A DUTCH PERSPECTIVE ON COASTAL LOUISIANA FLOOD RISK REDUCTION AND LANDSCAPE STABILIZATION

Final Report

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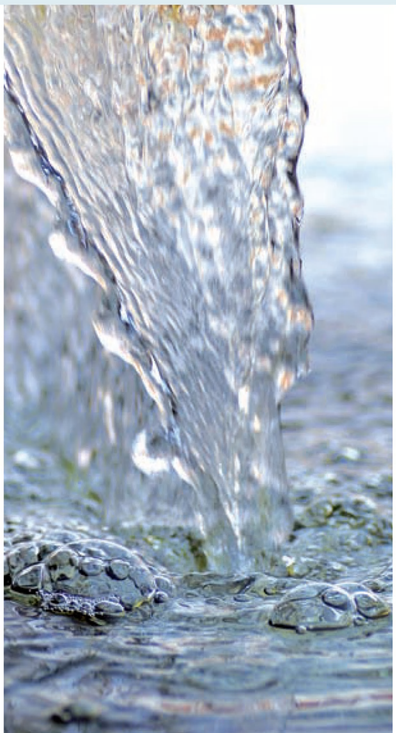

A DUTCH PERSPECTIVE ON COASTAL LOUISIANA
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Final Report

by

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14. ABSTRACT

Final report of a reconnaissance level research project carried out by a consortium under the Netherlands Water Partnership. The project was aimed at identifying options for the long-term reduction of flood risks and landscape stabilization in Planning Areas 1 and 2 in Louisiana, in the framework of the Louisiana Coastal Protection and Restoration project (LACPR). The report formulates a planning framework, identifies possible measures and alternative strategies, and formulates a preferred strategy. Appendices provide background information.

15. SUBJECT TERMS

Coastal Louisiana, flood risks, landscape stabilization.

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Preface

After the disaster that Hurricane Katrina caused along the Gulf coast and in particular in New Orleans (August-September, 2006), many in the United States looked at how the Netherlands protects itself against extreme flood events. Flood protection levels in the Netherlands are very high compared to those of most other countries but nevertheless are affordable. Could the strategy followed by the Dutch be the example that should be used when considering the long-term flood risk management in Louisiana? And given the rapid loss of wetlands in the Mississippi Delta, could Louisiana benefit from the recent change in policy in the Netherlands, in which preference has shifted from relying only on structural approaches involving levees and flood barriers towards a combination of "building with nature" and traditional approaches?

The current planning activities of the Louisiana Coastal Protection and Restoration project (LACPR) aim to develop possible strategies for long-term flood risk management options as well as for restoration of the rapidly deteriorating Mississippi Delta. In common language: LACPR focuses on both flood protection for Category 5 hurricanes and coastal restoration.

The U.S. Army Corps of Engineers (USACE) and the Netherlands Rijkswaterstaat (under the Netherlands Ministry of Transport, Public Works and Water Management) signed a Memorandum of Agreement in May, 2004. Ongoing co-operation between these two organizations based on that agreement led to the idea of developing a Dutch perspective on the topics covered by the LACPR project, i.e. flood risk reduction and landscape stabilization. As a result, a consortium under the Netherlands Water Partnership (NWP, an umbrella organization of Dutch governmental organizations, contractors, consultancy firms, research institutes and NGOs) was commissioned by the U.S. Army Corps of Engineers to carry out a research and planning project entitled "A Dutch Perspective on Coastal Louisiana Flood Risk Reduction and Landscape Stabilization".

Many of the specialists involved in this Dutch Perspective project visited New Orleans and the Mississippi Delta after Hurricane Katrina and were involved in meetings and workshops with USACE and other organizations in Louisiana. Various Internet sites provided an overwhelming amount of information and the project team reviewed reports drafted in the framework of LACPR and Louisiana's Comprehensive Master Plan for a Sustainable Coast (by the Coastal Protection and Restoration Authority of Louisiana, CPRA). The progress in analyzing Hurricane Katrina and her effects is impressive and the Dutch team considered it a challenge to contribute to this process of evaluation and planning. At the same time, the team feels privileged to be involved in finding flood risk management and nature restoration solutions beneficial to the people of Louisiana.

For the people in the Netherlands, and in particular for those involved with the flood protection system, Hurricane Katrina served as an eye-opener. Catastrophic flooding could also happen in the Netherlands, especially if attention is weakened or the forces of nature are underestimated. What would the Dutch do, what would be their response to a major disastrous flooding in the Netherlands? The U.S. interest for flood management in the Netherlands as an example of doing things right brought reflection on the Dutch response to the 1953 flooding disaster. What were the main decisions taken and how do they translate or compare to what might be the right way forward for Louisiana? The Dutch response to the 1953 disaster was built on eight centuries of dedication to protecting the country against rising water. The recorded history of the Louisiana people struggling against rising Mississippi water and hurricanes may not be that long, but is at least as dynamic.

The assignment by USACE to the Dutch team is not intended to produce a comprehensive master plan for the Mississippi Delta as an alternative for, or in competition with, that of LACPR or CPRA. It merely tries to contribute to it, in an attempt to translate the Dutch experience to the Mississippi Delta, and compare technologies that might or might not differ from what American engineers and scientists know and can do. The project team fully appreciates the differences in background and political context and realizes that there is not a single truth or wisdom. The Dutch team will, however, make certain choices as to what planning principles and measures will be selected for further investigation and will be included in the final report as recommendations.

For this research and planning project, the Dutch team did not have direct consultation with the people and communities involved, some of which might directly be affected by the consequences of certain principles or measures recommended in this report. Also, vested local interests in land ownership, and rules and regulations regarding, for example the mitigation of adverse ecological impacts, are deliberately not taken into account in this planning effort. This is in order to come up with a truly outsiders' perspective on the issues at stake; a perspective that is as much as practically possible not colored by local opinions about the preferred course of action.

It goes without saying that deciding about which course of action to pursue is up to the people of Louisiana and of course the U.S. Congress. The project team hopes that the Dutch perspective contributes to making informed decisions about what is the best course of action for the Louisiana coastal area and New Orleans in particular.

Disclaimer

The strategic alternatives and information presented in this report represent only preliminary and alternative conceptual possibilities. The strategies reviewed therein are only some of the possible solutions. Further or other studies may also include other reasonable alternatives. Additionally, the setting forth of these conceptual possibilities should not be taken as either a reflection or an indication of a Government-preferred alternative or Government-selected alternative.

No party should place any reliance on, or make any decisions based upon the described strategic alternatives. None of the information contained therein should be relied upon in creating any proposals in response to a Government contract solicitation or in preparing any designs, plans, cost estimates, etc. For example, in the development of the conceptual strategies, estimates are given for the "10,000 year storm event maximum water levels" and structure elevations.

However, stated water levels and elevations are only estimates at this time and may change as they have not been finalized.

The views expressed in any commentaries or cost estimates reflected therein, including any research, studies, analysis, engineering and design, etc., are those of the authors and do not reflect the official policy or position of the U.S. Army Corps of Engineers. All items contained in the study are "pre-decisional" and only one aspect of the United States Government's deliberation process. This document is provided only to aid the Government in its deliberative process and for no other purpose.

One-page Summary

This report describes a plan for long-term flood risk reduction of coastal Louisiana and for strengthening the natural ecosystem functions of the Mississippi Delta, aimed at stabilizing the landscape. It is drafted by an independent team of flood management specialists from the Netherlands and as such is an external contribution to the ongoing planning in the Louisiana Coastal Protection and Restoration Project (LACPR).

A cost-benefit analysis leads to the conclusion that it is economically justified to provide flood protection to the city of New Orleans at a level of at least 1/1,000 per year, which is considerably higher than the existing protection level. Regarding landscape stabilization, a series of options was identified to not only stabilize the remaining wetlands in the Mississippi Delta, also given sea level rise, but also to create new wetlands. The role of wetlands in hurricane surge level reduction and wave attenuation is a linking pin between the issues of flood risk reduction and the degradation of the delta ecosystem.

Several alternative strategies were designed to illustrate the available options. These strategies include an open system, a semi-open system and a closed system, with gates that can be closed during hurricanes. Based on the characteristics and impacts of these strategies the project team formulated a Preferred Strategy, which includes:

- Non-structural measures, aimed at improving the organization of flood risk management in the region.
- For New Orleans: upgrading the levee system to a safety level of 1/1,000 per year or better and enclosing it where possible in a belt of fresh water cypress tree swamps.
- For the Pontchartrain Basin: either creating a closed or semi-closed system, with a levee along the C90 highway, combined with gates in the Chef Menteur and Rigolets passes, or keeping the basin open and (further) heightening the levees of New Orleans along Lake Pontchartrain. The current study does not lead to a clear conclusion about these alternatives. In addition, existing wetlands should be stabilized and new wetlands be created, including filling-in part of Lake Borgne in order to reduce surges and waves and to close the proposed belt of fresh water swamps.
- For the Barataria Basin: (re-)creating an open system with wetland stabilization measures, combined with careful management of freshwater diversions and infrastructure improvements.

The Net Present Value of the total costs of the Preferred Strategy is estimated at $20 billion. Four conditions have to be met for proper management and maintenance: (1) political commitment to the strategic goals and to the framework for tactical goals and measures; (2) designing and implementing the specific tactical measures within the approved framework; (3) regular updating of tactical planning (once every 1 to 10 years, depending on the type of measures); and (4) funding for operational management and maintenance. Provided that these conditions are met, and provided that stakeholder participation is combined with a genuine political commitment to protect New Orleans and enhance the Mississippi Delta ecosystem, the project team is convinced that the Preferred Strategy is realistic, feasible and achievable.

Executive Summary

Introduction

The human and ecological disaster caused by Hurricane Katrina in New Orleans and along the Gulf Coast in August 2005 motivated the United States to examine whether flood management practices in the Netherlands would be applicable and affordable in Louisiana. Dutch protection against extreme flood events is very high but nevertheless very cost-effective. Furthermore, there was a desire to find out if Louisiana could protect its wetlands by adopting the recent Dutch policy of relying on a combination of "building with nature" and traditional approaches such as building levees and flood barriers.

The U.S. Army Corps of Engineers (USACE) and the Netherlands Rijkswaterstaat (under the Netherlands Ministry of Transport, Public Works and Water Management) signed a Memorandum of Agreement in May, 2004. Ongoing co-operation between these two organizations based on that agreement led to the idea of developing a Dutch perspective on the topics covered by the LACPR project, i.e. flood risk reduction and landscape stabilization. A consortium was set up under the Netherlands Water Partnership (NWP) - an umbrella organization of Dutch government organizations, contractors, consultancy firms, research institutes and NGOs - and commissioned to carry out a research and planning project entitled "A Dutch Perspective on Coastal Louisiana Flood Risk Reduction and Landscape Stabilization".

Objective

The overall objective of this project is to draft a plan for the long-term flood risk reduction of coastal Louisiana together with a plan to strengthen the natural ecosystem functions of the Mississippi Delta and thus stabilize the landscape. The project team has outlined the strategy and options to be considered. It is intended that this report will contribute to the ongoing planning in the Louisiana Coastal Protection and Restoration Project (LACPR).

Project overview

This project addresses two main issues in coastal Louisiana: flood risks and the degradation of the delta ecosystem. Other important issues related to the various functions of the delta are not considered here. Since Hurricane Katrina, the issue of flood risks has become evident. This is aggravated by the dramatic and ongoing loss of wetlands in the Mississippi Delta, which is a more gradual process caused by the limited supply of fresh water and river sediments to the delta, subsidence of the delta, salt water intrusion and wave action in the many man-made canals in the delta.

If the ongoing loss of wetlands is not stopped, the future of the wetland area of the delta is bleak. More and more wetlands will be lost, which will not only have disastrous consequences for the ecosystem and other societal functions of the delta like fisheries and recreation, but will also lead to a significant increase in hurricane surge levels in the delta, including the levees around New Orleans. Sea level rise will further aggravate the problem. The role of wetlands in hurricane surge level reduction and wave attenuation is a linking pin between the issues of flood risk reduction and the degradation of the delta ecosystem.

Method

The project team has made use of publicly available information, which has been supplemented with information provided by USACE. Field visits to the Mississippi Delta and New Orleans have provided additional insight. Direct consultation with the people and communities has deliberately not been sought at this stage. The team has used an outsider's perspective to apply the experience of the Dutch to the Mississippi Delta. This has produced a reconnaissance study, in which a first, preliminary identification of options has been carried out. This should be followed by more in-depth analyses before final decisions are made. It is a contribution to the work being carried out by LACPR, which is currently developing options for both flood protection for Category 5 hurricanes and coastal restoration.

The project team applied a policy analysis method to carry out the project. After identifying possible measures, a screening process led to a set of promising measures. These were then used to develop a number of strategies: alternative paths that could be used to reach the objectives. An impact assessment resulted in an overview of pros and cons of these strategies. It is noted that the level of detail, especially regarding hydrodynamic modeling, is less than the level of detail in the LACPR project.

Planning principles

Several planning principles were derived from the lessons learned from both the Mississippi and Dutch Delta and from the idea that a long-term sustainable solution is necessary to protect people and economic values in the coastal area and to cope with the uncertainties of sea level rise, subsidence and general transgression (migration) of the overall Mississippi Delta.

The five main principles to take into account in the planning process are:
1. The urban areas would be defended using levees and other structures in the short term as well as in the long term, and the protection level would be based on a balance between costs and the reduction in flood risks;
2. Easy-to-adapt measures are preferable to those that are difficult to change;
3. The natural system would be kept in place and the obstruction of natural upstream-downstream pathways would be avoided;
4. Natural processes for restoration and enhanced flood protection would be strengthened;
5. The relocation of the river mouth and abandoning the Mississippi Delta "Birdfoot" would be considered.

The plan, characterized by the slogan "Protected City, Sustainable Delta System" consists of a set of measures that will lead to flood risk reduction, landscape stabilization, and the retention and development of socio-economic values in the region. To measure the effect of these measures, criteria for evaluation were applied.

Categories of possible measures

An inventory was made of possible measures to either reduce flood risks directly by levees or other engineered features and/or to reduce flood risks indirectly by consolidating, restoring or changing the overall dynamics of the delta. Non-structural measures are outside the scope of this inventory. Five categories of possible measures were identified:

1) Direct protection of built-up areas
Existing levees, floodwalls and gates would be upgraded and/or redesigned and realigned. These are fairly simple engineered structures that could be built in a relatively short time and would provide immediate protection after completion.

2) Closed basin hurricane surge protection
Flood protection barriers would close off the Pontchartrain and/or the Barataria basins during a hurricane threat. This would partly avoid the need to upgrade the existing levee and floodwall systems and might provide a more cost-effective solution. Gated levee barriers are proven structures already applied in the Netherlands and elsewhere in the world. The scheme would be within present state-of-the-art technology and could be implemented within a reasonable time frame. Nevertheless, the impact on the overall basin dynamics is difficult to predict and negative effects will need to be mitigated.

3) Measures to consolidate and increase natural flood protection (wetlands)
Healthy marshlands and swamps can help to reduce hurricane surges by absorbing a significant portion of the energy generated by the passing of wind fields. These measures are aimed at consolidating and restoring natural protection against flooding while also improving the health and integrity of the ecosystem.

4) Basin surge reduction measures
The purpose of these measures is to limit the effect of hurricane surges entering the basins by absorbing its energy either through reshaping the existing outer barrier islands or through creating a new string of man-made "ridge-levees". Ridge-levees have very gentle slopes on both sides and a wide but eco-friendly footprint in the Pontchartrain and Barataria basins. A string of ridge-levees would have openings for existing natural channels and man-made canals and the natural flow of water and migration of species would be essentially unobstructed.

5) Delta system intervention for long-term natural surge reduction
The purpose of this option is to further reduce the current loss of sediment resources into the deep parts of the Gulf of Mexico. This could be done by either dredging openings in the banks of the river to enable the formation of crevasses, or by dredging relatively narrow but deep channels on both river banks, which could be used as a shorter navigation route to the Gulf.

A set of promising measures was subsequently identified that most closely satisfied the five main planning principles.

Possible strategies

The main purpose of the strategy development process is to find the best *set of measures* to reach the overall objectives for flood risk reduction and landscape stabilization, if possible enhancing the local and regional economy.

Five possible strategies were designed based on the list of promising measures. The most important planning issue to be addressed is whether or not the Mississippi Delta should be closed off with flood defense systems. The five strategic alternatives for the Pontchartrain and Barataria basins are:

Strategy 1, 2 and 3: Open Estuary System (three alternatives)
Strategy 4: Semi-Open Defense System
Strategy 5: Closed Defense System

Measures to provide flood protection to the metropolitan area of New Orleans have been grouped under the heading "Protected City". For Plaquemines Parish, it is suggested that the existing, long and narrow levee ring are replaced with smaller rings of sufficient height around villages, and long stretches of levees are removed in rural and empty spaces in order to allow hurricane surges to dissipate. Each strategy includes the "Protected City" flood protection measures, but on different scales. Similarly, each strategy includes non-structural measures, but these measures are not detailed in concrete ideas for organizational changes, or ideas for laws and/or regulations.

In Strategies 1, 2 and 3, the estuary system would remain in open connection with the Gulf, and there would be surge reduction by nature. There would be stabilization and revitalization of the natural system, which would create marshland and minimize sediment loss. Landscape stabilization would be fully related to providing additional flood protection and ecosystem functioning. The three alternatives in this strategy relate to the speed of implementation and to the total area of wetlands to be restored or created.

In Strategy 4, there would be enhanced passive surge reduction by means of ridges or stretches of levee that will reduce surges but not fully stop them. Under normal circumstances, the natural water, sediment and nutrient exchange would remain unobstructed. There would also be stabilization of the natural system. The "Protected City" measures would be less extreme when compared with Strategies 1, 2 and 3 because of passive surge reduction in the delta.

In Strategy 5, there would be active surge reduction. The landscape stabilization and revitalization would be managed and there would be surge reduction measures per basin by levees and gates. Also in this strategy, under normal circumstances, the natural water, sediment and nutrient exchange would remain unobstructed. This would be realized by constructing culverts in the levees at regular intervals. Landscape stabilization would not necessarily be related to flood protection. The "Protected City" measures would be less extreme when compared with Strategy 4 because of active surge reduction in the delta.

Characteristics and impact of these strategies

A Cost/Benefit analysis, in which the cost of structural measures is compared with the reduction in flood risks that these measures bring about, concludes that a substantial increase in the flood protection level of the metropolitan area of New Orleans to a level of about 1/1,000 per year or better (for example, 1/10,000 per year) is economically justified. This protection level is considerably higher than the existing protection level which in the current situation (2007) is estimated at roughly 1/100 per year.

The costs of the Strategies 1 to 5 range between $18 and $23 billion. These costs, expressed as net present value, include investment costs over a period of several decades as well as maintenance costs. Surprisingly, the costs in relative terms for these various strategies do not differ substantially. This is because the levees and gates around New Orleans can be constructed with a lower height in the case of a closed or semi-open system when compared to the height required in an open system.

The various structural components of the strategies can be realized within a period of about ten to twenty years. After implementation, levees, gates and floodways will immediately contribute to reducing flood risks. Although measures like canal-plugging will have an immediate effect on ecosystem functioning, much more time is required for the full maturation of the effects of landscape stabilization measures: trees need to grow, wetlands need to develop. This will take at least several decades. As a result, the protection level will gradually increase over time, assuming that the currently projected sea level rise is not accelerated.

Creating new navigation outlets that also keep the river sediments close to the shoreline is an expensive measure due to the large amounts of dredging involved. Other measures with similar or better effects on the ecosystem are more cost-effective and therefore it is not recommended to include this measure in the strategy of choice.

Preferred strategy "Protected City and Closed Soft Coast"

The Preferred Strategy is composed of various elements of the five strategies described above. The Preferred Strategy is not the same in the Pontchartrain and Barataria basins and it provides the city of New Orleans with a protection level of 1/1,000 per year or better.

The strategy is composed of the following elements:

- For New Orleans: upgrade the levee system and enclose it where possible in a belt of fresh water cypress tree swamps of between 1 and 6 miles wide (wetland revitalization and creation of 140 square miles);
- For the Pontchartrain Basin: either create a closed or semi-closed system, with a levee along the C90 highway, combined with gates in the Chef Menteur and Rigolets passes, or keep the basin open and (further) heighten the levees of New Orleans along Lake Pontchartrain. The current study does not lead to a clear conclusion about these alternatives. In addition, the Preferred Strategy for the Pontchartrain basin includes wetland stabilization (750 square

miles) and wetland creation (80 square miles), including filling-in Lake Borgne in order to reduce surges and waves and to close the proposed belt of fresh water swamps.
- For the Barataria Basin: (re-)create an open system with wetland stabilization measures (600 square miles); careful management of freshwater diversions and infrastructure improvements.

The Net Present Value of the total costs of the Preferred Strategy is estimated at $20 billion. The various cost components are listed the following table. The tables also specifies the number of culverts and diversion, and the number of square miles in the various marshland stabilization and marshland creation measures.

