}$$

With the bed at z = -d and free surface at z =ζ. Consequently, the z-dependent velocity u(z) in (2) is the velocity, spatially averaged over the cross section occupied by water in between the leaves.

The following drag force is added to the momentum equation for u(z):

$$F_d(z) = \tfrac{1}{2} \cdot \rho_0 \cdot C_D \cdot \phi(z) \cdot n(z) \cdot (u(z))^2 \tag{3}$$

Per unit fluid volume and using reference density ρ_0. In the 1DV horizontal momentum equation, the drag force per computational layer of thickness Δz therefore equals $F(z)\Delta z$.

Eq. (3) is based on turbulent flow or wakes downstream of each leaf. Eq. (3) is not applicable to laminar flow (should be linear then).

Likewise, the effective height of the plant is flow dependent because of the drag forces bending the stems, tending to align them into flow direction. In principle, this bending can be accounted for simply by solving the static equations for the force balance on a thin rod subjected to (3) while using the elasticity modulus of the rod. The assumption is made that the leaves are infinitely rigid and that the leaves can only twist around the bending point.

Similar to (2), the specific area ($1-A_p$) occupied by fluid is considered as representative for the possibly z-dependent cross sectional area that is available for the vertical exchange of horizontal momentum, turbulence-properties, sediment etc. Consequently, ($1-A_p$) appears in the vertical exchange of horizontal in the following 1DV momentum equation:

$$\rho_0 \frac{\partial u}{\partial t} + \frac{\partial p}{\partial x} = \frac{\rho_0}{1-A_p} \cdot \frac{\partial}{\partial z}\left\{(1-A_p) \cdot (\upsilon + \upsilon_T)\frac{\partial u}{\partial z}\right\} - F \tag{4}$$

In (4), the horizontal pressure gradient is adjusted such that (2) is satisfied i.e. including the z-dependent specific area ($1-A_p$).

For the 1DV model, the equation for turbulent kinetic energy *k* simplifies to:

$$\frac{\partial k}{\partial t} = \frac{1}{1-A_p}\frac{\partial}{\partial z}\left\{(1-A_p) \cdot (\upsilon + \upsilon_T / \sigma_k)\frac{\partial k}{\partial z}\right\} + P_d + P_k - B_k - \varepsilon \tag{5}$$

in which appears again the specific area ($1-A_p$) of fluid but also the additional turbulence source term P_d. The remaining terms are production P_k by velocity shear, dissipation ε and conversion B_k into potential energy.

The source term P_d equals the power spent by the mean flow due to work against the drag force F i.e.

$$P_d(z) = F_d(z) \cdot u(z) \tag{6}$$

In (6) and (3), laminar effects are neglected i.e. all work done by the mean flow is transferred into turbulence without notable direct viscous dissipation.

Similar to (5), the following equation for dissipation rate ε in the k-ε model is expressed by

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{1-A_p}\frac{\partial}{\partial z}\left\{(1-A_p)\cdot(\upsilon+\upsilon_T/\sigma_\varepsilon)\frac{\partial \varepsilon}{\partial z}\right\} + P_d\tau^{-1} + P_\varepsilon - B_\varepsilon - \varepsilon_\varepsilon, \tag{7}$$

Appendix 46 Dimension optimization variants artificial seaweed

I. sea-grass variant

Boundary conditions and assumptions

Conditions/ assumptions	Value	Unit
Waterdepth	7.00	[m]
Cost per cubic meter	10,000 [96]	[$]
Cost per anchorage	2	[$]
Present $U_{average}$	0.50	[m/s]
Present Chezy	50	[m/s]
Present i	2.29E-04	[$m^{0.5}$/s]
Drag coefficient	1.4	[-]

Table 46-1 Conditions and assumptions sea-grass dimension optimization

Constraints and requirements

Constrains	Min	Max	Unit
Vegetation velocity	0.01	0.50	[m/s]
Turbulence free height	1.50	7.00	[m]
Height seaweed	0.10	2.00	[m]
Diameter seaweed	0.01	0.01	[m]
Density seaweed	1.00	1000.00	[m^{-2}]
Cross section area	0.00	1.00	[m^2]

Table 46-2 Constraints and requirements sea-grass dimension optimization

Optimized initial dimensions sea-grass variant

Dimension	Optimized value	Unit
Height seaweed	2.00	[m]
Diameter seaweed	0.01	[m]
Density seaweed	714	[m^{-2}]

Table 46-3 Cost optimized dimensions sea-grass variant

[96] Chapter 19

II. rigid-flaps variant

Boundary conditions and assumptions are equal for each variant, Table 46-1.
The capital costs are assumed \$10,000 per cubic meter material (chapter 19) and \$ 20 per anchorage.

Constraints and requirements

Constrains	Min	Max	Unit
Vegetation velocity	0.01	0.50	[m/s]
Turbulence free height	1.50	7.00	[m]
Height seaweed	0.10	2.50	[m]
Diameter seaweed	0.10	0.50	[m]
Density seaweed	1.00	1000	[m^{-2}]
Cross section area	0.00	1.00	[m^2]

Table 46-4 Constraints and requirements rigid-flaps dimension optimization

Optimized initial dimensions rigid-flaps variant

Dimension	Optimized value	Unit
Height seaweed	2.50	[m]
Diameter seaweed	0.10	[m]
Density seaweed	7.55	[m^{-2}]

Table 46-5 Cost optimized dimensions rigid-flaps variant

III. “Bending finger” variant

Boundary conditions and assumptions are equal for each variant, Table 46-1.
The capital costs are assumed $10,000 per cubic meter material (chapter 19) and $ 20 per anchorage.

Constraints and requirements

Constrains	Min	Max	Unit
Vegetation velocity	0.01	0.50	[m/s]
Turbulence free height	1.50	7.00	[m]
Height seaweed	0.10	2.50	[m]
Diameter seaweed	0.20	0.50	[m]
Density seaweed	1.00	1000	[m^{-2}]
Cross section area	0.00	1.00	[m^2]

Table 46-6 Constraints and requirements bending finger dimension optimization

Optimized initial dimensions bending finger variant

Dimension	Optimized value	Unit
Height seaweed	2.50	[m]
Diameter seaweed	0.03	[m]
Density seaweed	3.81	[m^{-2}]

Table 46-7 Cost optimized dimensions bending finger variant

Appendix 47 Construction and placement of the artificial seaweed

Sea-grass variant

Construction

A possible construction method of the sea-grass variant (Figure 47-1):

I. The nylon thread with a total length of 9 meters is put through a predrilled cylinder, leaving a length of 4.5 meter on both sides of the cylinder.
II. The threads are folded around the cylinder in a vertical position
III. The cylinder is attached to a geo-textile with a width of about 2 meters.
IV. The geo-textile is filled with sand and sown together to a small geotube.

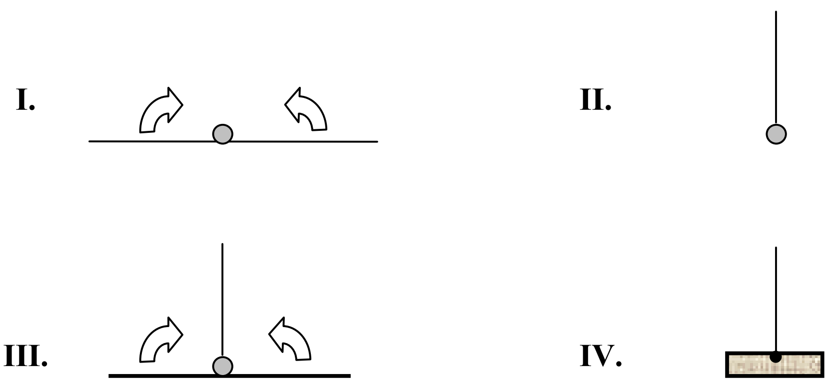


Figure 47-1 Construction of the sea-grass variant

Placement

The geotubes can be lowered to the sea-bottom from any seaborne equipment.