	Net Present Value Cost (in million $)	**Remarks**
Protected City measures	$9,585	
Ring levees Plaquemines	$1,485	
Culverts in existing Barataria interstate + railway	$68	5 culverts
Fresh Water Diversions	$203	3 diversions
Marshland Stabilization Pontchartrain	$3,591	750 sq. miles
Marshland Stabilization Barataria	$2,835	600 sq. miles
Marshland Creation Pontchartrain	$810	80 sq. miles
Marshland Creation Barataria	$608	60 sq. miles
Marshland Creation Landbridge	$675	
Total (Net Present Value)	**$19,860**	

Discussion

Due to the strength of hurricanes and the location of New Orleans in the Mississippi Delta, it is recognized that the primary measure to provide flood protection to New Orleans is and will be a system of levees. However, continued loss of wetlands in the future will have a substantial negative effect on surge levels and waves around the city. The stabilization and creation of wetlands, and in particular the restoration of a belt of fresh-water cypress swamps around the levee rings of New Orleans, are not only of importance to protect the ecosystem and the societal functions that depend on this ecosystem, but are also important for flood management. Cypress swamps can be important in reducing the impact of surges and waves. This is why in each strategy the upstream diversion of limited amounts of fresh water and sediments from the river is a crucial measure, which will result in salinity gradients in the basins, and the creation of fresh water cypress swamps.

As indicated in the above, the current study does not lead to a clear preference regarding whether to build a levee along the C90 highway, combined with gates in the Chef Menteur and Rigolets passes, or alternatively keep the basin open and (further) heighten the levees of New Orleans along Lake Pontchartrain. A study that is more detailed than the current reconnaissance level study is required to clarify this issue.

Many uncertainties play a role in the outcome of this study. These uncertainties can only be reduced with an ongoing effort to gain more knowledge about flood management in coastal

Louisiana, including the improved estimation of extreme events (hurricanes and associated surge levels), improved knowledge about the movement of sediments in the delta, and improved knowledge on how to most effectively restore wetlands and create new wetlands.

From the viewpoint of management and maintenance, the strategic and tactical goals of the flood protection scheme need to be interlinked. The Dutch concept of regular safety assessment (every 5 years) including a risk assessment (every 25 to 50 years) is highly recommended for coastal Louisiana and the New Orleans area.

It will take two to five decades before the benefits of any implemented strategy are fully realized. During this period the strategic goals of the plan will probably have to be modified several times. This recognition needs to be reflected in a management and maintenance strategy for the project.

It will be crucial to integrate and coordinate the activities of the various authorities involved and essential to find a suitable balance between their role and actions.

Concluding remarks

A high level of flood protection and stabilization of the delta landscape are realistic goals that can be reached in exchange for an investment that is relatively modest when compared to the damages caused by Hurricane Katrina. The proposed measures will also enhance the local and regional economy, both short term and long term.

The engineering aspects of the project should not be considered as the major challenge: except for the construction and functioning of ridge-levees, the various recommended measures are based on proven technology. Less is known about the best way to stabilize the landscape. It is for this reason that the implementation of a series of pilot projects has been recommended to be carried out in the short term ("learning by doing"). Organizational aspects, including the development of effective institutions that can tackle landscape stabilization, and the laws and regulations to enable that work, will also require much attention. Finally, the importance of a continued involvement of the general public in the upcoming efforts is essential: each member of the public is in fact a stakeholder.

The goals and aims laid down in this document are both realistic and achievable when appropriate stakeholder participation is combined with a genuine political commitment to protect New Orleans and enhance the Mississippi Delta ecosystem.

1 Introduction

Context of the project

The project entitled "A Dutch Perspective to Coastal Louisiana Flood Risk Reduction and Landscape Stabilization" has been realized in the framework of the Louisiana Coastal Protection and Restoration project (LACPR).

The U.S. Army Corps of Engineers (USACE) and the Netherlands Rijkswaterstaat signed a Memorandum of Agreement in May, 2004. Ongoing co-operation between those two organizations based on that agreement led to the idea of developing a Dutch perspective on the topics covered by the LACPR project, i.e. flood risk reduction and landscape stabilization. As a result, a consortium under the Netherlands Water Partnership (NWP, an umbrella organization of Dutch governmental organizations, contractors, consultancy firms, research institutes and NGOs) was commissioned by USACE to carry out this project.

Project objective

The objective of the project is to draft a plan for the long-term flood risk reduction and landscape stabilization of part of coastal Louisiana, if possible enhancing the local and regional economy.

The level of detail in the project is that of a reconnaissance study. Hence, it does not reach the level of a feasibility study, let alone detailed designs of possible measures or strategies.

This report attempts to be clear on the options and the kind of measures to be taken into consideration, and provides suggestions for the order in which measures should be taken over time to implement the strategy. The report intends to contribute to the ongoing planning effort in the framework of LACPR.

This report is only a small step in the long process of re-evaluation of flood risk management and landscape stabilization in Louisiana. A relatively small endeavor like this is by no means sufficient to obtain a detailed picture on the diverse development issues, or to resolve the divergent views around complicated issues existing in the area, and it is certainly not sufficient to draft an integrated plan, ready for implementation. It can only contribute to the process of decision-making, and that is what the project team hopes to achieve with this "outsiders' perspective".

Project area

The project area for the Dutch Perspective project includes the Pontchartrain Basin and almost the entire Barataria Basin. This corresponds (see Figure 1) to the LACPR Planning Area 1 (Pontchartrain) and a large part of Planning Area 2 (Barataria). The border area between Area 2 and 3a (Houma) is not part of the project area. The LACPR Project focuses on the entire coastal area of the State of Louisiana.

Figure 1 Schematic map indicating Planning Area 1 (Pontchartrain Basin) and Planning Area 2 (Barataria Basin) (source: LACPR)

Approach

This project has been conducted in the Netherlands using specific information provided by USACE, as well as publicly available information from USACE and other websites. Direct consultation with the people and communities involved has deliberately not been sought by the project team. This is to ensure that the team comes up with a truly outsiders' perspective.

Activities

The project officially started on March 30, 2007, with the signing of a contract by USACE and NWP. Before that date, however, activities had already started by order of the Netherlands Rijkswaterstaat to enable team mobilization, data gathering and scope tuning.

Activities included:

- A familiarization of the project team with the problem at hand, which included literature reviews, various field visits and discussions with numerous U.S. experts on a variety of topics (in particular during the week of 12 to 16 March, 2007);
- Study of the various components of the delta system, including geology, hydraulics, morphology, ecology, flood risks, soil mechanics and options for a variety of structural flood protection measures;
- Drafting of a set of possible strategies for long-term flood risk reduction and landscape stabilization, and determining the impact of these strategies; and
- Based on the results, the formulation of a strategy preferred by the project team.

Acknowledgements

The project team thanks the many U.S. experts contacted during the project activities for their useful suggestions and help during the project. In particular, the help, guidance and constructive comments given by Mr. Edmond Russo, Mr. Al Naomi and Mr. Carl Anderson and their staff (all USACE) during the project are gratefully acknowledged. The authors of this report remain solely responsible for the way the input was condensed and presented in this report.

The staff and management of CH2M HILL (New Orleans) helped the project team tremendously by organizing two full-day field trips in the Mississippi Delta and New Orleans.

The team also wishes to thank Ms. Claire Taylor for her contributions to the final English language editing of this report.

The NWP Consortium for this project

The Netherlands Water Partnership is an independent foundation set up by the Dutch private and public sectors in the Netherlands to act as a national coordination and information centre for water-related issues abroad. The NWP is the channel through which government bodies, NGOs, research institutes and private organizations in the water sector all share information on their activities and services. The NWP has currently 135 members: 71 private sector companies, 24 public authorities, 19 knowledge institutes, 14 NGOs and 7 water supply companies.

For the Dutch Perspective project, NWP has set up a team of specialists, which is composed of staff members of the following member organizations of NWP: WL | Delft Hydraulics, Arcadis, DHV, GeoDelft, TNO, Royal Haskoning, Fugro, Alkyon, HKV Consultants, Infram, and Rijkswaterstaat. Appendix M lists the members of the project team. Rijkswaterstaat not only provided expert input in the project team, but also gave guidance to the project team and extended additional financial support to the project.

Overview of the contents of this report

This report consists of a concise main part, with many appendices. The appendices provide background information on the various focus areas of the work that was carried out.

2 Project area overview

2.1 Existing situation and future without measures

This chapter provides a brief description of the Mississippi Delta, including the natural system, the man-made system (including all functions that the delta has for society), or the institutional setting. For a detailed description reference is made to the LACPR report.

A few key characteristics of the existing situation in the project area of relevance to the current project are in brief:

1. Built-up areas include the Metropolitan area of New Orleans, predominantly rural land use in Plaquemines Parish, and small towns on the barrier islands. The vast majority of the land surface of the project area is in its natural state.

2. Current flood protection is provided by a system of levees and flood walls around (parts of) New Orleans and – in the form of long, parallel levees – around the built-up areas in Plaquemines Parish. The current flood protection level there is around 1/100 per year.

3. Human activities in the delta area include the important navigation industry (transport routes, port facilities), fishing industry (oysters, crawfish, shrimps, etc.), recreation (fishing, hunting, etc.), and a wide variety of activities related to the substantial oil and gas industry.

4. The cyclic geological development of the Mississippi Delta is the driver of a cycle of habitats and biodiversity at each location in the Delta, spanning many millennia. The Pontchartrain and Barataria basins are at present in the high-biodiversity, slow "deterioration-phase" of this cycle. The so called Birdfoot of the Mississippi Delta is an example of the natural fast growth-phase as part of the same cycle. Louisiana's coastal wetlands provide important habitat for migratory waterfowl.

5. Land loss in the delta over the past decades has been dramatic. According to the United States Geological Survey (USGS, 2007), Louisiana lost approximately 1,900 square miles (about 5,000 km^2) of coastal land, primarily coastal marshes, during the 20th century and could lose another 700 square miles (1,800 km^2) over the next 50 years if no new restoration takes place. That means that by 2050 one third of coastal Louisiana will have vanished into the Gulf of Mexico. Based on USGS data, land loss rates amounted to 39 square miles per year (100 km^2/yr) between 1956 and 1978 and 24 square miles per year (60 km^2/yr) from 1990 to 2000, which is equivalent to about one and a half football field lost every hour. Except for isolated recent diversion sluices, the supply of Mississippi River water, nutrients and sediments to the delta has been blocked by the construction of levees along the river. Canal excavation (mainly to support the oil and gas industry) over the past decades is considered to be one of the most important causes of marshland loss. Canal formation has altered the hydrodynamics. Where this caused changed flooding frequencies,

marsh accretion has been affected. Opening up of marshes is increasing erosion by increasing wave fetch and current speeds. In addition, marsh browning disease and overgrazing by nutria, an invasive rodent species that is native to South America, is reducing marshland areas further.

6. Coastal Louisiana contributes about 20% of the nation's total commercial fisheries harvest (DNR, 1998). On 2004 Louisiana commercial landings exceeded one billion pounds with a dockside value of $274 million. Annual expenditures related to non-commercial fishing in Louisiana can amount to between $701 million and $1.2 billion. In 2001, hunting-related expenditures in Louisiana amounted to $446 million and expenditures related tot wildlife-watching amounted to $168 million. Trapping in Louisiana coastal wetlands generated approximately $2 million annually. The Louisiana alligator harvest is valued at approximately $30 million annually (Coastal facts, 2007). Commercial fisheries resources maintain between 50,000 and 70,000 jobs statewide (DNR, 1998). In addition, many people are employed in the outdoor industry.

Regarding the future, the following key developments are of relevance to the project:

1. The sea level will rise. Following the conclusions of the Inter-governmental Panel on Climate Change (IPCC), it is assumed that the sea level will rise by two feet over the coming century. The relative sea level rise will be greater, depending on the rate of subsidence.

2. If no large-scale measures are taken, the process of wetland loss that occurred in recent decades will continue in the future. Given the importance of the wetlands for hurricane surge and wave reduction, this further loss of wetlands will increase flooding probabilities in the region. If levee systems are not modified to this change, flooding probabilities will increase in areas protected by these levees.

3. It is assumed that in the near future the Mississippi River Gulf Outlet (MRGO) will be closed. Recent evaluations of this issue indicate that decommissioning MRGO as a deep-draft navigation canal is to be preferred. Reasons include economic as well as environmental considerations, the latter because of the reduction of the salt water intrusion. Although the legislation for such decommissioning is not yet in place, the project team assumes that this will be the case in the near future. Hence, in the current planning effort it is assumed that MRGO will be closed, either by completely plugging the canal, or by turning it into a shallow draft canal by filling it in.

Figure 2 Aerial photograph Mississippi Delta (source: Google)

2.2 Lessons learned in Louisiana and in the Netherlands

Looking back in history, it can be concluded that the present state of both the Mississippi Delta and Netherlands Delta have been shaped by human intervention. There are many differences as to geology, scale and type of interventions and land-use, but it is obvious that both deltas are beyond a "free" natural state. Both deltas have adapted and are still adapting to man-made conditions. In the Netherlands, these interventions span ages dating back to roughly the tenth century. Significant interventions in the Mississippi Delta date back some two centuries. In both deltas flooding through rivers or the sea triggered swift and large-scale interventions, and these were the main force for finding quick and proven solutions. Immediate action was and is required to be prepared for the next flooding or storm season.

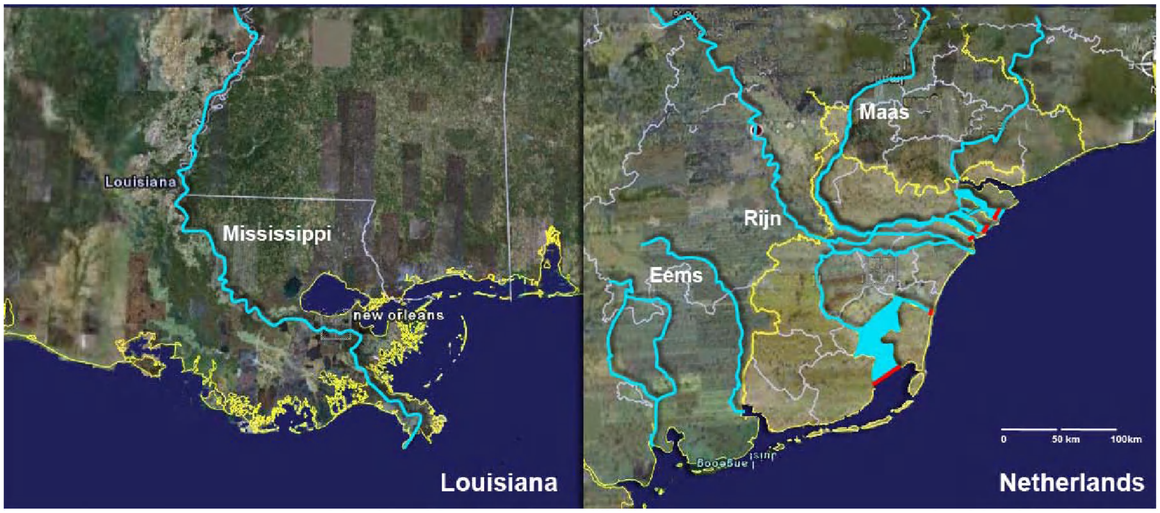

Figure 3 Mississippi Delta and the Netherlands, outlining fresh water bodies (similar scale, image of the Netherlands oriented South and pointing upwards)

The search for solutions for flooding at a certain point of time is obviously dominated by the opinions and interests of landowners, business leaders and public leadership. History shows that besides providing flood protection, the development of the Dutch Delta has been dominated by agriculture (marshland cultivation / fresh water economy) as the most important economic factor besides trade. Keeping out salt water was and continues to be the mainstream thinking in the low-lying Western part of the Netherlands. This eventually led to the cultivation of nearly all marshlands and closure of many estuaries (triggered by flooding disasters) and was a guiding principle in finding the response to the 1953 flood disaster as explained in The Dutch Case (see below). Doing the right thing after 1953 was based on centuries of thinking and acting to cultivate the Delta, to store fresh water and to keep salt water out. The Dutch find themselves in a safe and green, yet completely man-made and managed environment.

The Dutch Case

The Netherlands Delta has developed through the ages to its present state through the reclamation of marshlands, improved water management technologies and through response programs to flooding disasters. Land reclamation and water management in the Netherlands were driven by economic considerations. The first large-scale reclamations in the 16th century were private initiatives to create new cultivated land outside the crowded cities. Triggered by a major flood in 1916, the closure of the Zuiderzee protects the central part of the Netherlands against flooding, and enabled the reclamation of large formerly tidal areas for agriculture and the construction of a large fresh water basin for drinking water supply and to flush out salt water in the bordering Province of North-Holland, again for agricultural needs.

In response to the (coastal) flood disaster in 1953, the Delta Act prescribed closing off most of the last open estuaries to increase the level of flood protection and to save costs on upgrading a considerable length of levees along these estuaries. It was in the 70's that a growing environmental awareness pushed the need for less drastic solutions. The main issue was whether or not to close the Eastern Scheldt Estuary and turn it into a fresh water basin. The decision was to go for a gated solution, and keep the estuary in a (semi-) natural state, which at that time was a technically challenging approach. Although driven by safety considerations, the Delta Project enabled the creation of additional fresh water storage and an overall improvement in the fresh-water-management system. Only the Western Scheldt estuary was left open, in order to guarantee access to the port of Antwerp (Belgium). The other salt water and intermediate estuaries, with the Eastern Scheldt estuary as the exception, were all turned into fresh water systems, effectively separating the fresh and salt water systems. Although the gated barrier in the Eastern Scheldt allows tidal water into the estuary, it effectively blocks sediments, introducing a series of shoaling and erosion patterns.

However, there are no solutions without regrets. The decision to build a gated barrier in the Eastern Scheldt was clearly a compromise between the demand for flood protection and environmental considerations. The current appreciation for environmental values leads many to regret the choice of a gated solution in the Eastern Scheldt and other estuaries.

The Mississippi Delta Case

The Mississippi River Flooding in 1927 required a new and integrated approach to protect values bordering this mighty river and its branches. New and stronger levees were built and now confine the river within defined limits. Overflow bypasses were created to relieve downstream flooding. Bayous were closed off to provide sufficient downstream navigational water depth. The overall effect is, however, that the main fresh water discharge and sediments are not distributed into the marshlands along the river but concentrated into the main river with a single outlet into deep water: the Mississippi Delta Birdfoot.

Disruption of fresh water inflow and sediments, the excavation of many canals to support the oil industry, in combination with land subsidence and sea level rise have caused an ongoing loss of salt and brackish marshlands and a further intrusion of salt water in what used to be intermediate or freshwater-dominated areas. Tide and wave-induced erosion under prevailing conditions and during storms are a significant aspect of this ongoing process. Restoration projects now include the feeding of closed bayous with Mississippi water and the creation of wetland with dredged materials.

Following Hurricane Betsy in 1965, the U.S. Congress approved legislation to build a Hurricane Protection System around New Orleans. This system would provide a flood protection level of about 1/200 – 1/300 per year. Unfortunately, this system was never completed, and New Orleans protection levels were negatively influenced by – amongst other factors – subsidence and possibly also by the ongoing process of wetland loss.

3 Approach

3.1 Policy analysis approach

The policy analysis approach, applied in this project, has two main characteristics: (1) providing information that is relevant for decision makers (i.e. criteria) and (2) presenting a number of different strategies which together cover the "playing field" of possible solutions. The policy analysis approach contains the project activities as outlined by Figure 4.

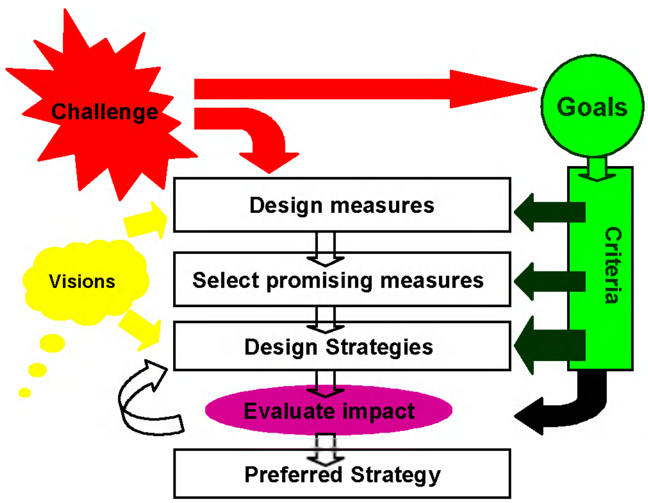

Figure 4 Schedule planning process

Obviously, the trigger for the project was the flooding disaster caused by Hurricane Katrina. With this trigger in mind the goals and objectives of the project have been defined and possible measures have been identified. The process of identifying possible measures and strategies was enriched by the views of specialists in various disciplines and their views on the problem, its causes and possible solutions.

Next, the project objectives were detailed by specifying criteria, which were used for the screening of measures. A quick scan of measures provided a comprehensive overview of discussion points and led to a relatively quick answer to the question whether or not a particular measure represents a realistic option or not. These discussion points proved important for the choices that needed to be made in the planning process. The quick scan also led to a differentiation between more promising and less promising measures.

After the selection of promising measures the design of possible strategies started, keeping in mind the different visions of the type of solutions and the relevant criteria for decision making. These strategies will be evaluated using the criteria. The final result is the presentation of a number of strategies, and a balance of pros and cons that can be presented to the decision makers. With that information a strategy preferred by the project team has been selected.