Rigid flaps variant

Construction
A possible construction method of the rigid-flaps variant (Figure 47-2):
I. A plastic (e.g. polyethylene) strip is placed under the geo-textile mattress.
II. The flap is positioned vertically. L-shaped elements are placed on both sides of the flap
III. The L-shaped elements are attached to each other.

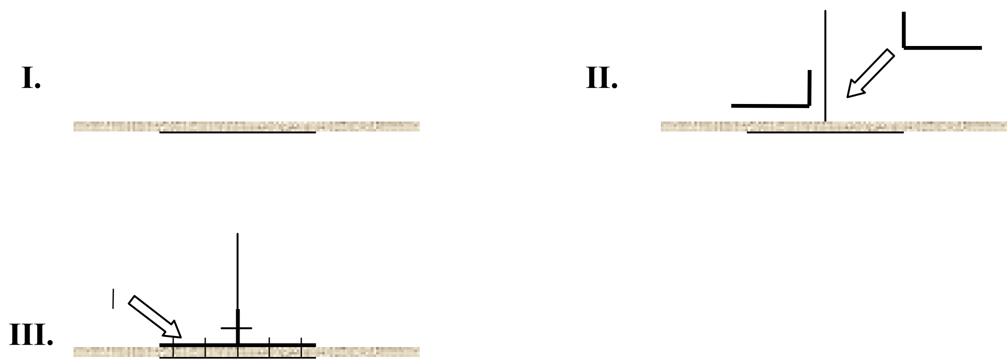


Figure 47-2 Construction of the rigid flaps variant

Placement
The anchorage system is rigid. Consequently it is not possible to roll the mattress and unroll it on the sea bottom.
The geo-textile mattress has to be lowered to the sea bottom by separate parts. The flaps can either be attached to the mattress on- or offshore.

Bending finger variant

Construction

A possible construction method of the bending-finger variant (Figure 47-3):

I.	The five polyethylene (PE) blocks are positioned horizontally
II. & III.	A strip of polypropylene (PP) is attached to the blocks by plastic screws.
IV.	A bending point is attached to the geo-textile mattress.
V. & VI.	The leaf of the artificial seaweed is attached to the bending point