3.2 Delta characteristics and related planning principles

Several planning principles, identified by the project team and applied in this study, were derived from the lessons learned from both the Mississippi and Dutch Delta cases (see Section 2.2) and from the notion that a long-term sustainable solution is required to cope with the uncertainties of sea level rise, subsidence and general transgression of the overall Mississippi Delta.

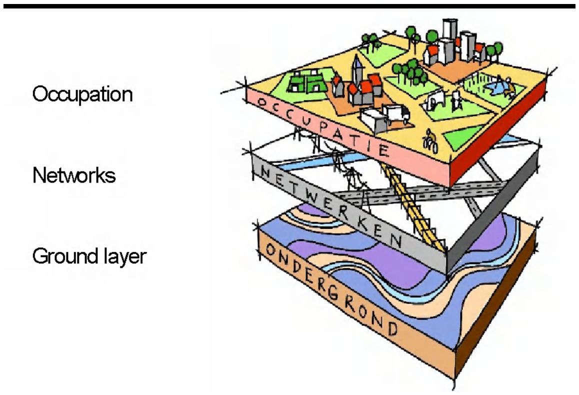

Figure 5 Layer Model

The so called 'Layer Model' (see Figure 5 and Appendix L) makes a distinction between the three elements that in combination define the use of space in a society, i.e. the ground layer (soil, water, flora and fauna), the networks (waterways, transportation infrastructure, civil engineering works) and occupation (living, working, recreation). This model allows a strong conceptual organization of societal elements. It should be noted that the amount of time needed to change properties of each layer will range from decades to hundreds of years, which is important when considering possible measures and strategies. Interactions between layers are obvious. For example, marshes (ground layer) provide some level of protection to the cities (occupation layer) against storm surges, while railroads and highways (network layer) cut across marshes and influence the flow of water and migration of animals, thereby to some extent influencing the protection of the citizens.

Planning principles related to the "ground layer"

The geo-morphological evolution of a delta (*the ground layer*) is marked by a spatial and temporal cycle, spanning thousands of years. The present delta plain and the associated barrier islands and submarine shoals are the products of cyclic delta building processes (see Appendix B). This is of relevance when considering both the physical and the biological functioning of the delta area. By stabilizing the present status, degradation can be slowed down, and this helps to gain time for adaptation to the long-term spatial and temporal cycle.

A distinction should be made between active and inactive lobes. Older lobes are gradually eroding over a time scale of thousands of years. Growth and loss are part of the natural cycle. The architecture of the delta has been fixed by past interventions, while delta lobe evolution has been accelerated. The subsidence of non-active lobes can be slowed down but cannot be stopped in the long run. It is logical to utilize the structuring potential of the active lobe and its sediment availability as much as possible. The priority for inactive lobes should be on stabilization, and for active lobes on wetland formation.

Keeping, restoring and improving as much as possible the existing fresh and salt water gradients in both the Pontchartrain and Barataria basins including sediment dynamics is a condition in preserving and improving the natural system of marshlands, swamps and land-bridges.

Planning principles related to the "networks layer"

As a result of the development of subsequent delta lobes, the delta is structured from upstream to downstream, and has a radial architecture. This is reflected in water-part of the existing *networks layer.* This architecture must be the leading consideration when deciding on delta functioning in the future (for example, fresh water diversions should be located upstream), and *building with nature* is an important means of influencing delta functioning.

Navigation on the Mississippi River and port activities are of paramount importance to the regional economy and in fact also for the entire Mid-West of the U.S. Navigation must be safeguarded and if possible improved.

Planning principles related to the "occupation layer"

A sufficient hurricane protection is required for people and values (*the occupation layer*) with an appropriate protection level, which might be different for particular areas. To allow the New Orleans society and economy to prosper again, protection from destructive sea and river flooding must significantly diminish the chances of another catastrophe.

A risk-based approach will have to determine which protection levels are appropriate for particular areas. This implies that the size of the flooding risk (defined as the multiplication of the amount of flood damage and the probability of such flood damage occurring) should drive decisions from the point of view of an objective performance and cost. This approach may give rise to prolonged discussions about, for example, which costs and which benefits of flood risk reduction measures can be applied in the evaluation. This may be one of the reasons why in the U.S. the traditional planning approach prescribes what can be taken into account in governmental flood risk reduction projects. These policies, in which for example flood damages in the flood-prone area are taken into account quantifiably as the Federal objective over other damages, should in the opinion of the Dutch team not be applied in the framework of LACPR since they do not sufficiently recognize the effects of flooding in the New Orleans area on Louisiana and on the nation as a whole.

Integration of layers

Given the economic values at stake in the Metropolitan area of New Orleans, the highest benefits of flood risk reduction measures will involve measures that protect the urban areas. The wetland areas in the delta can play an important supporting role in providing such protection. The city of New Orleans could be considered as the hard pit in a soft fruit: the "*fruit and pit concept*". In this concept, the city (the "pit") will be defended against flooding at the highest feasible protection level. The "fruit" is the delta with its diverse habitats and high productivity. This soft fruit protects the "pit". The sustainable functioning (health) is crucial for long-term protection and the livelihood of the citizens. The networks layer infrastructure should be adapted in order to protect or enhance the ground layer functions, which in turn would enhance flood protection as well as the quality of life for occupation layer functions.

Flexibility of planning and measures

Flexibility in the planning and implementation of flood risk reduction and landscape stabilization measures should be maintained and increased. One cannot predict the future with much accuracy and one must accept that significant gaps in knowledge exist. As much as practically possible, measures taken now need to be flexible and extendable in order to allow efficient and effective adaptation and mitigation in the future. A step-by-step approach in reaching the final objective, with regular updates of the original plan, is a prerequisite for final success. Experiments and pilot projects can help to reduce uncertainties. A proper phasing of interventions allows learning by doing. A flexible approach allows redesign and adaptation of measures based on increasing knowledge and experience.

Approach

The above ideas and guiding principles led to the following main concepts in the approach:

1. Defend the urban areas, in particular the metropolitan area of New Orleans. For the short term, this implies relying on levees and possibly other structures. Landscape stabilization measures that can possibly contribute to flood risk reduction generally need more time to mature. It is recognized, however, that also on the long term levees and other structures will continue to be the most important element of the flood protection system for urban areas.

2. In order to maintain flexibility, use measures that are relatively easy to adapt or change in the future in preference to measures that are difficult to change.

3. Keep the natural system in place and avoid obstructing natural upstream-downstream pathways of water, sediment, nutrients and species. Maintain natural waterway network flow patterns and density. Increase the supply of fresh water and nutrients gradually to prevent ecological shocks. Allow and provide space for the relocation of oyster cultures.

4. Strengthen natural processes for restoration and enhanced flood protection. Acknowledge the effectiveness of marshlands to reduce wave heights and to reduce storm surges. Expedite marshland maintenance and marshland building to compensate the loss of marshlands in recent history and further enhance flood protection. Use the active lobe for marshland expansion, stabilization and maintenance. Attempt to delay the deterioration of inactive delta lobes.

5. Consider the optimum size of the delta given the available discharge of sediments and fresh water and consider options for using the river sediment supply to enhance near-shore suspended sediment concentrations and the sediment budget for the coastal area. This includes relocating the river mouth by decoupling the Birdfoot and utilizing the sediment

for levee construction and marshland creation or combine this with the creation of an under-water sediment buffer which will likely form sand barrier islands on the long term.

6. How to best organize flood risk management in institutions, laws, regulations, etc. should be addressed in the in the context of the strategy selected for the future.

3.3 Criteria for evaluation

The overall goal of the project is to draft a plan for the long-term flood risk reduction and landscape stabilization of part of coastal Louisiana, which possibly also enhances a sustainable occupation and conditions for regional prosperity. Landscape stabilization is the strengthening of the natural functioning of the ecosystem, for example by reintroduction of natural gradients, by improving the sediment balance and by increasing biodiversity.

The plan consists of a set of measures that lead to flood risk reduction and landscape stabilization, and which enable economic development. To measure the effect of measures, criteria for evaluation are applied. Which criteria to use follows from the goal of the project. The goal is fulfilled by the following five main objectives:

1. Increase in flood protection (safety).
2. A more sustainable Delta
3. Retain and develop socio-economic values
4. High value/feasibility of measures.
5. Low costs (for investment and for maintenance).

The increase in flood protection is expressed in the flood risk reduction for urban and for rural areas. In the case of the project a more sustainable delta means improvement of the overall sediment balance, in salinity gradients and in ecosystem functioning. Important socio-economic values are navigation and other economic activities, historical values and social and cultural values. Also in the case of the project, a high value/feasibility of measures means a high technical feasibility of the measures including maintenance and robustness, a high flexibility in measures including adaptability and separability, a high public support for measures and the amount of time required for the implementation of measures. For some measures also time to maturity [1)] needs to be considered. The smaller the time required for implementation/maturation the better/higher the score on this objective/sub-goal.

These five main objectives and their related sub-goals are presented in a goal tree (see Figure 6). This goal tree provides insight in the five main objectives of the Dutch Perspective (the five items in enclosed in the blue frame) and gives an overview of sub-goals that need to be met as much as possible. The green goals in Figure 6 are related to goals set by the LACPR (see Appendix A).

1) Time to maturity is defined as the time period between the moment when investments are made to implement a measure and the moment that benefits are realized; for example in case of river diversions to stimulate wetland development.

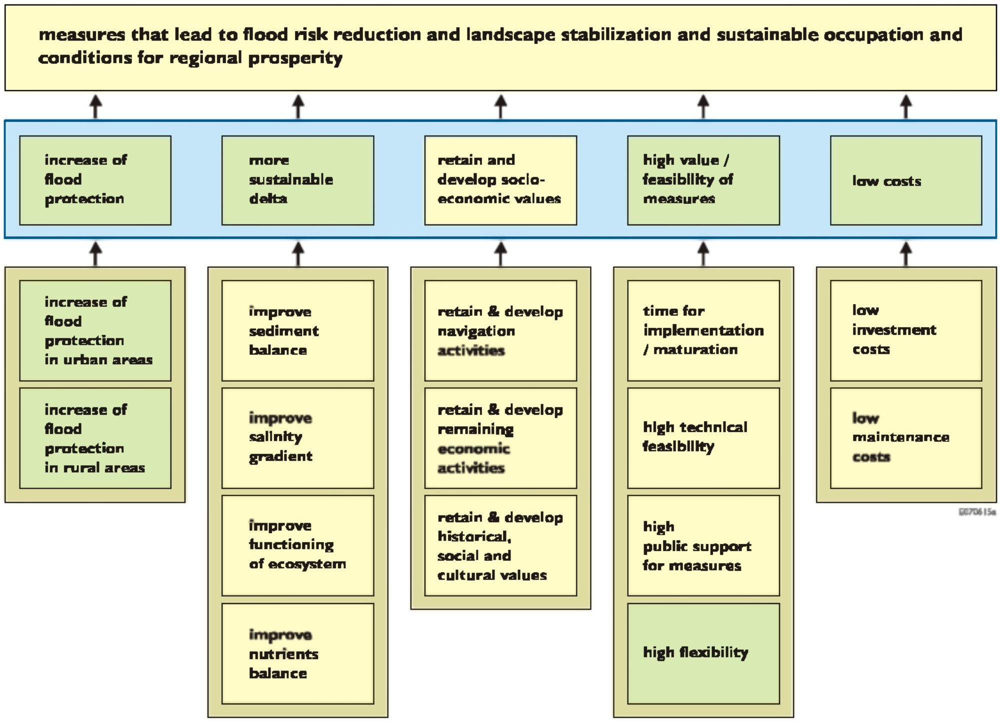

Figure 6 Goals and objectives of the project

The balance of pros and cons for each strategy will be presented with these five main objectives. If necessary, also the relevant sub-criteria will be addressed. It is emphasized that these objectives will obtain different weights in the decision making process about strategies and alternatives. These criteria are used for the screening of measures and for the evaluation of the strategies. Most of these criteria will be evaluated qualitatively by expert judgment.

3.4 Assumptions

Important assumptions made in the current project are:

- The sea level rise over the coming century will be about 2 feet (60 cm). The relative sea level rise will be greater, depending on the rate of subsidence.
- It is assumed that there will be no significant changes in the frequency of occurrence, possible tracks and strength of hurricanes. This assumption implies that the results of the IPET study [2)] which described the existing situation (for example: the relation between surge level and probability of occurrence), after correction for relative sea level rise, can also be applied for the future.
- It is assumed that in the future the distribution of Mississippi River water over the downstream stretch of the Mississippi River and the Atchafalaya River at the Old River Structure will remain unchanged.

2) IPET: Inter-agency Performance Evaluation Taskforce

4 Possible measures

The project team made an inventory of plausible measures to either reduce flood risks directly by levees and other engineered features and/or reduce flood risks indirectly by consolidating, restoring or changing the overall dynamics of the delta and in particular that of marshlands, swamps and the Birdfoot. Non-structural measures have not been addressed, partly because some important types of non-structural measures are already in place (flood warning, evacuation procedures), while other types (like flood proofing of houses and industries) are deemed to be very local and therefore considered complementary to increased risk reduction for the large New Orleans Metropolitan Area.

The preliminary plans by both LACPR and the State of Louisiana identified a large number of measures to achieve the objectives adopted for the planning. The Dutch team reviewed these measures in a number of workshops held in the Netherlands to try to understand their intentions and effects. From an overall perspective, there seems to be a broad consensus on what measures might be appropriate to at least achieve a part of the objectives. For the sake of comparison and eventually selection, the various measures identified and reviewed by the team in Planning Area 1 and 2 are grouped into five categories of flood risk reduction measures, which differ in time scale, effect and intention:

1. Direct protection of built-up areas;
2. Closed basin hurricane surge protection;
3. Measures to consolidate and increase present natural surge reduction;
4. Basin surge reduction measures; and
5. Interventions for long-term natural surge reduction.

Measures in groups 1) and 2) are engineered structures that, by definition, provide risk reduction to a pre-determined level, while the other (landscape stabilization type) measures are designed to reduce hurricane surges and are evaluated in terms of their contribution to risk reduction, both in a short-term and long-term perspective. Landscape stabilization in this grouping is considered to be a part of a "multiple lines of defense" strategy.

4.1 Direct protection of built-up areas

This group of measures aims to protect concentrated values within the Delta with a surrounding protection system (Figure 7). This is in line with the basic idea behind the present situation, where levee rings protect built-up areas from sea and river flooding. Basically, there are two groups of alternatives: (1) upgrading and completing the present levee and floodwall alignments and (2) adopting a new design and alignment to provide the appropriate level of protection.

The alignments chosen for evaluation are close to the alignments of the present (repaired and upgraded) system. Existing plans to close the three drainage canals in New Orleans, to gate the Industrial Canal and the Gulf Intracoastal Waterway (GIWW) are considered to be included and the project team assumes that the designs will be based on an appropriate protection level.

For a better protection of New Orleans Lake Front the Dutch team suggests the consideration of a new levee alignment in front of the existing one roughly one thousand feet into the lake as an alternative. Such a new levee, with gates to allow the outflow of pumped drainage water during normal conditions, would avoid upgrading the space-confined existing waterfront and would allow for a temporary storage of pumped drainage water in the water area protected by the new levee, and would avoid severe wave attack on more vulnerable structures outside the existing levee.

For Plaquemines Parish an option is to build ring levees around the more densely built-up parts of the parish (villages, industrial complexes) and to remove other levee stretches in order to dissipate hurricane surges.

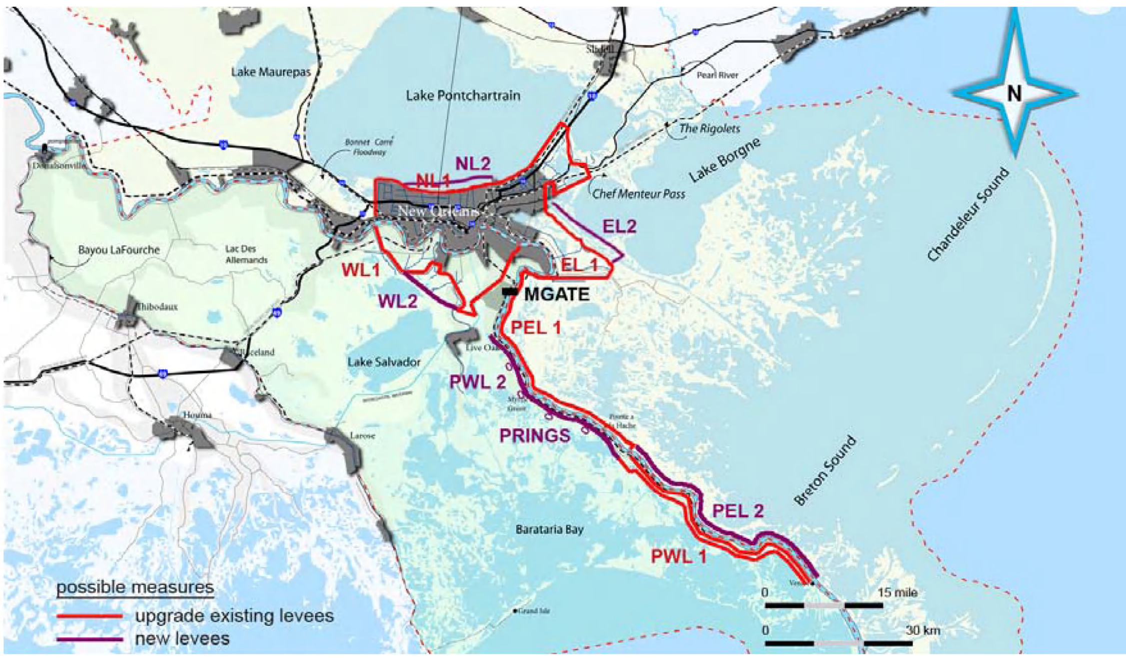

Figure 7 Alternative alignments for levee systems protecting New Orleans and Plaquemines Parish (codes of measures are explained in Appendix H).

In principle, levees and gates are, from a strategic planning point of view, simple engineered structures that can be build in a relatively short time. They provide immediate protection after completion. From an engineering and construction point of view these structures are complicated and challenging projects.

4.2 Closed Basin Hurricane Surge Protection

These alternative measures basically are features to close off either or both the Pontchartrain and Barataria basins during a hurricane threat. They prevent hurricane surges to penetrate the basins. Implementing this protection system would partly avoid upgrading the existing systems and might be an economical solution if proven to be effective.

Lake Pontchartrain Gated Levee Barrier

Hurricane Katrina caused a surge in water levels in Lake Pontchartrain because large amounts of water rushed over the land-bridge from the Gulf into Lake Pontchartrain and through the Chef Menteur and Rigolets passes raising the lake water level by some six feet. On top of that, a significant increase of the water level in the Lake Front area occurred because the hurricane-force winds pushed the water in that direction. A Lake Pontchartrain barrier scheme (Figure 8) will prevent the surge in water level but cannot avoid a significant wind set-up on the lake itself.

A barrier scheme was already investigated in the 1960's but then rejected for environmental and other reasons. Closing off Lake Pontchartrain with a barrier is an alternative for upgrading the New Orleans lake front and will also provide protection to Slidell and other areas bordering the lake. LACPR indicates various alignments. Two alignments were selected for further consideration, one along the I10 and the other along the C90 highway.

Barataria Basin Gated Levee Barrier

Closing off the Barataria basin (Figure 8) seems to be an effective measure to provide protection to the upper part of the basin. It would avoid construction and/or upgrading levees along the borders of the basin and around isolated values. LACPR studies an alignment following that of the GIWW. This is an obvious choice. The Waterway is an excellent route supporting construction and can already be regarded as a hydrological and ecological barrier splitting up the basin. The barrier, and in particular the gates provided in it, would allow for better water control (to prevent salt intrusion, for instance) but will undoubtedly further change the basin into a human-controlled environment instead of an open estuary system.

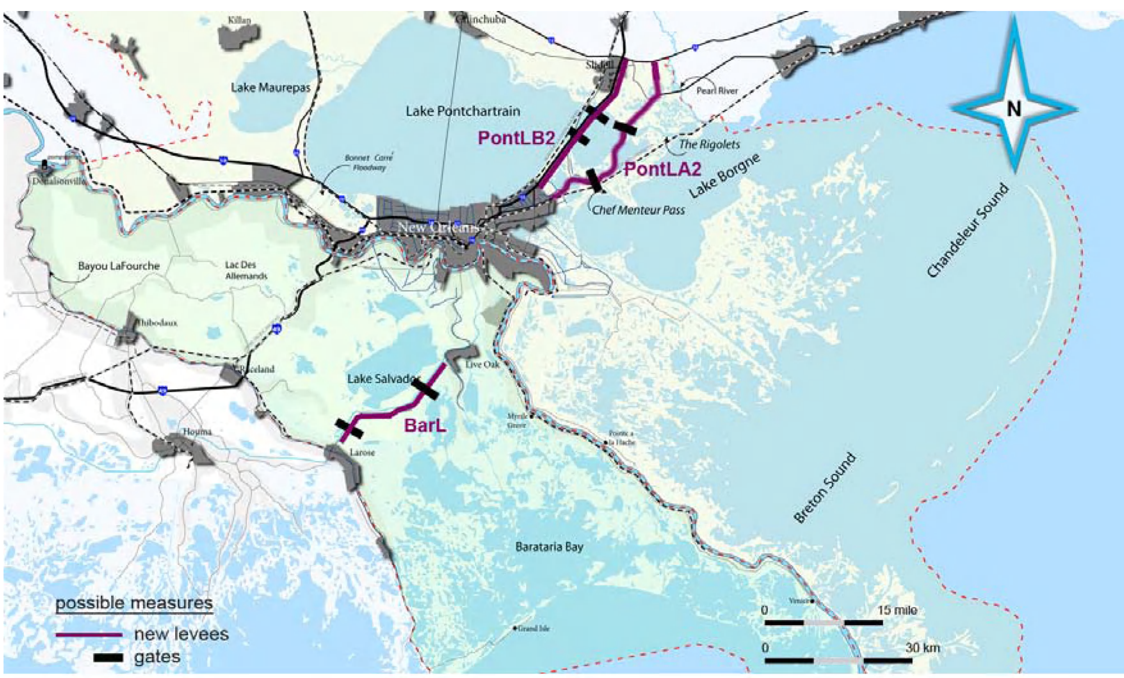

Figure 8 Possible measures for closed hurricane surge protection (Appendix H explains the codes of measures).

From a technical point of view, gated levee barriers are proven structures applied in the Netherlands and elsewhere in the world. Although the project scale is large and the logistic conditions are difficult, the scheme is most probably within the present state-of-the-art capability and could be implemented within a reasonable time frame. However, the impact on the overall basin dynamics in terms of water, sediments and ecology is difficult to predict and the scheme probably needs extensive compensation efforts to mitigate effects.

4.3 Measures to Consolidate and Increase Present Natural Surge Reduction

Healthy marshlands and swamps to a certain extent reduce hurricane surges and absorb a significant portion of the (surge and wave) energy generated by the passing wind fields. The general notion is that degrading marshlands and vanished swamps contributed to Hurricane Katrina's detrimental effects and that consolidating and restoring natural protection should be an essential part of the overall protection plan. Such measures would not only contribute to a reduction of flood risks, but would also address concerns about the health and integrity of the ecosystem.

Considering the geo-morphological evolution of the delta, increased (upstream and lateral) diversion of fresh river water and in particular fine sediments into the basins are the key factors in landscape stabilization. However, restoring the basins to a healthier system requires a combination of measures that will at the very least simulate the natural dynamics of an open system. Existing fresh water diversions have proved to be effective in consolidating certain areas from a water quality point of view (to prevent further salt water intrusion) but up to now have failed to build up new marshlands. Present structures divert water and not (enough) sediments. For a significant risk reduction, large and continuous marshlands (many miles with as few canals as possible) and swamps are needed to reduce storm surge heights. There are many ideas on what type of measures are required to achieve the overall objectives, but unfortunately little reported experience. The following measures are included in the evaluation:

Mississippi Fresh Water Diversions

The lack of (external) nutrient-rich freshwater supply in the Pontchartrain and Barataria basin is one of the main reasons for increased salt-water intrusion and consequent deterioration of the typical freshwater cypress swamps. Additional diversions are probably required to balance further intrusion and balance general subsidence. The ideal or achievable distribution of Mississippi water over the main channel and into the basins considering human needs, navigation, ecology and other factors is not a simple analysis and most probably a matter of compromise. And yet this distribution is a conditional factor for all ideas and plans to stabilize and restore the natural landscape. Considering the total capacity of the existing diversion works compared to the average river discharge, additional diversions seem to be feasible and hence are part of the strategies.

Marshland Stabilization

Marshland stabilization aims to consolidate existing marshes by filling or closing the network of canals as much as possible to stop further erosion and to reduce salt water intrusion through this network of open water. The degradation of existing salt water, intermediate brackish, and fresh water wetlands, in which marshlands either switch from one type to another, or turn into open water, is an irreversible process that is to a large extent caused by saltwater intrusion as a result of canal dredging. Considering the urgency and necessary scale of the operation, innovative solutions are required for realizing marshland stabilization against saltwater intrusion in a reasonable time and against reasonable costs. This calls for the development of dedicated equipment and most certainly new and dedicated working methods. Marshland stabilization is considered an essential measure that needs to be implemented as a matter of priority.

Marshland/Swamp Creation

Marshland creation aims to turn open water back into fresh water swamps. Nature creates marshes and swamps by a combination of nutrient-rich freshwater, fine sediments and vegetation. Essentially, there are three methods to turn (shallow) open water into marshland:

1. By simulating (and accelerating) natural processes through water and sediment diversions from the Mississippi River into designated areas. Either by constructing new diversion works (capable of diverting sufficient sediments) or by creating natural overflows along the riverbank at certain locations to simulate flooding events and stimulate crevasse building. Both techniques are already being applied in the Mississippi Delta. These methods would serve a long-term strategy to create a sequence of new freshwater marsh areas from upstream to downstream along the Mississippi ridge.
2. By filling shallow open water with piped sediments to create new wetlands as a basis for the growth of vegetation. A number of projects were executed in the Mississippi Delta by USACE under the program for "Beneficial Use of Dredged Materials". The continuous supply of nutrient-rich freshwater is obviously required to build up freshwater vegetation. The process of filling can be very fast, depending on the equipment employed and availability of sediments.
3. By constructing of saline, brackish or freshwater marshland polders to serve accelerated growth of vegetation without the initial supply of large quantities of piped sediments. The idea builds on the methods of land reclamation in the Netherlands to create agricultural land. The first step is to enclose a designated shallow water area with relatively low levees, after which the flooding cycle, water table and sediment supply is maintained at such a level that the optimal growth of marsh vegetation is realized. Some areas could be partly filled by piped sediment supply to provide a more favorable starting point for marsh formation. Depending on the size of the polder, simple, even wind-driven, pumps could be used. The system will be open for migrating aquatic species. The new vegetation in the polder serves as a starting point to build up organic sediments. The second step is to gradually increase the polder's water table to stimulate accretion, by maintaining growth, trapping fine inorganic matter and reducing oxidation of organic matter. The third and last step is to reinstate "natural" open connections with surrounding water by removing parts of the

enclosure levees after sufficient bed accretion is obtained. In the Netherlands, polder marshlands were created unintentionally but now are among the richest (and most protected) environmental areas in Europe. These new marshlands will also serve as sinks for carbon dioxide.

A combination of methods could indeed create significant areas of new marshlands in the Delta although it would take a number of decades to do so. In the Netherlands, some 150,000 hectares of land was reclaimed in a period between 1930 and 1960, serving the fresh water economy. Louisiana in principle could do the same, serving its marshland ecology and estuarine economy.

The overall target (at least for this evaluation and preliminary costing purposes) is to apply up to 20% of the annual Mississippi sediment load for marshland stabilization and creation in the Pontchartrain and Barataria basins. It is recognized that upstream marshland creation using Mississippi sediments could ultimately lead to an increased erosion of the Birdfoot.

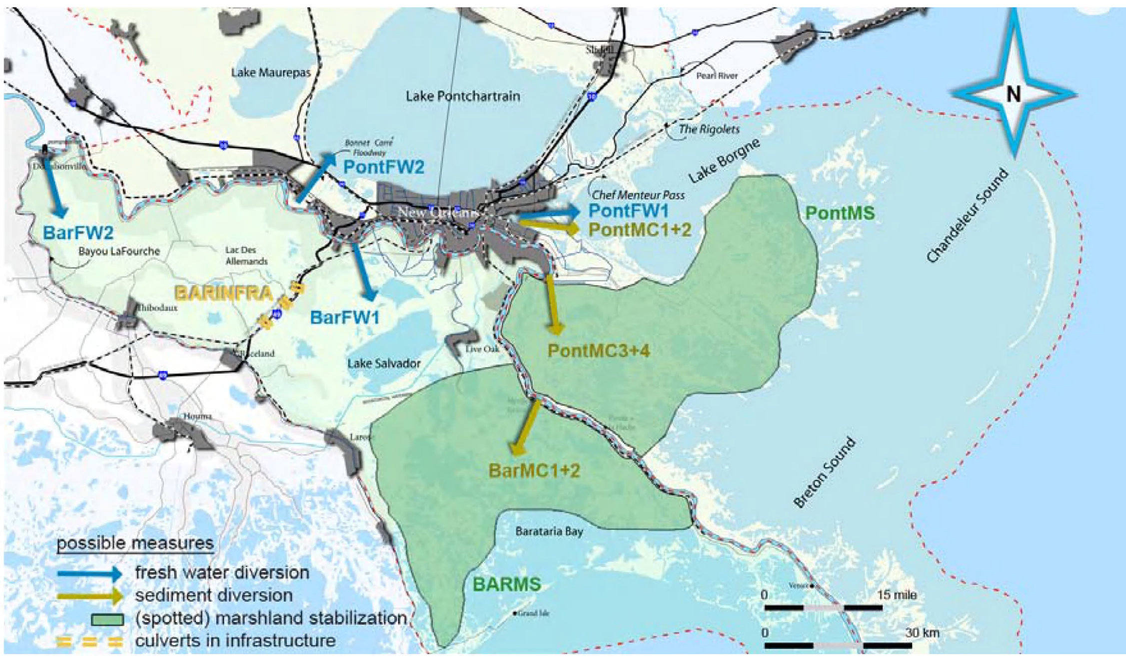

Figure 9 Measures to Consolidate and Increase Present Natural Surge Reduction (codes of measures are explained in Appendix H).

4.4 Basin Surge Reduction Measures

The purpose of these measures is to limit the effect of hurricane surges entering the basins by adsorbing its energy either through reshaping the existing outer barrier islands or through creating a new string of man-made levees (ridges) inside the Pontchartrain and Barataria basins. Figure 11 indicates possible alignments.

This surge-reduction barrier consists of what the project team has started to call "ridge-levees". These levees are unlike traditional (U.S. and Dutch) levees and are marked by very gentle slopes on both sides and a wide footprint. They are intended to be built from locally available materials with a sufficiently large cross-section to deal with slope erosion and wave overtopping in extreme conditions. The purpose is not to stop the hurricane surge, but to reduce the surge and waves behind it to an acceptable level. The system obviously requires sufficient space to receive and store overtopping surges and a secondary levee system to prevent flooding of protected values. Damage and erosion after an extreme event of course will have to be repaired. This may require a significant management and maintenance effort. Lacking special armoring on slopes and crest, it is relatively easy (and cheap) to heighten the ridge-levee when required in case of further subsidence and/or higher surge levels.

The ridge-levee barrier is not a continuous levee over many miles, but has openings for existing natural and man-made channels and canals. Hence, the natural flow of water and migration of species is essentially unobstructed. In addition, if used as multiple lines of defense, they may not require very significant elevation above sea level (approximately 10 to 15 feet at the crest / 3.5 to 4.5 m) to sufficiently detain storm water from propagating into the basin interior, and thus effectively reducing the storm water hydrograph at levees.

Another way to interpret the ridge-levee is to consider it as a natural ridge, comparable to the ridges that are found in many places along the rivers in the delta. The French Quarter, for example, was built on such a ridge. The big difference with natural ridges is that the ridge-levees are positioned essentially perpendicular to the waterways and more or less parallel to the coast.

The design of a ridge-levee is based on the following concepts (see Figure 10):

- The application of gentle slopes to avoid expensive subsoil improvements (drained solutions).
- The use of local sediments (silt) as much as possible.
- The application of a design that can safely deal with overflow and overtopping waves, in order to reduce crest height.
- The inclusion of landscaped surge-buffering zones, which at various elevations increases ecosystem diversity. This also provides increased area for over-wintering waterfowl resting areas along the Mississippi Flyway route. Another benefit is the provision of shelter for animals from drowning during storms.
- The possible inclusion of "perched" freshwater wetlands along the crown of the ridge-levee.
- The possible construction through existing shallow open waters, avoiding covering over existing wetlands, and reducing the open water fetch.

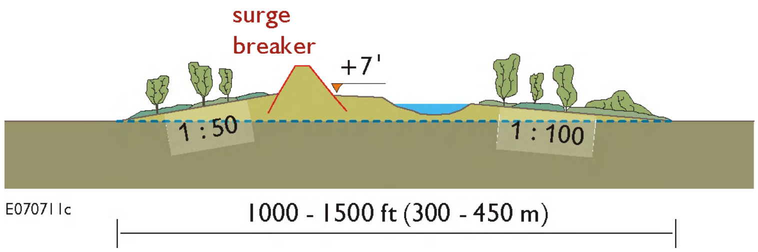

Figure 10 Schematic cross-section of a ridge-levee.

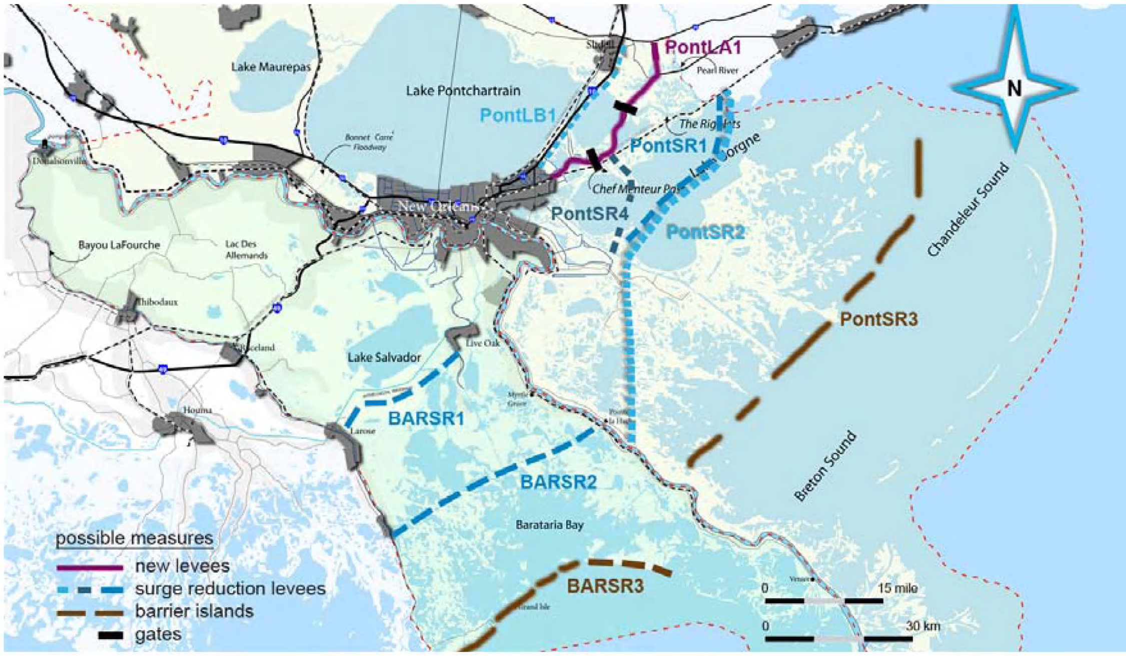

Figure 11 Basin surge reduction measures (codes of measures are explained in Appendix H).

Depending on crest height, the levee is within a range of 1,000 to 1,500 feet (300 to 450 m). The existing levee and floodwall system is considered to be a secondary system.

The overall system (crest height, spacing and openings) must be carefully sized in order to create a sufficiently large reduction of a hurricane surge and to prevent system failure by progressive erosion during a hurricane attack in particular in and around the openings.

Another type of measures that fits this group is the development of new barrier islands along the outer rim of the marshland (see Figure 11). These islands reduce the tide, wave, and coastal storm attack from the Gulf on the saltwater marshes bordering the seashore. Natural barrier islands still protect the Barataria basin but have more or less vanished in the Pontchartrain basin. These islands could be reshaped (raised and extended) to significantly contribute to the protection of marshes and hurricane-surge reduction, similar to the above explained ridge-levee concept.

4.5 Interventions for Long-Term Natural Surge Reduction

The final group of flood risk reduction measures is illustrated by Figure 12. The idea is to reduce the current wastage of sediment resources, which are now to a large extent dumped in the depths of the Gulf of Mexico.

Reducing current wastage of sediment resources can be realized by *large-scale crevasse building measures.* Alternatively, dredging large-scale openings in one or both banks of the Mississippi River downstream of Pointe à La Hache can do this; the main flow of the river can be diverted. Hence, the freshwater and sediments conveyed by the river would stay in the near-shore area, and sediments could settle downstream in the marshland area. Such sediment deposition is not only the result of the flow of river water, but the tidal flows and wave action contribute to the redistribution of sediments. Natural processes would be used in this way to build marshland, which helps to reduce hurricane surges. In essence, this measure would imply "giving up the Birdfoot".

It goes without saying that navigation interests must be safeguarded at all times. River navigation is too important for the region and the nation to allow compromises.

The project team identified several options for this measure:

- Dredging a 3 mile (5 km) wide opening in the West bank of the river. The depth of this opening is 17 feet (5 m). River navigation would continue to use the existing navigation channel.
- Dredging two relatively narrow (0.6 mile / 1 km) but relatively deep (50 feet / 15 m) channels on the East and West bank of the river respectively. These new channels would be the access channel for ocean-going navigation to reach the Mississippi River. In this alternative, the existing Birdfoot would no longer be maintained and would eventually – after a long process of decay – disappear, while its sediments would benefit the coastal zone.

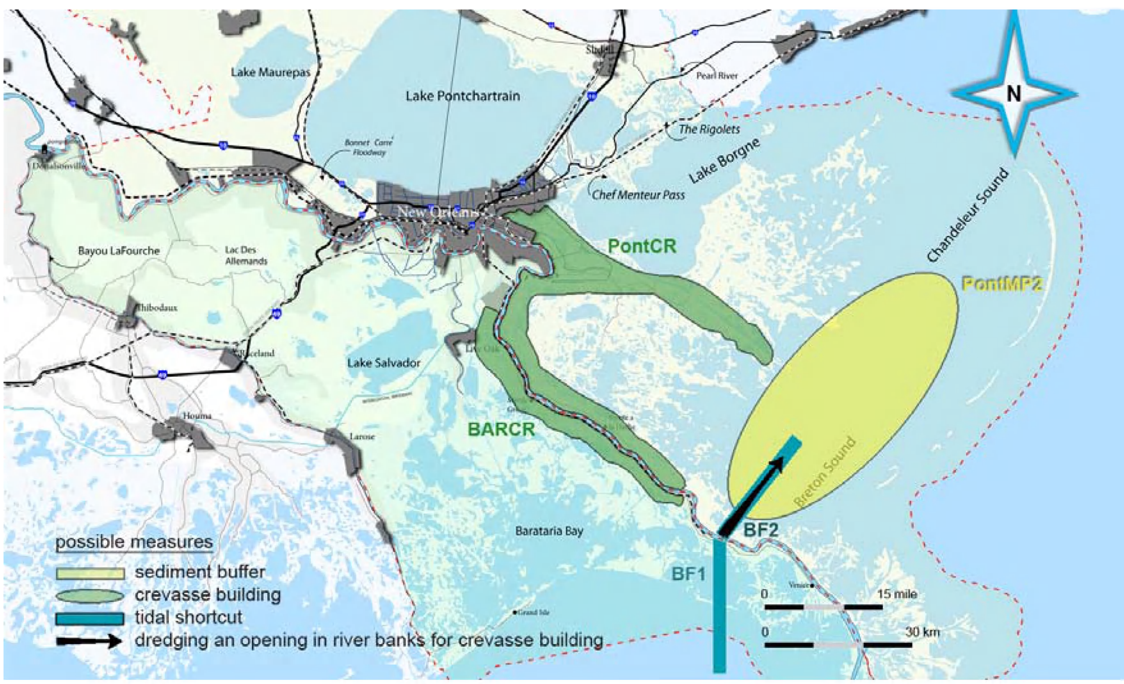

Figure 12 Interventions for long-term natural surge reduction (codes of measures are explained in Appendix H).

In order to compensate for the loss of the Chandeleur barrier islands as marshland protection in the Pontchartrain basin, an alternative option is to create the conditions for the building of beach barriers by natural processes (wave action). Comparable to shoreface nourishment, a sub-tidal plateau of dredged material could be put in place, which will lead to natural barrier buildup by wave action. This plateau could be optimized to provide a large scale habitat for oyster beds. The large amounts of material that is required for such measures calls for the use of high-capacity and high-efficiency dredging equipment. Similar large-scale dredging projects (be it for different purposes) are currently being executed in Dubai and other places involving the handling of up to 1 billion cubic yards of sediments in a few years for a reasonable price.

4.6 Screening of measures

The screening of measures is aimed at making a distinction between so called promising measures and measures that should be considered as not-promising with regards to the project objectives and goals. In essence, a "negative" approach is followed in this step, and the question is addressed whether or not there is a reason why a particular measure should be excluded from further consideration in the next steps of the analysis. The screening of measures is described in Appendix H.