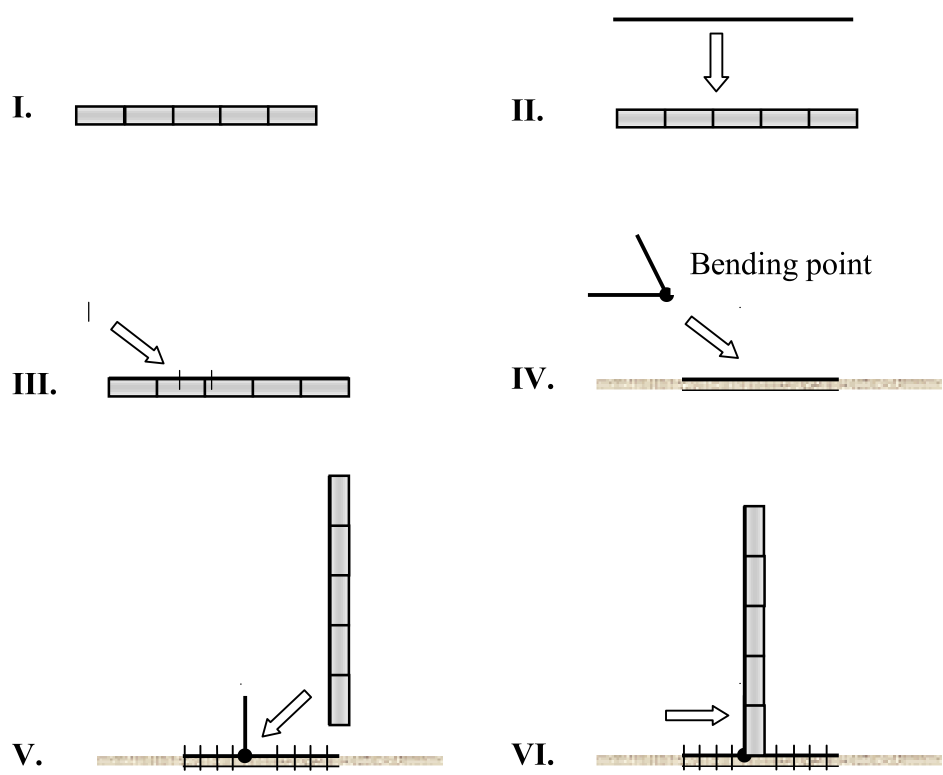


Figure 47-3 Construction of the bending-finger variant

Placement

The anchorage system is flexible in one direction. Consequently it is possible to roll the mattress on shore and unroll it on the sea bottom.

Appendix 48 Dimensions bending finger variant

Dimension	value
Height	2.5 m (5 blocks of 0.5m)
Width	0.1 m
Thickness	0.04 m
Density	3.81 leaves per m^2
Material density	980 kg/m^3
Distance (flow direction)	1.3 m
Distance (perpendicular to flow direction)	0.1 m

Table 48-1 Dimensions of the artificial seaweed

A distance of 1,3 m in the flow direction will allow the leaves to lay on top of each other.
One side of the blocks (opposite to the strip) is slightly curved to prevent sediments accumulating on the blocks, when the construction lies horizontally on the sea bottom.

The front view of the bending finger variant is given in Figure 48-1.

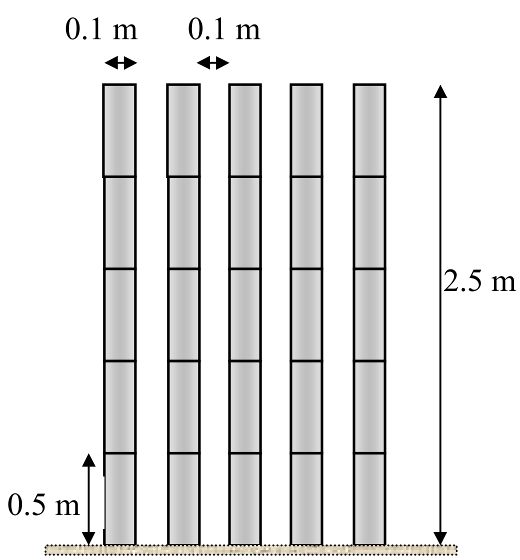


Figure 48-1 Front view of the bending finger variant

The side view of the bending finger variant is given in Figure 48-2.

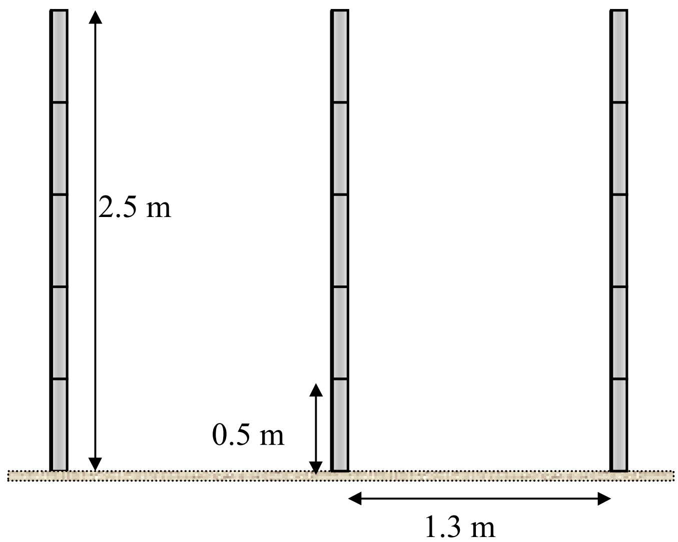


Figure 48-2 Side view of the bending finger variant

The top view of the bending finger variant is given in Figure 48-3.

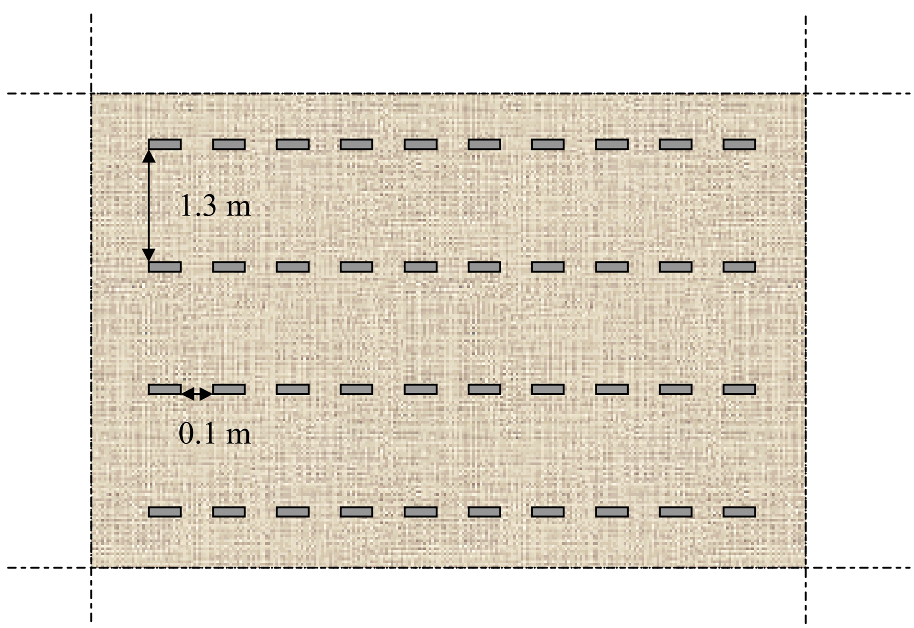


Figure 48-3 Top view of the bending finger variant

Appendix 49 Forces on the bending finger variant

Figure 49-1 gives an impression of the forces on the bending finger variant (the velocity distribution in the figure is not constant, however in the calculation of the forces on the structure the current velocity is assumed constant over the height of the artificial seaweed).