The screening of measures led to the following conclusions (see Appendix H for more details):

1. Large-scale supply of sediment to the wetlands by means of the diversion of river water is unfeasible given the (current) sediment concentrations in the river water. There are two options, and both of them are not feasible: (1) Either very large diversion flows would be diverted to supply sufficient sediment, but this would bring in so much fresh water that salt water marshes would be devastated, or (2) smaller diversions could be selected in order to maintain the outer salt water marshes, but this would not bring sufficient sediment to the wetlands. Large-scale supply of sediment will have to depend on piped sediment supply, and the preferred salinity gradient (and any seasonal patterns in that gradient), ranging from fresh water in the upstream part to salt water near the Gulf, determines the amount of fresh water that can and should be diverted
2. Levee development in Plaquemines Parish following alignments that are comparable to the current levee alignments (long stretches of levee) is not feasible. Given the increase in hurricane surge levels that can be expected before these levees, the crest level of these levees should be substantial, and the reduction of flood risks in the parish is not expected to outweigh the high construction costs. An alternative measure to replace the existing, long and narrow levees with smaller rings of sufficient height around villages and industrial complexes in the parish, and to remove long stretches of levees in rural and empty spaces along the Mississippi River in order to allow hurricane surges to dissipate.
3. Measures that are located at or near the existing barrier islands or the outer rim of the salt water marshes and that are aimed at reducing hurricane surge levels are located too far away from New Orleans to be effective in reducing hurricane surge levels near New Orleans.
4. A storm surge barrier in the Mississippi River is not feasible.
5. The development of large scale openings in the river banks, including the option to dredge new navigation outlets close to the current shoreline of the Pontchartrain and Barataria Basins (effectively "*giving up the Birdfoot*"), will ultimately bring substantial amounts of sediments to the wetlands. The effects of the large-scale freshwater diversion on the salinity levels in the salt water marshes, however, is the reason that such measures are considered as not-promising.

5 Possible strategies

5.1 Strategy development for flood risk reduction and landscape stabilization

The planning process is aimed at finding the best set of measures to reach the overall objectives for flood risk reduction and landscape stabilization, if possible enhancing sustainable occupation and conditions for regional prosperity. To focus their evaluations and recommendations, the project team designed possible strategies that differ significantly in type of flood protection measures and overall effect. These strategies are shaped on what the Dutch team considers to be the most important planning decision for the future of the Mississippi Delta: whether or not to close off the basins with (gated) barriers and change the present (natural) state into managed land and water.

The strategies for both the Pontchartrain and Barataria basins are therefore formulated according to this key planning decision:

Strategies 1, 2 and 3:	Open Estuary System (three alternatives)
Strategy 4:	Semi Open Defense System
Strategy 5:	Closed Defense System

From a strategic point of view, protecting built-up areas against hurricane surges by means of levees and gates is an accepted and effective way of reducing flood risks. A levee system could be enhanced with additional features (additional lines of defense) that contribute to the desired flood protection level. Levees and gates are proven measures that, in principle, could be implemented in a relatively short time period (leaving aside budget and land ownership complications) and would serve as the primary protection.

Landscape stabilization is a secondary but important means to add sustained flood protection in the long term, thus introducing the "multiple lines of defense" principle. The "open" system in the long term relies heavily on the effectiveness of landscape measures that are (probably) complicated and difficult to plan and implement. A "closed" defense system avoids being reliant on landscape stabilization for risk reduction purposes and provides protection for a large area behind it. However, even equipped with gates to pass water, the structure will be a definite morphological and ecological barrier separating the basins into separate fresh and saltwater areas thereby losing (some) of its important intermediate areas. The "Semi-Open Defense System" obviously tries to combine the better of the two extremes, but requires innovative solutions to achieve the goals of risk reduction.

Each strategy consists of (1) a set of measures for a well-protected city and (2) a second set of measures aimed at realizing a sustainable delta. Schematically, the possible strategies are outlined in Figure 13. Which measures are part of which strategy is detailed later in this chapter.

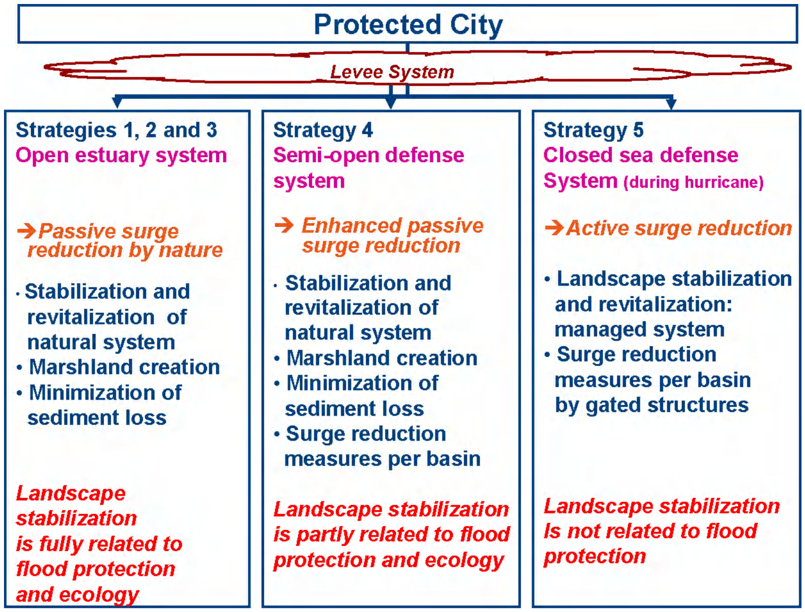

Figure 13 Overview of the main characteristics of possible strategies for flood risk reduction and landscape stabilization

Each of the various strategies will lead to a different requirement in the height of the levees for the city of New Orleans, since the level of surge reduction in the Pontchartrain and Barataria Basins differs between the strategies. For example, with a Closed Defense System the heights of the levees in the city of New Orleans can be lower than with an Open Defense System to realize the same flood protection level. This is due to the additional line of defense that is included in the Closed Defense System.

5.2 Flood protection levels

A preliminary economic optimization for the flood protection level of the Metropolitan area of New Orleans, based on indicative but realistic estimates for input data, evaluated the balance between on the one hand the costs for investment and maintenance of flood protection measures (expressed in Net Present Value) and on the other hand the reduction in the expected value of flood damage. Cost estimates were derived in this project (see Appendix J), while information on damages was obtained from the IPET study.

The optimal protection level for the downtown New Orleans levee ring (see Figure 14) is estimated to be in the order of magnitude of 1/5,000 per year. This outcome proves not very sensitive to changes in damage level and in investment costs. Only when substantially lower damages are assumed, the optimum level of protection is reduced to 1/1,000 per year. The optimal level of protection for the New Orleans East levee ring and the levee ring south of the Mississippi River (see also Figure 14) are 1/1,000 per year.

The protection levels are calculated taking into account the projected further deterioration of the coastal marshes, which may take place over a time span of 50 to 100 years. These levels correspond with protection in the current situation at a roughly ten times higher protection level.

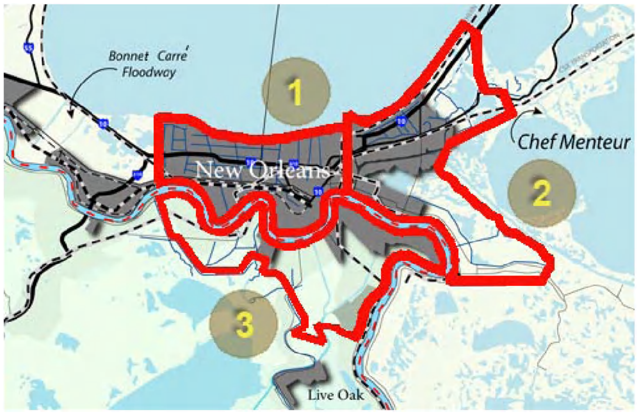

Figure 14 Overview of the three levee rings analyzed in the risk analysis: (1) Northern levee ring 1: central part; (2) Northern levee ring 2: East Orleans and St Bernard; (3) Southern levee ring.

The results indicate that for densely-populated areas, such as the Northern levee rings of New Orleans, it is justifiable to choose a considerably higher protection level than the current level of 1/100 per year. Although the investment costs will be high (billions of dollars), a very large amount of flood damage can be prevented. The investment is expected to be cost-effective.

The outcomes also show that a differentiation in protection levels between areas could be justified based on the economic optimization. Such a differentiation in protection levels between areas also exists for levee rings in the Netherlands. The most valuable levee ring areas in the Netherlands have a protection level of 1/10,000 pear year, while other levee rings have protection levels of 1/4,000, 1/2,000 and 1/1,250 per year.

The result of the economic optimization is in fact technical advice to the decision makers, based on the (direct) economic flood damages. The decision which protection level to select is of course a political choice, which can include more factors than only economic factors, for example other consequences, such as loss of life, or considerations regarding equity between various parts of the city. Although this has not been done in the presented analysis, it is possible to include other damage categories like loss of life in terms of economic damage. This would lead to a higher damage level and thus to a better level of protection. Also, alternative risk criteria could be developed. For example, risk limits could be set that indicate for which probability a certain number of fatalities is considered to be acceptable.

The flood protection levels that resulted from this economic optimization were consequently used to select the protection level that the various strategies should offer. The cost estimate of measures and strategies is based on a 1/10,000 flood protection level.

5.3 Description of the various strategies

This section describes the main components of the five strategies. This description is preceded by an outline of the Autonomous Development, which serves as a comparison base for describing the impact of strategies. After the outline of the Autonomous Development, the various measures for direct protection of built-up areas are described. It is noted that these measures (be it with different levee heights) are part of all the strategies.

Autonomous Development case

The Autonomous Development case is defined as the long-term future situation when no measures are taken in the framework of landscape stabilization. It is assumed, however, that also when no measures are taken to stabilize the landscape, the urban areas will be protected at a level that is justified from an economic point of view, i.e. a flood protection level of 1/1,000 or better. Because it is assumed that in the Autonomous Development no measures are taken to stabilize the landscape, it is expected that further loss of wetland will occur in the future (see Section 2.1).

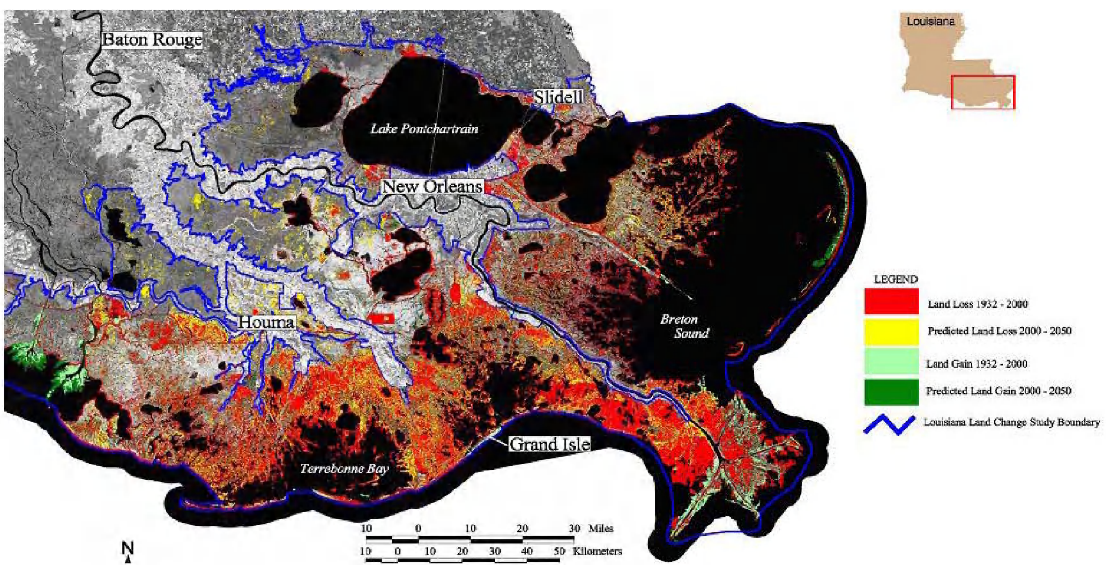

Figure 15 Land loss in Southern Louisiana in the period 1932-2000 (red), and predicted for the period 2000-2050 (yellow). Source: USGS, http://www.nwrc.usgs.gov/upload/landloss8X11.pdf

Without positive human intervention, land loss caused by erosion, subsidence, and other factors will continue for the next 50 years. Between 1990 and 2000 wetland loss was approximately 24 square miles per year (equivalent to one football field lost every 38 minutes). The projected loss over the next 50 years, with current restoration efforts taken into account, is estimated to be approximately 500 square miles (Louisiana, 2007). See Figure 15.

In the Autonomous Development, the wetland buffer that now to a certain extent protects New Orleans from storm surges will gradually disappear. By 2050 the city will be closer to and be more exposed to the Gulf of Mexico. As barrier islands erode and wetland erosion and submergence continue over the next 50 years, it is likely that higher salinity levels will occur at more inland locations.

Protected city

Given the level of protection that is economically justified for the City of New Orleans (Section 5.2), the choice for a strategy for the delta affects the required heights of the levees for a protected city. For example, with a closed defense system the heights of the levees around the city of New Orleans can be lower than with an open defense system.

Each of the five possible strategies includes a set of measures for a better-protected city. For the short-term protection of the city, the main question is to choose between upgrading the existing levees or building new levees (or a combination of these two options). The answer to this question depends on various aspects, including costs, but also depends on future space requirements for the city of New Orleans. The project team is unable to address the latter issue, and therefore suggests where relevant alternative options for the various levee stretches.

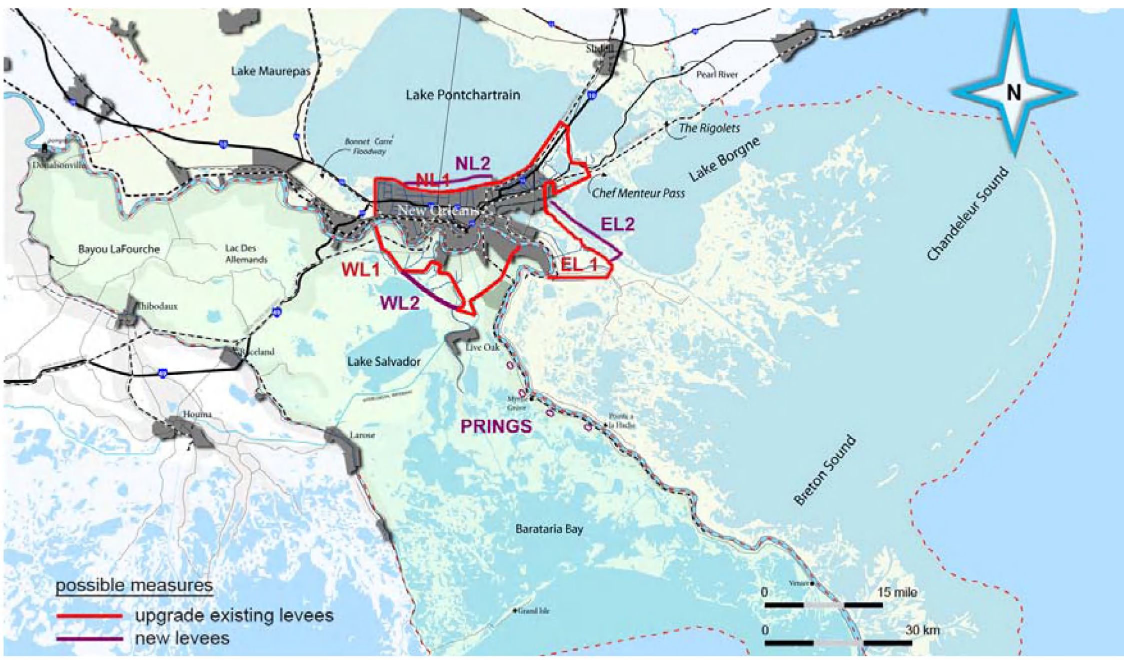

Figure 16 Possible measures in the category "Protected City" for the levee systems protecting New Orleans and part of Plaquemines Parish (codes of measures are explained in Appendix H).

The choice between upgrading an existing levee or constructing a new levee refers to the following levee stretches (see also Figure 14 and Figure 16):

- For the Northern levee ring 1 (central part of the city): either the upgrading of the existing levee (measure NL-1) or the construction of a new levee in Lake Pontchartrain, in front of the existing levee (measure NL-2), including storm surge barriers in these alignments.

- For the Northern levee ring 2 (East Orleans and St. Bernard): the upgrading of the existing levee, including storm surge barriers in that alignment (measure EL-1), or the construction of a new levee (measure EL-2)
- For the Southern levee ring: either the upgrading of the existing levee (measure WL-1) or the construction of a new levee in front of the existing levee (measure WL-2), including storm surge barriers in those alignments.

Strategies 1, 2, and 3: open estuary system

The idea behind the open strategies 1, 2 and 3 is to stabilize the delta wetlands, thereby preventing further degradation, and, depending on the strategy, measures to not only stabilize but also create wetlands. Three possible strategies are distinguished:

1. Open estuaries with only marshland stabilization measures.
2. Open estuaries with marshland stabilization measures and marshland creation measures.
3. Open estuaries with marshland stabilization measures and measures to minimize sediment loss to the Gulf of Mexico (Birdfoot).

Strategy 1: open estuaries with marshland stabilization measures

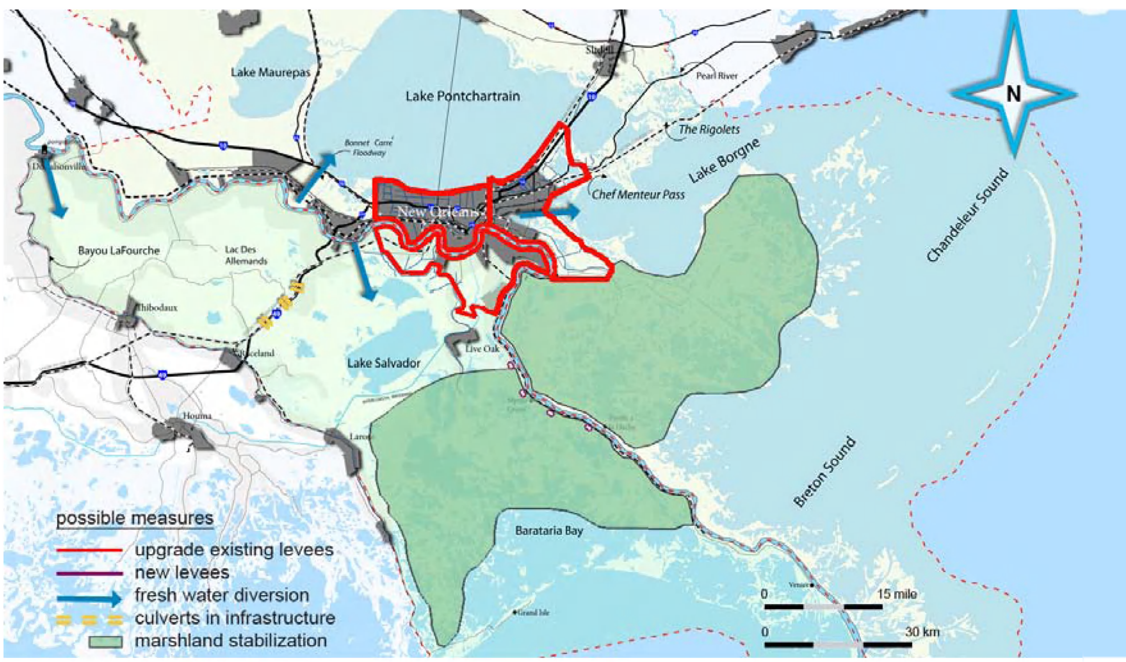

Figure 17 Measures in Strategy 1: Open estuary with only marshland stabilization measures.

Figure 17 illustrates the measures in this strategy. The idea behind this strategy is to increase the Mississippi River water supply with the objective of revitalizing fresh water swamps and bringing sufficient sediment to the wetlands to stabilize existing marshland. The main measures in this strategy are:

- Fresh water diversions to both the Pontchartrain and Barataria basin wetlands to optimize fresh water flow in order to stabilize the salinity gradients and provide nutrients to the marshland.
- The mechanical supply of about 3/8 of an inch (1 cm) of sediment on average per year for a period of 50 years to a wetland area of 700 square miles (1,800 km^2) in the Pontchartrain basin and 600 square miles (1,500 km^2) in the Barataria basin. This is equivalent to some 24 million cubic yards per year for the Pontchartrain basin (18 million m^3/yr), and some 20 million cubic yards per year for the Barataria basin (15 million m^3/yr) This sediment is used for the plugging and filling of existing canals in marshlands and for filling small lakes or separating open water into compartments in order to reduce wind fetch and thereby the erosion process. Figure 18 provides an impression of the different options to implement this. Small cranes and barges bring sediment in the area. As a source of sediment, a large hopper or cutter dredger takes sediment from the bottom of the Mississippi River, the Birdfoot area or elsewhere and creates deposits for the small-scale equipment working in the salt water marshes. On top of the 3/8 of an inch brought in artificially, the accumulation of plant detritus will naturally add another half an inch per year. This work will be continued every year during the forthcoming decades in order to achieve a new natural equilibrium that will sustain itself despite sea level rise.
- The provision of culverts under the Interstate I10 and railway that cross the Barataria basin at regular intervals (about every few miles) to allow the flow of water, sediments and nutrients and the migration of species.