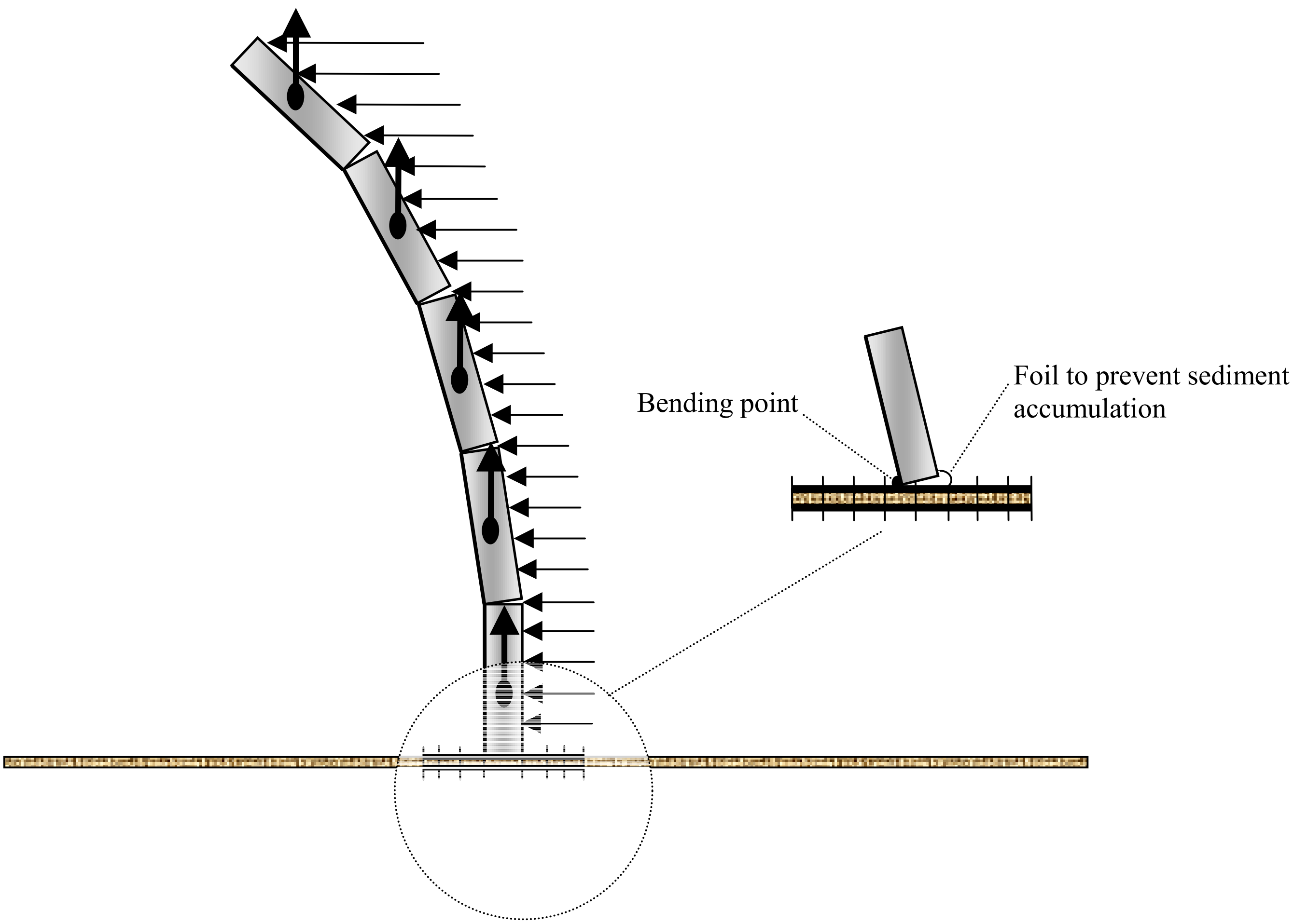
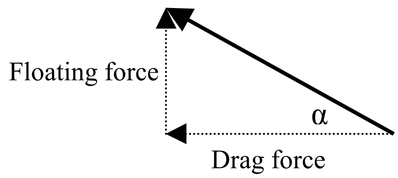
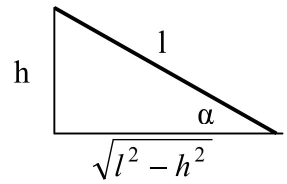


Figure 49-1 Forces on the bending finger

When assuming a constant velocity distribution over the height of the artificial seaweed the alignment of the blocks is in the same direction.
The position of the blocks can be calculated using (approach paragraph 20.1.4):





$$\cot \alpha = \frac{F_d}{F_f} = \frac{\sqrt{l^2 - h^2}}{h}$$

$$F_f = l \cdot b \cdot d \cdot g \cdot (\rho_w - \rho_s) \quad \text{and} \quad F_d = \frac{1}{2} \cdot C_d \cdot \rho_w \cdot h \cdot d \cdot v^2$$

Symbol		Unit	Explanation
F_f	-	[kN]	Floating force
F_d	-	[kN]	Drag force
l		[m]	Length block
h	-	[m]	Height artificial seaweed above the bottom
d		[m]	Thickness block
b		[m]	Width block
C_d	1.4	[-]	Drag coefficient of the vegetation[97]
ρ_w	1000	[kg/m^3]	Density (salt)water
ρ_s	980	[kg/m^3]	Density artificial seaweed
v	-	[m/s]	Current velocity

Table 49-1 Position of the artificial seaweed

The effective height (h) for a specific current velocity can be calculated using:

$$v^2 = 2 \cdot \frac{\sqrt{l^2 - h^2}}{h^2} \cdot \frac{l \cdot b \cdot g \cdot (\rho_w - \rho_s)}{C_d \cdot \rho_w}$$

[97] Based on measurements by Tsujimoto & Kitamura (1990) [ref 67 (p42)] a drag coefficient of 1.4 has been used to calculate the hydraulic roughness of the artificial seaweed.

The effective height for a specific current velocity is given in Figure 49-2. (Dimensions l = 2.5m ($5 \cdot 0.5 = 2.5$); width = 0.1 m; thickness = 0.04 m)

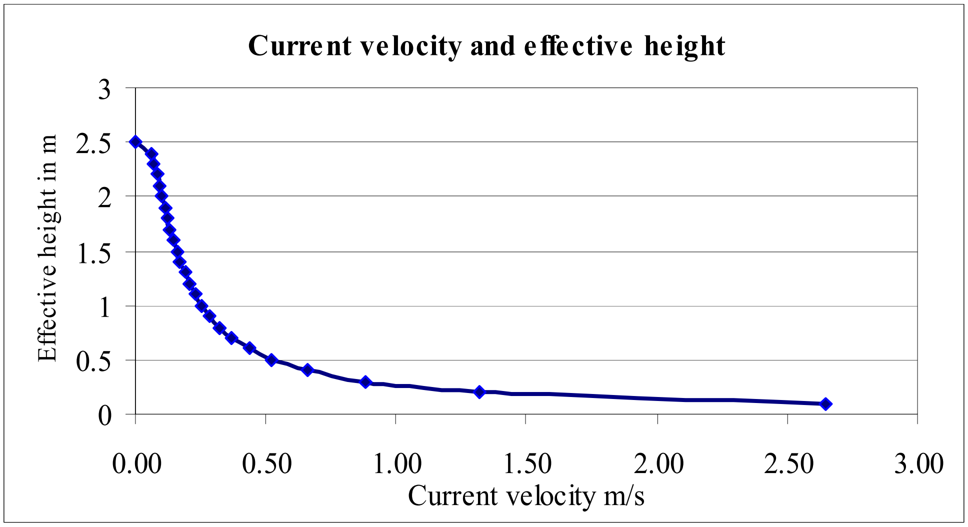


Figure 49-2 Current velocity and effective height

Consequently the resulting force on the anchorage system for a specific current velocity is given in Figure 49-3.

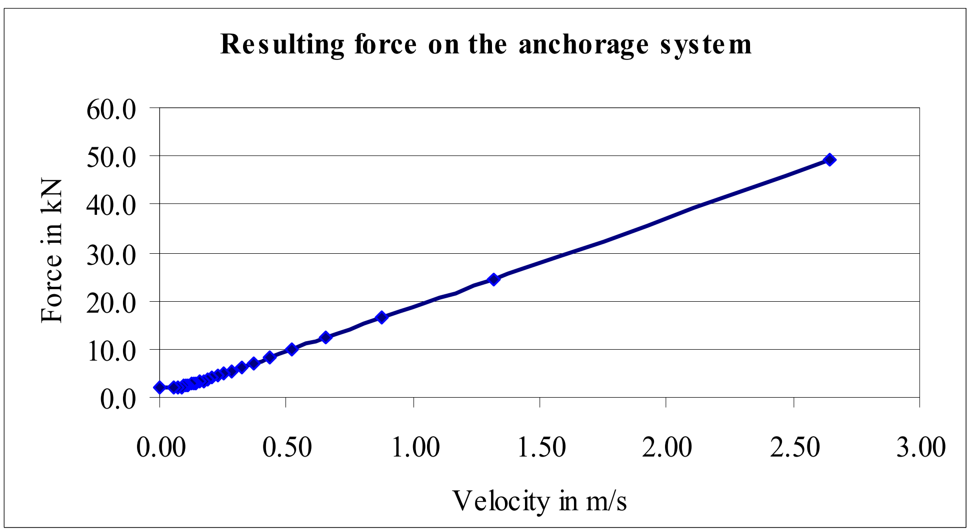


Figure 49-3 Resulting forces on the anchorage system