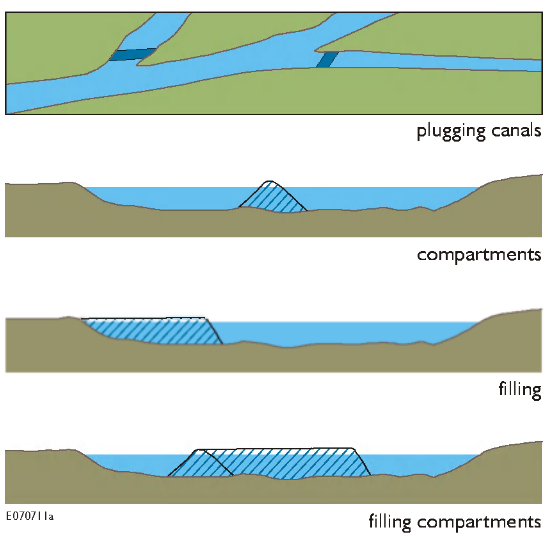

Figure 18 Overview of fetch reduction measures and canal plugging for marshland stabilization

Strategy 2: open estuaries with marshland stabilization and marshland creation measures

Figure 19 illustrates the measures in this strategy. This strategy contains the same measures as Strategy 1 but in addition also marshland creation measures. The marshland creation is aimed at revitalizing and creating fresh water marshland buffers immediately around the city of New Orleans. The aim is a zone up to 6 miles (10 km) wide of fresh water swamps. This buffer will contribute to hurricane surge reduction. Part of this up to 6 miles wide zone and adjacent to the levees around the city, a 1 mile wide (1.6 km) wide cypress swamp zone, is planned to realize wave reduction and hence the wave load on the levees. The total surface area of this buffer zone in the Pontchartrain basin amounts to 135 square miles (350 km^2) and in the Barataria basin 175 square miles (450 km^2). The distribution of sufficient amounts of fresh water, either by gravity canals or pumping, is included in this measure. It is noted that in the past cypress swamps were common around the then-New Orleans.

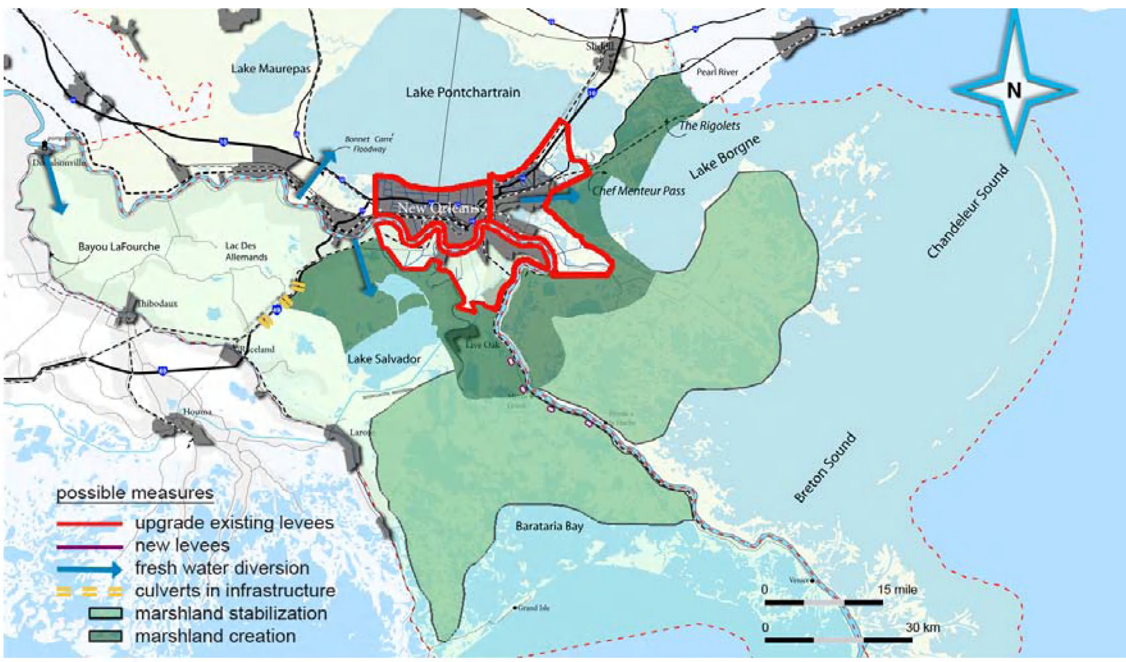

Figure 19 Measures in Strategy 2: Open estuary with marshland stabilization and marshland creation

Cypress swamp creation can be realized in two distinctly different ways (see Figure 20):

1. Sediment fill of confined areas with piped sediment supply.
2. Developing freshwater marshland polders to kick-start the rapid development of vegetation. This can be done by creating a temporary polder with low and simple levees using compartments and lowering the water table by pumping out the water while creating optimum growing conditions.

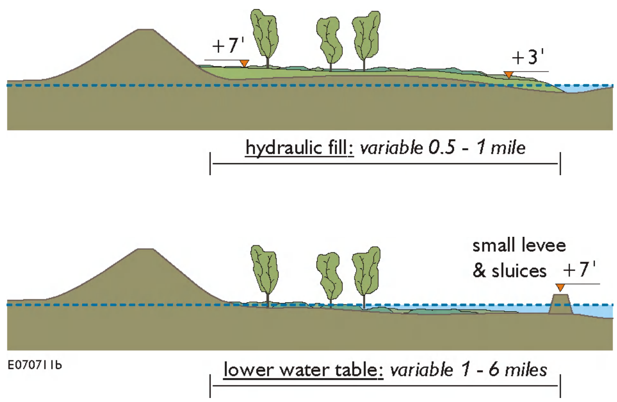

Figure 20 Options for freshwater marshland creation, aimed at a natural growth of 0.5 inch per year; 90% organic material: hydraulic fill method (top figure) and polder principle (bottom figure)

Strategy 3: open estuaries with marshland stabilization measures and measures to minimize sediment loss

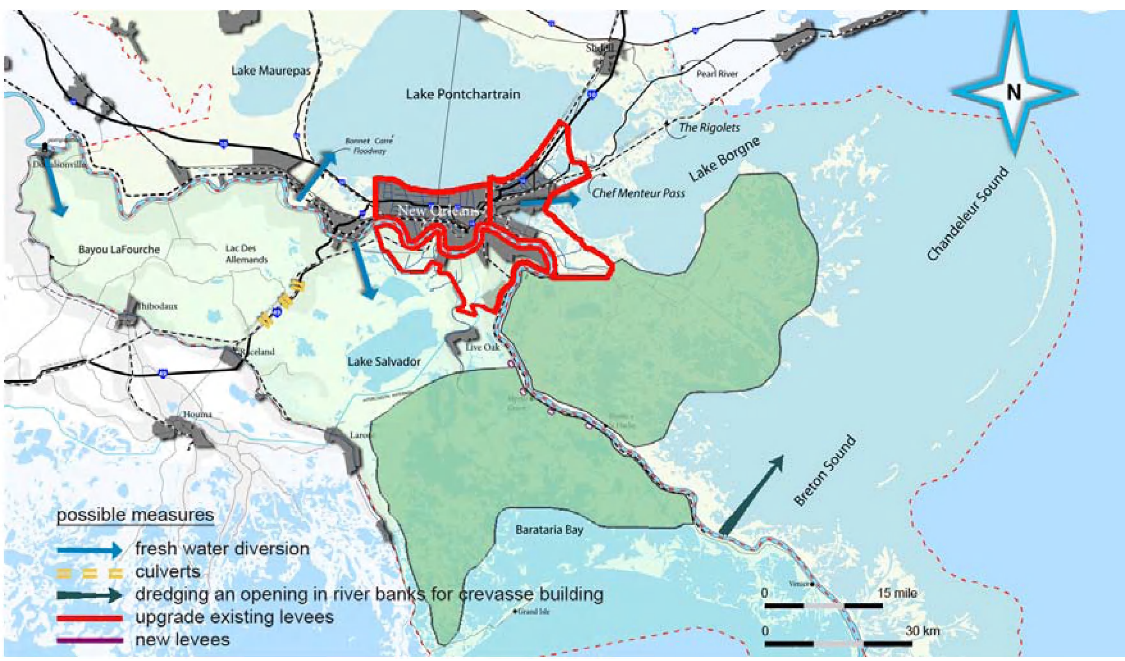

Figure 21 Measures in Strategy 3: Open estuary with focus on marshland stabilization and minimization of sediment loss.

Figure 21 illustrates the measures in this strategy. This strategy contains the same measures as Strategy 1 but in addition it also has measures to minimize the loss of sediments from the delta. The idea is to use the resources of the Mississippi River to rebuild the coast, in contrast to the existing situation in which the river is constrained between levees, and the resources of fresh water, sediments and nutrients are forced to flow into the deep parts of the Gulf of Mexico. Several possible measures were identified to prepare this strategy, but most of them proved not to be promising. Dredging new navigation channels on both sides of the river (Figure 12) or alternatively a 3-mile wide but shallower channel in order to keep the sediments close to the shoreline (in essence "cutting off the Birdfoot") proved not to be an option because the large fresh water flows are expected to devastate the salt water marshes (see also Appendix D). Therefore, this strategy includes a measure based on a comparable idea regarding sediment supply to the delta, namely to create a fairly large opening at the same location (see again Figure 21) towards the Pontchartrain basin.

Strategy 4: semi-open sea defense system

Figure 22 illustrates the measures in Strategy 4. This strategy contains the same measures as Strategy 1 but in addition the semi-open sea defense strategy relies on surge reduction measures in the Pontchartrain Basin and the Barataria Basin. At regular intervals (roughly every few miles) culverts are built in the proposed ridge-levees to allow water, sediment and nutrient exchange. For the Pontchartrain Basin, a surge reduction levee (either in the form of a traditional levee or in the form of a ridge-levee) on the land-bridge separating Lake Pontchartrain and the Gulf along the C90 highway is included in this strategy.

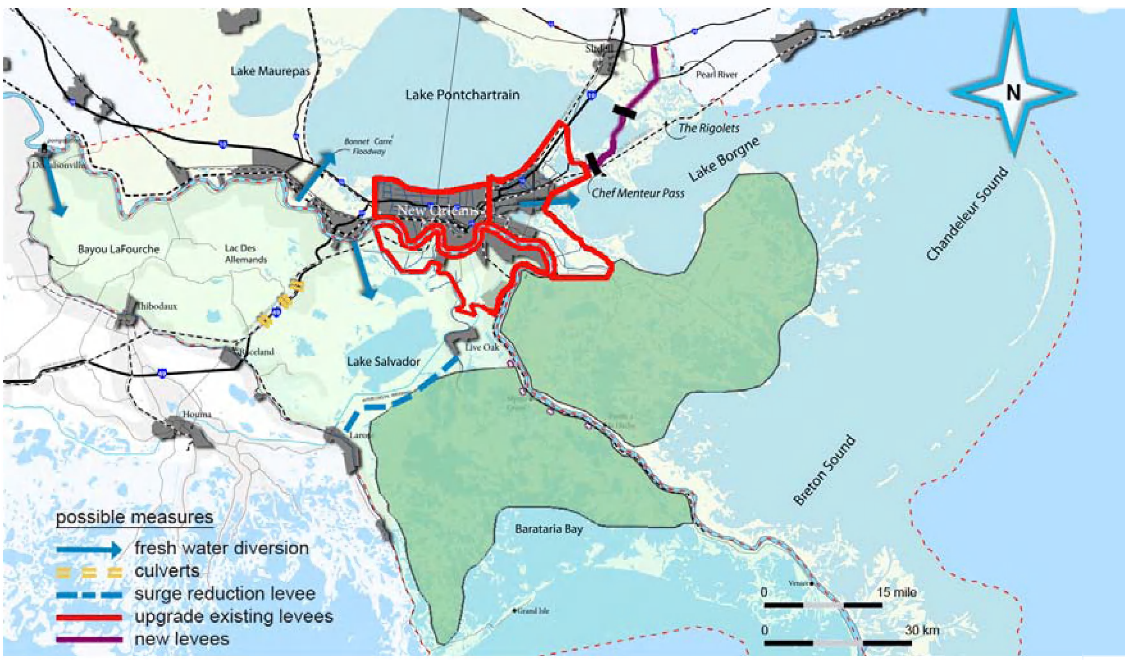

Figure 22 Measures in Strategy 4: Semi-open sea defense system.

Strategy 5: closed sea defense system

Figure 23 illustrates the measures in Strategy 5. This strategy contains the same measures as Strategy 1 but in addition the closed sea defense system contains closed hurricane surge protection measures in both basins. These are levees, located in the Pontchartrain basin on the land-bridge that separates Lake Pontchartrain from the Gulf, and in the Barataria basin along the Gulf Intracoastal Waterway. Where these alignments are crossed by natural channels or important navigation canals, storm surge barriers are provided. At regular intervals (roughly every few miles) culverts are built in the levee to allow water, sediment and nutrient exchange. The gates are closed only during a hurricane event.

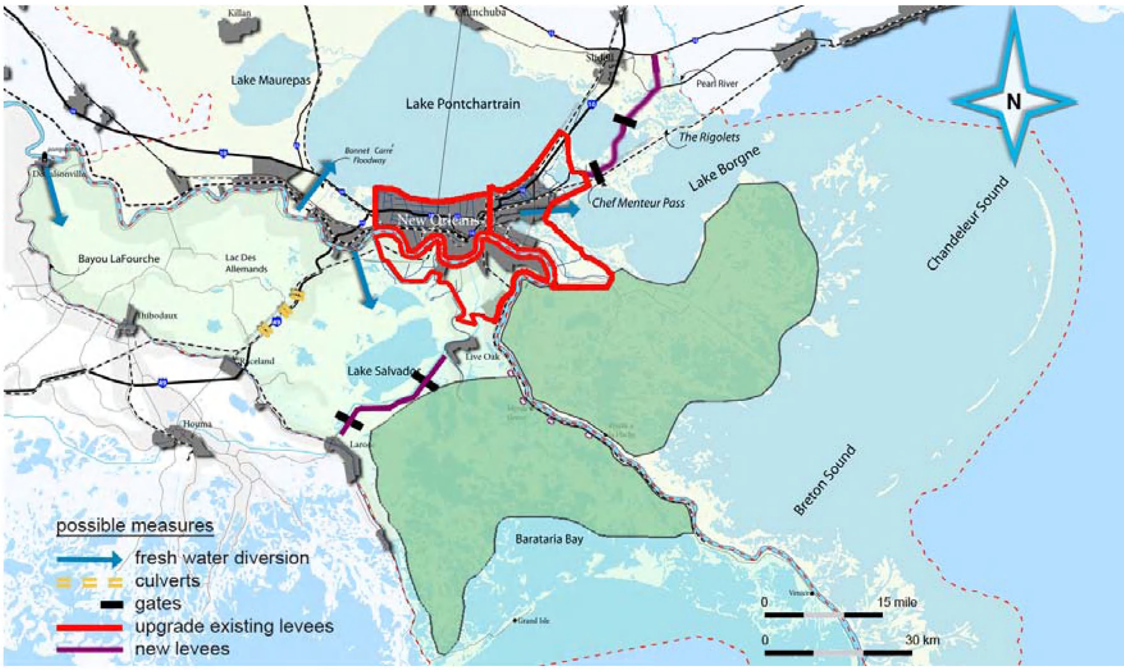

Figure 23 Measures in Strategy 5: Closed sea defense system.

Brief discussion of the characteristics of the possible strategies

Each of the five strategies has at least the following two components: (1) a set of measures (levees and gates) to provide flood protection for the built-up areas at a selected protection level; and (2) a set of measures aimed at marshland stabilization. These components are considered crucial in reaching the goals of LACPR, namely flood risk reduction and landscape stabilization.

The various strategies differ in the amount of marshland creation (in addition to stabilization), and in the provision of additional measures that influence surge levels (additional lines of defense); either by providing surge reduction or by closing off the estuaries.

This opens the way to decide on what the project team considers the key decisions that need to be made:

- whether or not to close off the basins with (gated) barriers and change the present natural state into what is essentially managed land and water;
- whether or not to initiate a large-scale program for marshland creation (in addition to marshland stabilization) at selected locations; and
- whether or not to relocate the Mississippi River mouth and in essence abandon the Mississippi Delta Birdfoot.

Table 1 provides a summary overview of the types of measures that are included in the Autonomous Development case and in the five strategies.

Table 1 Summary overview of types of measures included in the Autonomous Development case and in the five strategies.

Type of measure	**autonomous development**	**strategy**				
		1 open / marshland stabilization	**2 open / marshland creation**	**3 open / focus on sediment loss**	**4 semi-open system**	**5 closed system**
measures for direct protection (levees and gates)	**X**	**X**	**X**	**X**	**X**	**X**
measures that increase present natural surge reduction		**X**	**X**	**X**	**X**	**X**
long-term natural surge reduction measures				**X**		
basin surge reduction measures					**X**	
closed basin surge protection measures						**X**

6 Impact assessment

This section provides an overview of the expected impact of the five strategies on the five objectives and their related sub-goals, described in Section 3.3.

Increase in flood protection level

All strategies contain measures for a protected city, so all strategies will result in an increase in flood protection level of the urban areas, especially the city of New Orleans, from the existing protection level of about 1/100 per year to a level of 1/1,000 per year or better.

When compared to Strategy 1, the other strategies include additional measures that either in the short term or the long term will have a positive impact on flood protection levels and will result in the creation or strengthening of other lines of defense when compared to only the levee system. It is noted, however, that the effect of these measures on surge levels and waves is taken into account when determining the height of the levee system. In other words: the reasoning here is that these additional measures do not provide *additional* flood protection. Instead, the effect of these additional measures on flood protection is already taken into account. Therefore all strategies have a score [++] in Table 2.

In the rural areas the picture is different. In the Autonomous Development the flood protection level will further decrease due to subsidence and loss of wetlands, hence the score [–] in Table 2 for rural areas. The Strategies 1 thru 5 generally result in an increase in flood protection in rural areas. In the open system with marshland stabilization there will be an increase in safety in the long term: depending on the results of marshland stabilization, the protection level will gradually increase year by year (score [+] in Table 2). In Strategy 4 there will be an increase in flood protection in the rural areas behind the surge reduction levees. For the closed system an increase in flood protection for rural areas is also to be expected in the region behind the gated levees. Therefore, both the semi-open system and the closed system score [+/++] for rural areas.

Table 2 Impact assessment for possible strategies: increase in flood protection level (score ++: meets goal completely; score +: on the right track; score 0: neutral; score -: moves away from goal; and --: does not meet goal)

	strategy	**increase in flood protection**	
		urban areas	**rural areas**
	Autonomous development	++	--
1	Open: marshland stabilization	++	+
2	Open: marshland creation	++	+ / ++
3	Open: focus on sediment loss	++	+
4	Semi-open system	++	+ / ++
5	Closed system	++	+ / ++

Strategy 3 and Strategy 1 score similarly on the increase in flood protection in rural areas: both [+]. Only in the very long term, the additional measures in Strategy 3 (opening of the river banks) is expected to contribute to flood protection in rural areas in the Pontchartrain Basin. The creation of freshwater swamps in Strategy 2 motivate a score [+/++] on the increase in flood protection in rural areas around New Orleans (see Table 2)

More sustainable delta

For the objective of achieving a more sustainable delta, the sub-goals are improvements of the sediment balance, the salinity gradient and functioning of the ecosystem. In the open system there will be a slight improvement in the sediment balance: over 50 years a modest amount of extra sediment is brought to both basins yearly. In the semi-open and closed system the improvement of the sediment balance is the same as in the open system. The Autonomous Development will lead to, firstly, a further decline in the sediment balance due to subsidence, secondly, erosion due to wave impact, and thirdly, the continued lack of riverine sediments input, hence a score [- -] in Table 3. The opening of bank of the Mississippi River to allow crevassing in Strategy 3 motivates a score [+/++] in Table 3.

In the Open, Semi-open and Closed system the salinity gradient is improved due to fresh water diversions. In order to get a diversity of fresh water swamps, brackish and salt water marshes the amount of extra input of fresh water is, however, limited. The salinity gradient is controlled by the fresh water diversions. All strategies except Strategy 3 received a score [+] in Table 3. The large diversion of fresh water in Strategy 3 motivate a score [-/+] on this point. The opening of the river banks in Strategy 3 will bring extra sediment and much fresh water in the Pontchartrain coastal area. This fresh water will destabilize the salinity gradient and also cause an ecological shock to the salt water marshes. There is a chance that these salt water marshes will change into lakes with additional negative effect on storm surge protection.

Given the scores of the strategies regarding the sediment balance and salinity gradient, there is no significant difference between the open system, semi-open and closed system strategies.

Louisiana's coastal wetlands are essential for numerous species of fish and wildlife, food production, habitat for fish and wildlife reproduction and nursery activities, and overall support of the food chain. See (DNR, 1998) and Appendix C. Important factors to judge the improvement of the ecosystem functioning are habitat stability, habitat diversity and total area of habitats. After stabilization, natural growth of the marshes should be able to cope with natural subsidence. Hence, in all strategies with marshland stabilization measures the functioning of the ecosystem will improve. In the open Strategy 2 with marshland creation measures a coherent zone of fresh marshes close to New Orleans will give an extra impulse to the ecosystem. Therefore, Strategy 2 scores [++] on ecosystem functioning and Strategy 1 scores [+/++]. In the semi-open system there will be some loss of marshland as a result of constructing surge reduction ridge-levees. On the other hand, on the levees new habitats will develop, so there will also be a gain of new habitats. In the closed system there is also a loss of marshland as a result of the construction of the gated levees. The semi-open and closed systems score [-/+] in Table 3. The score for Strategy 3 on ecosystem functioning is negatively influenced by the expected salinity shock that is expected to result from bringing large amounts of fresh water to the coastal area in the Pontchartrain Basin.

In the Autonomous Development with continuous subsidence and loss of wetlands a new ecosystem will develop and the next stage in the ecosystem cycle will begin with drastic consequences for human activities. The appreciation of the ecosystem will affect whether this will be seen as a positive or negative development, but the project team expects that the dramatic additional loss of wetlands will be valued as negative.

Table 3 Impact assessment of possible strategies: sustainability aspects (score ++: meets goal completely; score +: on the right track; score 0: neutral; score -: moves away from goal; and --: does not meet goal)

	Strategy	improvement in sediment balance	improvement of salinity gradient	improvement ecosystem functioning
	Autonomous development	--	--	--
1	Open: marshland stabilization	+	+	+ / ++
2	Open: marshland creation	+	+	++
3	Open: focus on sediment loss	+/++	- / +	- / +
4	Semi-open system	+	+	- / +
5	Closed system	+	+	- / +

Retain and develop socio-economic values

The economic well-being of Louisiana's coastal communities and the competitiveness of the coastal industries are important not only to the State but also to national growth and prosperity. Millions of tons of cargo are shipped annually to and from foreign or U.S. locations. Important economic activities are offshore oil and natural gas production and all related service industries, fisheries industry particularly shrimp and oysters, petrochemical processing and manufacturing, industries related to navigation, agriculture (rice, sugar cane, soybeans and cattle), aquaculture especially the pond aquaculture of crawfish, extensive tourism and recreational activities (DNR, 1998). All these important values (see also section 2.1) will be threatened in the Autonomous Development due to subsidence, wetland loss and salt water intrusion. As protective marshes continue to disappear, the maintenance costs for local drainage and flood control infrastructure will continue to increase. It is assumed that the Autonomous Development does not severely impact navigation, hence a score [0] in Table 4 regarding navigation. Most of the other economic activities depend on the delta ecosystem. With continued deterioration of the wetlands in the Autonomous Development, the impact on other economic activities is scored as [- -].

Each of the Strategies 1 thru 5 contains measures to stabilize the landscape. Wetland restoration is expected to lead to favorable conditions for the other economic activities, and therefore all strategies received a score [++] on this aspect. In the open system there will be ample opportunities for oysters and other kinds of fisheries: an optimal transition from fresh water swamps to brackish and salt water marshes will be maintained or restored. This will also be the case in the semi-open and closed system. With respect to navigation activities and other economic activities there is no difference between the strategies, except Strategy 3, in which the river discharge is slightly influenced by the total diverted flow, which in turn may lead to increased sedimentation in the navigation channel, calling for an increased maintenance dredging effort. All in all, each strategy was scored neutral on impact on navigation.

Traditionally, thousands of people in Louisiana have depended on shrimp, oysters, crabs and commercial finfish harvesting and processing. The continued deterioration of coastal wetlands is a great concern. Habitat loss and major chances in the balance of fresh water and salt water can led to the loss of fisheries sensitive to this balance, significantly disrupting Louisiana's vitally important seafood production sector. Also agriculture experiences crop losses caused by salt water intrusion and concerns about continued supply of fresh water. Coastal Louisiana communities share a basic connection to their surrounding environments; their cultures and economies are part land-based and part water-based and most have become similarly threatened by the conversion of land to water. The human settlement of the region is a history of utilizing opportunities and resisting constraints. It is very likely that the future loss of marsh will tip the balance toward the constraints in all of these communities (DNR, 1998).

The Autonomous Development (subsidence, loss of wetlands) will lead to a significant loss of historical, social and cultural values (score [- -] in Table 4). At many places where marshland stabilization is successful, social and cultural values can be restored. This implies a [+] score for Strategies 1 and 3 on impact on historical, social and cultural values. In Strategy 2, an open system with marshland creation, the historic presence of fresh water cypress swamps close to the city will be restored and this will contribute to retaining historical values, hence a score [++]. In Strategies 4 and 5 some new levees will be built in the marshland area, which could lead to a possible loss of historical (and maybe also some social and cultural) values.

Table 4 Impact assessment of possible strategies: socio-economic values (score ++: meets goal completely; score +: on the right track; score 0: neutral; score -: moves away from goal; and --: does not meet goal)

	Strategy	**retain and develop**		**retain**
		navigation activities	**other economic activities**	**historical, social and cultural values**
	Autonomous development	0	--	--
1	Open: marshland stabilization	0	++	+
2	Open: marshland creation	0	++	+ / ++
3	Open: focus on sediment loss	0	++	+
4	Semi-open system	0	++	+ / -
5	Closed system	0	++	+ / -

High feasibility of measures

The development of new levees around New Orleans will take approximately 15 years in each of the strategies and in the Autonomous Development. Marshland stabilization will take several decades, if not 50 years. Marshland creation will also take several decades (a period of 25 years is estimated). The opening of the river bank in Strategy 3 will lead to crevasse building, estimated to take also 25 years (see Table 5)

The construction of new levees is less flexible when compared to marshland stabilization and creation measures. This motivates for Strategies 1 and 2 a score [++] on flexibility and for Strategies 4 and 5 a score [+] in Table 5. Opening the river bank in Strategy 3 leads to some inflexibility, although this measure could relatively easily be changed or undone if needed, leading to a score [+] on flexibility for this strategy.

The gated levees are based on proven technology (score [++] on technical feasibility for Strategy 5), but this is not the case for surge reduction ridge-levees (score [+] on technical feasibility for Strategy 4). Also marshland stabilization and marshland creation is marked by many uncertainties. This why this report strongly suggests to start pilot projects, in order to gain knowledge and experience.

Public support for measures (an element of the set of criteria, see Appendix A) is obviously also an important issue, but the project team is not sufficiently familiar with the local situation to derive a score on this evaluation criterion.

Table 5 Impact assessment of possible strategies: time required for implementation, feasibility and flexibility (score ++: meets goal completely; score +: on the right track; score 0: neutral; score -: moves away from goal; and --: does not meet goal)

	Strategy	**time for implementation of**			**technical feasibility**	**high flexibility**
		levees	**wetland stabilization**	**other measures**		
	Autonomous development	15 years	n.a.	not applicable	++	+
1	Open: marshland stabilization	15 years	50 years	not applicable	+	++
2	Open: marshland creation	15 years	50 years	25 years	+	++
3	Open: focus on sediment loss	15 years	50 years	25 years	+	+
4	Semi-open system	15 years	50 years	not applicable	++	+
5	Closed system	15 years	50 years	not applicable	++	+

Costs of measures

The total costs of the strategies (expressed as Net Present Value, see Table 6) range from $18 to $23 billion. In the Autonomous Development the maintenance effort is limited to maintenance of levees and structures. Despite this limitation, it will be a considerable effort. The marshland stabilization measures over 50 years (in all the strategies) require a large effort. In the semi-open and closed systems the maintenance efforts will be even slightly higher: in addition to the efforts for landscape management also maintenance of the surge reduction levees (semi-open) and for the gated levees (closed system) is required. All in all, the maintenance effort for all strategies is summarized as a large effort .(see Table 6)

Table 6 Impact assessment of possible strategies: costs and maintenance effort.

	Strategy	**investment costs (Net Present Value)**	**maintenance effort**
	Autonomous development	$16.6 billion	considerable effort
1	Open: marshland stabilization	$19.5 billion	large effort
2	Open: marshland creation	$18.1 billion	large effort
3	Open: focus on sediment loss	$19.5 billion	large effort
4	Semi-open system	$20.8 billion	large effort
5	Closed system	$23.3 billion	large effort

Overview of the impact of the various strategies

The previous sections of this chapter described the impact of the five strategies on the five main objectives for each of the sub-goals. This section gives an overview of the impacts on the five main objectives of the project.

Regarding the increase in flood protection all strategies lead to a substantial increase in flood protection to a level of 1/1,000 or better, as illustrated by Table 7. This is also the case in the Autonomous Development, because it is assumed that also in that case levees and gates around the built-up areas will be developed.

From the viewpoint of social-economic values there is no difference between Strategies 1 thru 5 in impacts on and other socio-economic activities. Differences between the strategies regarding impact on historical, social and cultural values determine the differences in Table 7 regarding impact on socio-economic values.

The technical feasibility of measures the semi-open and closed defense system is high. Given uncertainties in how to best implement marshland stabilization and creation, the open defense strategies score less favorably in this respect. This further underlines the need for pilot projects related to wetland restoration. See Table 7.

From the viewpoint of costs there is only a relatively small difference between strategy 1 to 5: the total costs (expressed as Net Present Value) range from $18 to $23 billion.

Table 7 Overview impact assessment of the various possible strategies (score ++: meets goal completely; score +: on the right track; score 0: neutral; score -: moves away from goal; and --: does not meet goal)

	Strategy	protec-tion	sustainable delta	socio-econo-mic values	feasibility	total costs
	Autonomous development	--	--	--	++	$16.6 billion
1	Open: marshland stabilization	+	+ / ++	+	+	$19.5 billion
2	Open: marshland creation	++	++	++	+	$18.1 billion
3	Open: focus on sediment loss	+	-	+	+	$19.5 billion
4	Semi-open system	++	+	+ / -	++	$20.8 billion
5	Closed system	++	+	+ / -	++	$23.3 billion

7 Preferred strategy

7.1 Introduction

In the preceding sections of this report, five possible strategies were defined and evaluated. The results form the basis for the selection of the strategy that is preferred by the project team.

The Preferred Strategy is entitled "*Protected City, and Closed Soft Coast*", and this strategy is constructed by combining the best ranking measures from the original set of five possible strategies. With the Preferred Strategy, the overall study objective of long-term flood risk reduction and landscape stabilization in the Southeastern part of coastal Louisiana, on the basis of the *Protected City Sustainable System* concept, was achieved in the optimum way. This chapter describes and discusses the Preferred Strategy.

In developing this Preferred Strategy, the project team of course gave ample attention to the flood risk reduction strategy that was chosen in the Netherlands after the 1953 disaster. A high level of flood protection was achieved by shortening the exposed coastline by closing off tidal inlets and estuaries with large-scale flood defense infrastructure such as dams and storm surge barriers. Half a century later, this concept still holds. However, in the Netherlands the shortening and "hardening" of the coast had considerable ecological and economic impact.

Based on the lessons learned in the Netherlands, the concept of a "*Closed Soft Coast*" is preferred for coastal Louisiana, implying maximum shortening of the coastal defense, while at the same time maintaining the unhampered flow of water, sediment and nutrients, utilizing and nurturing the potential of nature to add to coastal flood protection and produce a sustainable ecosystem and landscape. As far as this study is concerned, *Closed Soft Coast* is in fact a mix of the Open System and Closed System Strategies.

7.2 Elements of the Preferred Strategy

The risk analysis that was carried out in the framework of the project led to the conclusion that a protection level of 1/1,000 per year or better for the Metropolitan area of New Orleans is economically justified. It is this level of protection that the Preferred Strategy will provide.

The Preferred Strategy is a combination of effectiveness at a reasonable cost, aiming at a synthesis of flood reduction and landscape stabilization. It is considered the best from an overall perspective of flood risk reduction and landscape stabilization.

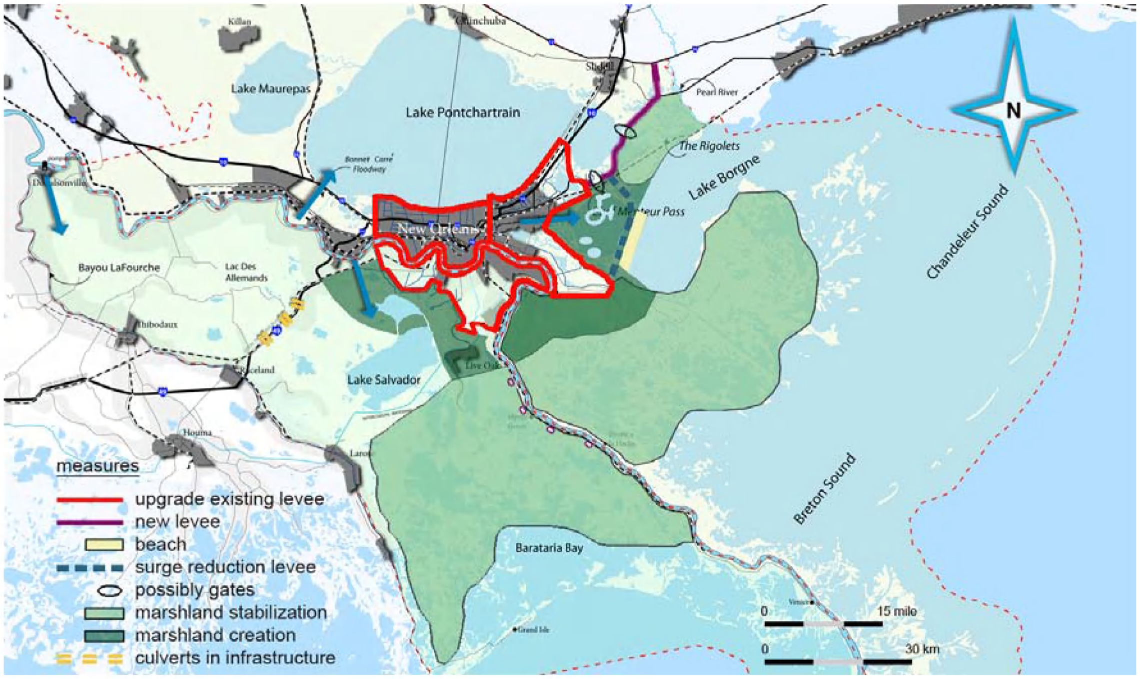

Figure 24 Measures in the Preferred Strategy.

The Preferred Strategy consists of the following structural measures, which are illustrated by Figure 24:

Levees around the metropolitan area of New Orleans. These levees consist of three robust levee rings (see Figure 14), including storm surge barriers in the various navigation and drainage canals:

- Ring 1, the central part of the city with a protection level of 1/5,000 per year or better;
- Ring 2 and 3, the Eastern and Southern parts of the city, with a protection level of 1/1,000 per year or better.

Possibly closing off Lake Pontchartrain with storm surge barriers. In addition to the levee rings for the city, at the land-bridge between Lake Pontchartrain and the Gulf a relatively low levee and barrier system will prevent the inflow of large volumes of water in the case of a hurricane surge. This measure will also provide protection to Slidell and other areas bordering the lake. Under normal circumstances, the gates in the Rigolets and Chef Menteur passes are open. They will only be closed during an extreme hurricane event. An alternative for closing off Lake Pontchartrain in case of storm surges is to (further) raise the levees that protect New Orleans on the Lake Pontchartrain side. The outcome of the current reconnaissance level study does not allow for a clear preference on whether or not to close off Lake Pontchartrain in case of storm surges. Further study of this issue is strongly suggested.

Open Barataria Basin. In the Barataria area, no levees or barriers are proposed. Wetland stabilization will provide surge reduction. Culverts under the Interstate I10 and railway that cross the Barataria basin at regular intervals (about every few miles, to reinstate all former connections) will allow the flow of water, sediments and nutrients and the migration of species.

Salt marsh stabilization. Introducing large-scale salt marsh restoration, 750 square miles (1,900 km^2) in the Pontchartrain Basin and 600 square miles (1,500 km^2) in the Barataria Basin will stabilize the landscape, and surge and wave reduction will result. As these measures are planned to take as much as 50 years, however, no immediate effects on surge and wave reduction have been taken into account when determining the height of the levee system around the city. In fact, salt marsh restoration aims to prevent further degradation of the natural protection system. These restoration measures in fact will reduce future costs for levee and barrier upgrading.

Fresh water marshes (cypress swamp) revitalization and creation are planned in a wide zone (between 1 and 6 miles wide) immediately around the levee rings in the New Orleans area, totaling 140 square miles (about 350 km^2). This measure serves multiple objectives: not only landscape stabilization and development but also surge reduction and in particular a reduction of the wave loads on the levee system.

Converting part of Lake Borgne into fresh water marshland. Separating part of Lake Borgne from the Gulf by means of a ridge-levee, partly filling in Lake Borgne, and the provision of sufficient fresh water to create a fresh water cypress swamp in Lake Borgne is quite effective to reduce surges and waves for the Eastern part of the city. Furthermore, it completes the circle of fresh water cypress swamps around the city of New Orleans. Lake Pontchartrain will be flushed with Mississippi River water more frequently to improve the quality of the marshlands that border the lake and to limit salt water intrusion to the area near the Chef Menteur and Rigolets passes.

The Net Present Value of the total costs of the Preferred Strategy is estimated at $20 billion. The various cost components are listed in Table 8. That table splits the total costs over the various (groups of) measures included in the Preferred Strategy. The tables also specifies the number of culverts and diversion, and the number of square miles in the various marshland stabilization and marshland creation measures.

Table 8 also present a split of the total costs over on the one hand one-time investments for structures and wetland creation and on the other hand annual costs for wetland stabilization. This assumes that all structures and wetland creation can indeed be considered as one-time investments, and annual maintenance costs for these measures are ignored. Marshland stabilization it considered as an effort that is maintained for 50 years with an annual budget. This is of course a rough distinction between one-time investments and annual costs, but is considered acceptable for illustration purposes.

It is stressed that a long-term maintenance strategy is required to ensure that the objectives and goals of the Preferred Strategy are maintained over time. In short, a successful infrastructure includes a successful maintenance program.

Table 8 Costs of measures for the **Preferred Strategy** (flood protection level 1 in 1,000) with a distinction between one-time investments for structures and wetland creation, and annual costs for wetland stabilization.

	Cost in million $	***Cost in million €***	**remarks**
Protected City measures	$9,585	*€ 7,100*	
Ring levees Plaquemines	$1,485	*€ 1,100*	
Culverts in existing Barataria interstate + railway	$68	*€ 50*	5 culverts
Fresh Water Diversions	$203	*€ 150*	3 diversions
Marshland Stabilization Pontchartrain	$3,591	*€ 2,660*	1,900 km^2
Marshland Stabilization Barataria	$2,835	*€ 2,100*	1,500 km^2
Marshland Creation Pontchartrain	$810	*€ 600*	200 km^2
Marshland Creation Baratari	$608	*€ 450*	150 km^2
Marshland Creation Landbridge	$675	*€500*	
Total (Net Present Value)	**$19,860**	***€ 14,710***	
One-time investments for structures and wetland creation	$13,434	*€ 9,950*	
Annual cost for wetland stabilization	$321	*€ 238*	

It can be expected that societal preferences will change over time. This calls for the provision of as much flexibility as possible. In practical terms, this implies avoiding certain types of "hardened" structures (for example concrete T-walls) as much as possible because such structures are difficult to alter in the future.

Furthermore, solving a series of organizational issues is of critical importance for success. These include the need for effective institutions, effective laws and regulations, and possibly a cost recovery mechanism to fund maintenance work.

Finally, it is well understood how important the continued involvement and support of the general public is for the success of the strategy. To ensure such support, a continued effort of involving the public in the strategy development and implementation is of crucial importance.

7.3 Discussion of the Preferred Strategy

The various structures that are included in the Preferred Strategy are all based on proven technology. Considerably less is known about the most efficient way to stabilize the landscape or create marshland. With this in mind, a series of pilot projects, to be carried out in the short term, has been designed to increase knowledge and gain experience especially regarding wetland restoration.

The benefit-cost analysis which led to the conclusion that a protection level of 1/1,000 per year or better for the metropolitan area of New Orleans is economically justified is based on the flood damage information provided by the IPET study, and cost estimates derived in the current project. It is noted that these cost estimates are to be considered as conservative, that is to say, that these estimates are on the high side. With lower costs, the protection level would further increase.

This high protection level provides the additional benefit that the city can serve as an evacuation destination in the case that another hurricane will hit the area. Obviously, evacuation to higher grounds further away from the city is to be preferred, but for individuals that cannot be evacuated in time, the high level of protection that the city offers would allow the use of the city as an alternative evacuation destination.

In addition to the levee rings for the city, at the land-bridge between Lake Pontchartrain and the Gulf a relatively low levee and barrier system will prevent the inflow of large volumes of water in the case of a hurricane surge. This measure will also provide protection to Slidell and other areas bordering the lake. However, such barrier system may at the same time increase flood risks along the coast of the state of Mississippi due to higher surge levels (with closed gates, water that is prevented to flow into Lake Pontchartrain may lead to higher surge levels in that area). Under normal circumstances, the gates in the Rigolets and Chef Menteur passes are open. They will only be closed during an extreme hurricane event. An alternative for closing off Lake Pontchartrain in case of storm surges is to (further) raise the levees that protect New Orleans on the Lake Pontchartrain side. The cost estimates for these two alternatives suggest that raising the levees is considerably cheaper than building barriers. However, the cost estimate for raising the levees may not properly reflect the actual costs of raising the levees in the lakefront area, in which land-use at several locations is intensive on both sides of the existing levee. A more detailed cost estimate for raising the levees is required, but this is outside the scope of the current project. The outcome of the current reconnaissance level study does not allow for a clear preference on whether or not to close off Lake Pontchartrain in case of storm surges. Further study of this issue is strongly suggested.

For marshland stabilization, it is critical to restore and stabilize the flooding cycles and salinity gradients of all existing marshes in both the Barataria Basin and the Pontchartrain Basin. This can be realized by regulating the fresh water discharge from various optimally located river diversions. Impact of existing infrastructure, which is blocking the natural flow of water (levees, highways, railroads), will be mitigated by providing a series of culverts in that infrastructure. Channels that destabilize marshes by influencing salinity fluctuations or flooding and that act as conduits of storm surge will be plugged step by step during decades to come in an area of more than 1,000 square miles.

It is noted that the sediment availability from freshwater diversions is too small to restore lost marshes within a reasonable time frame. Therefore, large-scale long-term piped sediment transport is required to gradually compensate the lost marshland area, in combination with innovative measures such as the creation of marshland polders and "*kwelderization*" (see Chapter 10 on recommended pilot projects). It is expected that after a certain period, recreated, continuous and vital marshlands that have again reached optimal vertical elevation, should be able to maintain themselves naturally assuming a long term background natural subsidence rate of about half an inch per year.

Due to the salinity shocks expected to occur with large scale crevassing, and considering the tendency of marshland transition to produce open water areas, large scale crevassing in the Barataria and Pontchartrain basins is not recommended.

By restoring a belt of fresh water marshes and stabilizing saltwater and brackish marshes, cultural values of the landscape will be safeguarded or restored. Production of oysters will not deteriorate and oyster growing areas will stop migrating further inland. In essence, the infamous "oyster squeeze" will be undone gradually. Production of species that spawn and feed in marshlands will be maintained. Nutrients that are fixed in vitalized and increased marshland areas will enhance the carrying capacity and reduce the impact on the ecosystem and commercial resources further offshore. Large amounts of carbon dioxide will be fixed in marshland bottom by peat formation and help compensate global warming. Last but not least, the storm surge reducing overtopping ridge-levee planned to protect the Lake Borgne marshlands will be stabilized with a sandy beach on the seaward side, providing a high quality recreation site close to the city centre.

The planned activities to create a well-protected city are based on proven technology and can be technically realized within a time frame of 10 to 20 years. The revitalization and creation of freshwater marshlands will result in additional protection within the same period, due to the strong reducing effect of dense bushes and even small trees on storm surge and waves. Stabilization of saline and brackish marshlands, however, will take decades. The way to realize this is to carry out a continuous program of stabilization works to span about 50 years. The creation and stabilization programs will be flexible and will prioritize the stabilization of the most vulnerable areas and will start to produce benefits directly after the start of the program. Roughly about half an inch of sediment per year will be added to the marshland areas. Pilot projects will help to provide information on the most effective and feasible technical solutions and will provide input to adaptive marshland management strategies. The plan to create a marsh land in Lake Borgne while protecting it with a ridge-levee and beach will need careful planning, but will be very visible for the general public and therefore could create high public support for the concepts and measures of this strategy.

If the Preferred Strategy is implemented, it should be expected that a future hurricane that hits the area will damage ridge-levees and the wetlands, which are both elements of the (integrated) flood protection system. Such damage will reduce the effectiveness of the ridge-levees and marshes in reducing a next hurricane surge. After a hurricane, time will be needed to repair the system. During that repair period, the flood risk will temporarily be higher. On the other hand, it is noted that the probability of another hurricane hitting the same area during the repair period is relatively small, assuming that the repair period does not span many years. It was not possible to address in the framework of the current project this increased risk during the repair period, but it might be significant. This issue requires clarification before a decision can be made to what extent the flood protection of New Orleans can depend on the surge reduction effect of ridge-levees and marshes.

8 Management and Maintenance

Management and maintenance is essential for the performance of any coastal restoration and/or hurricane protection scheme now and in the future. Obviously, existing flood protection schemes must be maintained to continue functioning as planned. Improvement of structures or the entire scheme is needed if they show weaknesses or if they do not meet the (modified) functional requirements. Given the changing conditions, management and maintenance require monitoring. This includes monitoring of the natural conditions, but also monitoring of the surroundings or society is necessary. Based on the Dutch experiences, management and maintenance is described in this chapter for the Preferred Strategy.

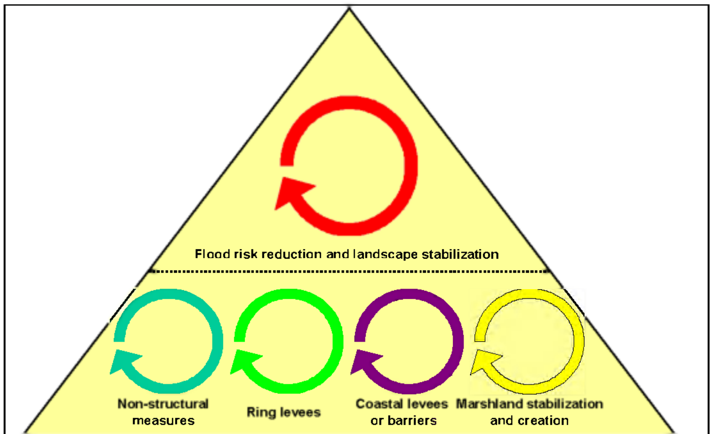

Figure 25 Strategic and tactical planning

Strategic and tactical goals of the flood protection scheme need to be interlinked and evaluated regularly. The Dutch concept of safety assessment (every 5 years) and risk assessment (every 25 to 50 years) can be applied to the Louisiana situation. Table 9 shows the current strategic and tactical goals for both the Dutch situation and for the Preferred Strategy for coastal Louisiana. Topics printed in *italic* are not discussed in the current report.

Table 9 Current and strategic goals for the Dutch situation and the Preferred Strategy for coastal Louisiana.

Goal	Dutch situation	Preferred Strategy
Strategic	To have and to hold a well-protected country	Flood risk reduction and landscape stabilization
Tactical	Maintain the coastline at the 1990 position	Wetland stabilization and creation (approximately 1,500 square miles)
	Flood stages linked to updated design discharges of major river will not exceed 1996 design water levels	*River management*
	Flood protection structures meet the legal safety standards (storm conditions ranging from 1/10,000 to 1/1,250 per year)	Coastal barriers and levees meet technical standards (1/1,000 to 1/5,000 per year)
	Non-structural measures	*Non-structural measures*
	Information and research	*Information and research*

The strategic goals will be reached by the various types of proposed measures. Each of these groups of measures has specific characteristics.

The ring levees are meant to protect metropolitan areas from flooding. The (re-)construction of these embankments will take about ten years. These measures can be described as "no-regret" measures to be implemented in the short term. The planning period for these levees should be between 50 and 200 years, depending on the type of structures applied. Structures that can easily be adapted can be designed using a short planning period, whereas the longer planning periods are required for (elements of the) structures that cannot easily be adapted.

The coastal levees and/or barriers will probably take more time to design because of the uncertainties in the performance and/or the complexity of the design. It will probably take a number of years to come up with a design that fits the strategic goals. During this research and design period a number of large-scale pilot projects can be tested in practice.

The marshland stabilization and creation is a long-term measure that will take many years to "create" significant developments. Also, the uncertainties attached to these measures are greater than for the coastal levees and/or barriers. Large-scale tests of these measures in the field are required.

The strategic goals of the preferred strategy cannot be reached in a short period of time. It is realistic to say that it will take decades (30-50 years) to achieve them. This inevitably leads to the conclusion that during this period the strategic goals may have to be adapted once or twice. This is an important aspect of developing the management and maintenance strategy. The tactical goals for the various measures need to be incorporated into the strategic time span of roughly 50 years. The combined effect of these measures will change over time (except for the non-structural measures).

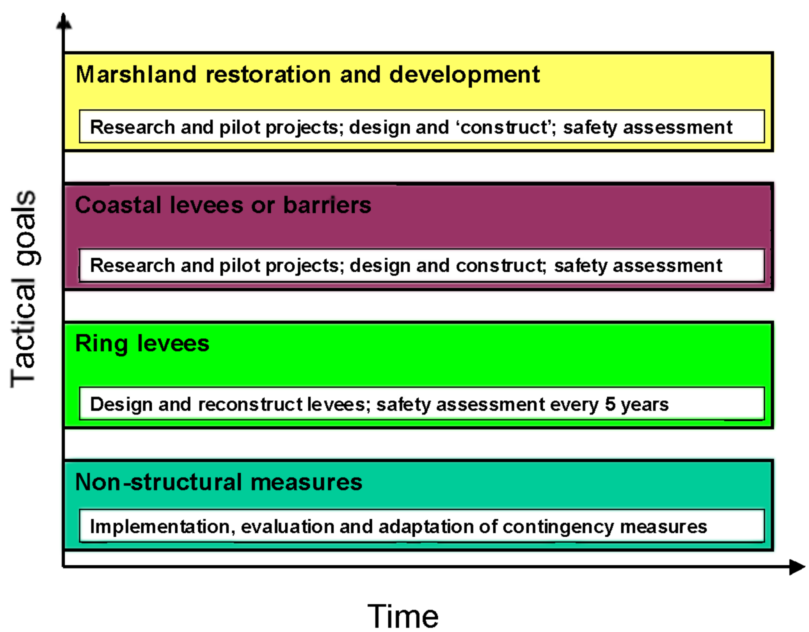

Figure 26 Tactical planning elements

After construction, the ring levees will slowly deteriorate due to the combined effect of sea level rise and settlement/subsidence. That effect can be compensated for by the time the coastal levees or marshland restoration and development measures start to bear fruit. This requires regularly assessing the actual performance of the various measures. For the levees a 5-year period is considered to be adequate.

The operational goals for management and maintenance can be derived from the tactical goals.

Integration and coordination

The multiple line of defense approach is only as robust as the quality of managing and maintaining the individual lines. The need for integrating and coordinating the activities of the various authorities involved is evident.

The key issue related to management and maintenance is to find a suitable balance between the role and actions of the various authorities involved. The current project does not address the organization of governmental institutions. However, based on European and American experience a number of relevant conditions for the optimal management and maintenance situation can be derived:

1. An appropriate planning level:
   a) planning based on the natural systems involved, i.e. the river and the coastal system;
   b) planning based on functions assigned to these systems such as flood protection, navigation, etc.;
2. Local authority:
   a) legislation, which gives (local) water authorities the authority to carry out their duties, to raise funds and to enforce their rights;
   b) taxation of the people in the jurisdiction area of the water authority for generating income to carry out its duties;
   c) representation of stakeholders in the water authorities, to create stakeholder commitment and to ensure democratic decision-making;
   d) capital funding for major investments, which is mainly found within the private sector;
   e) institutional development, addressing trained staff and tools such as accurate land registry and financial administration, needed for an effective and efficient operation;
3. Spatial and functional integration:
   a) functional integration;
   b) spatial integration;
4. Clear responsibilities, including checks and balances.

The first two conditions seem to be contradictory and need to be balanced. It is necessary to have a planning level that matches the scale of the natural system and the processes that take place. For example, the Mississippi River and the coast of the Gulf of Mexico need to be treated as a whole. On the other hand, flood protection measures need to be taken at the lowest level possible in order to keep local authorities involved and committed to their tasks. The local authorities are able to commit local residents to the project and to find optimal solutions based on the costs and benefits of flood protection measures.

The four conditions mentioned in the above are essential for proper management and maintenance. The recommended situation for management and maintenance of the future flood protection scheme in the greater New Orleans area can be described as follows:

- political commitment to strategic management goals and to the framework for tactical management goals and measures;
- designing and implementing the specific tactical measures within the approved framework;
- regular update of tactical planning (once every 1 to 10 years, depending on the type of measures); and
- funding for operational management and maintenance.

Given the tasks and responsibilities of various authorities involved it seems to be a requirement to discern two interlinked "chains of command", leading to both federal and state government, as suggested by the following table.

Item	**Authority**	**Task and responsibilities**
Integration / coordination	State	Risk management
Direct protection of the city	Levee board	Management and maintenance ring levee
Coastal management	USACE / State	Management and maintenance coastline
Coastal levees/barriers	USACE	Management and maintenance levees/barriers
Birdfoot/river management	USACE	River management
Non-structural measures	Parish / State	Spatial planning

9 Conclusions

Conclusions regarding flood protection

1. Based on the assumptions made, information available and methods used for analysis, a Cost/Benefit analysis suggests that a substantial increase in the flood protection level of the metropolitan area of New Orleans to 1/1,000 per year or better is economically justified.

2. The maintenance of the flood protection system is essential for the safety of the people living behind the levees and gates. It is important to consider (1) updating the hydraulic design parameters every five to ten years, (2) reviewing the flood protection system based on these updated hydraulic design parameters, and (3) adjusting the system when needed.

3. Marshlands are effective for hurricane surge and wave reduction, but locally surge levels may increase because of the hydraulic resistance marshlands have on storm surges. The effectiveness of wetlands in surge reduction depends on the spatial dimension relative to path and speed of the hurricane passing and the type of marshland. If a reduction of the surge levels due to the marshlands is taken into account in designing the flood protection system, the marshes will become an essential part of the protection system and will need to be maintained to ensure the level of protection in the future. However, healthy and extensive marshlands have not protected New Orleans from flooding during historic hurricane events (e.g. hurricane Betsy in 1965). Marshlands can only be a part of a flood protection system for New Orleans. The effectiveness of marshlands in reducing a hurricane surge also depends on the repair time after a previous hurricane in the same area.

4. The further degradation of the marshland ecosystem not only threatens the societal functions that benefit from the delta (nature, fisheries, recreation, tourism, etc.), but also leads to a considerable increase in surge heights and wave attacks on levee systems. Marshland stabilization will reduce surge heights and wave attacks, but only to a limited extent.

Conclusions regarding ecosystem functioning

5. Marshland loss rates are slowing down according to some authors (Morton et al. 2006). Good quality marshlands are able to maintain accretion speeds of between 0.25 and 0.5 inch per year, depending on flooding regime and sediment availability. This accretion speed is sufficient to outweigh sea level rise in the coming decades.

6. Sea food production in the lower Mississippi Delta is an important part of Louisiana's economy and part of its cultural heritage. Good quality wetlands and in particular fresh and salt water gradients are conditional to a diverse and productive ecosystem and therefore conditional for a sustainable aquatic delta economy. This aspect must be considered when deciding on a flood risk reduction and landscape stabilization strategy.

7. Safeguarding the long-term functioning of the delta ecosystem depends on restoring connections and gradients between the rivers and the coastal zone and providing suitable flooding regimes to provide sufficient nutrients and sediments to maintain accretion rates exceeding subsidence.

8. The present state of delta marshlands urgently calls for large-scale measures to provide suitable boundary conditions for healthy ecosystem functioning and to compensate for the marshland deterioration of past decades.

Conclusions regarding the design of measures

9. Available Mississippi sediment load has been reduced by a factor of three to four during the last century. Measures concerning the long-term ecosystem stabilization and restoration have to fit within this load. The amount of sediment supplied by the river is not large enough to recreate marshlands in all inactive lobes in the delta area. It is therefore considered logical to focus on marshland *stabilization* in the Barataria and Pontchartrain basins, thereby safeguarding present biodiversity and productivity, and to focus on marshland *creation* in areas that are prioritized due to the positive impact of surge and wave reduction near the active Mississippi lobe.

10. The marshland are can be stabilized by large-scale restoration of patched marshlands (especially by closing and plugging of the channels) and restoration of unimpeded freshwater flow from the river to the delta, flooding regimes and sediment availability.

11. The volume of sediment required to compensate marshland deterioration cannot be supplied exclusively using freshwater diversion from the Mississippi River. That would require large amounts of river water, which would disturb the salinity gradients in the delta basins. Hence, for large-scale marshland stabilization and marshland creation, a piped sediment supply is indispensable. Priority for marshland creation will be the freshwater marshlands surrounding New Orleans.

12. A step-by-step up-scaled approach for wetland creation and stabilization is recommended, supported by field (and laboratory) experiments aimed at reducing uncertainties (learning by doing). The implementation period will span several decades, with a step-by-step effect on storm surge reduction and the health of the ecosystem.

13. The option to divert the Mississippi River by means of a relatively narrow and deep channel but sufficiently large to accommodate the navigation flow on the river seems promising with regards to sedimentation issues. However, large amounts of fresh water will have devastating effects on the salt water ecosystem in a large area around this new channel. For this reason, this measure is not recommended.

14. Dutch levees are constructed in a very different way when compared to the standard approach used by USACE in Louisiana. Dutch levees are often constructed on soft soils, with covering either consisting of hard substrates or a grass-clay layer. In the U.S., soil

improvement by mixed-in-place techniques is often applied. It is proposed to study the cost-effectiveness of a Dutch type levee built on soft soil in the Louisiana context, considering soil characteristics, construction methods, construction speed, suitable vegetation, long-term stability. In addition, the pros and cons of both construction approaches should be identified, including organizational aspects (the Dutch approach may require a larger maintenance effort). This provides information required to decide on the best approach to use for large-scale application in Louisiana.

15. It is relevant to consider a levee design that can safely deal with wave overtopping and/or surge overflow with a buffering zone behind it. This is in order to limit the required height of the levees while maintaining the flood protection level. This approach is now being considered for some critical levee systems in the Netherlands.

Conclusions regarding possible strategies

16. Given the number of options available, three distinctly different strategies can be developed, i.e. an open, semi-closed, and fully-closed system. This implies that in the decision process, real and fundamental choices can be made.

17. Measures to protect the city of New Orleans against floods cannot be considered in isolation from the long-term development of the wetlands in the delta. Wetland restoration can improve flood protection, while continued wetland loss would seriously reduce flood protection levels in the city. Given the time to maturity for landscape stabilization measures, an improvement in flood protection levels in the urban areas in the short term can only be achieved by providing levees and gates.

18. Improvement in flood protection of urban areas and landscape stabilization should be realized in both the short term and intermediate term. Short and intermediate-term flood protection will be provided by levee systems, while landscape measures will provide additional flood protection in the intermediate and long-term.

Conclusions regarding integrated management

19. The following four conditions have to be met in order to realize proper management and maintenance: (1) political commitment to strategic management goals and to the framework for tactical management goals and measures; (2) designing and implementing the specific tactical measures within the approved framework; (3) regular update of tactical planning (once every 1 to 10 years, depending on the type of measures); and (4) funding for operational management and maintenance.

20. For successful wetland restoration, which is of crucial importance for both landscape stabilization and flood protection, a considerable management effort will be required. Knowledge and experience will have to be gained in the short term in order to start a process of wetland restoration. The continued management effort this requires asks for an organization that is dedicated to this objective, and continued funding is a prerequisite.

Institutions for traditional flood protection measures are well in place, but for wetland restoration institutions need to be strengthened.

21. Measures to restore wetlands are aimed at the overall stabilization and improvement of the ecosystem. These measures may temporarily have negative impact on the locally existing ecosystem. Such negative impact has to be considered in the context of the long-term overall objectives of these measures. Legislation on mitigating the environmental impact of measures has to accommodate such long-term restoration effort.

10 Recommendations on pilot projects and priority studies

10.1 Recommendations on pilot projects

The Preferred Strategy presented in this report is based on a mix of measures that are based on proven technology but also on innovative concepts. It is noted, however, that proven technology, suited for the typical Dutch environment and engineering technology, will need validation for the characteristics of the environment in the Louisiana coastal zone. Obviously, also proven technology can be improved upon, and this is especially relevant when large-scale and hence costly applications are anticipated like in the Louisiana case.

Especially the success of the Preferred Strategy in achieving sufficient marshland creation and long-term large-scale landscape stabilization depends on the successful implementation of innovative cost effective solutions.

Therefore, the project team suggests that pilot projects are implemented as a means to validate engineering solutions, to reduce uncertainties and to fill in knowledge gaps. Pilot projects should be implemented as soon as possible in order to provide information in time to feed the design and planning process to achieve the short-term and long-term project objectives and goals.

Pilot studies are proposed in four important areas, namely (1) levee construction and stability; (2) marshland stabilization; (3) marshland creation; and (4) priority studies on risk assessment and the effects of vegetation on surges and waves.

Due to the severe sensitivity to storm surge and short distance from the city it is proposed that the Lake Borgne area is selected as a primary site for the execution of pilot studies. The Preferred Strategy (Chapter 7) proposes to close Lake Borgne with a ridge-levee and promote extensive marshland formation in the area between the new levee and MRGO. Therefore successful pilots in this area will immediately contribute to improving the safety of the city and allow citizens to access the works and admire the activities and achievements.

10.1.1 Levee construction and stability pilot projects

a) Overtopping erosion tests on existing levees

Existing levees have been rebuilt and, where possible, strengthened or increased in height. Despite the heightening of levees, considerable wave overtopping during hurricane events may lead to sliding and/or erosion of the inner slope and consequently breaching. The real strength of these levees remains largely unknown. Recently, a new device, the *wave overtopping* *simulator* [3)], was designed and constructed in the Netherlands and field tests were performed on an existing levee (see Figure 27).

Figure 27 Recent field test in the Netherlands on the impact of overtopping waves on an existing levee.

Results showed that the combination of grass on clay may resist considerable overtopping, but bare (or hardly vegetated) clay is much less resistant. A geo-textile in the grass sod on the crest and inner slope of a levee gave even better results and are a possible way to "breach-free levees". This means that heavy wave overtopping may occur, without breaching. The project team suggests the consideration of performing field tests on existing repaired levees in order to get a good understanding of the actual strength of the existing levees and to provide ideas on ways to further improve the strength.

b) Ridge-levee pilot project

A new type of gradual slope, hydraulic fill, ridge-like levee covered with vegetation has been proposed in this project to be constructed in order to reduce storm surge levels in the area protected by this levee. This levee must have a sufficiently wide crest and inner slopes must be sufficiently gentle to deal with both overflow and overtopped waves during extreme events. The ridge-levee may be damaged during extreme events, but total failure must be avoided. In order to explore the uncertainties of the construction methods (including uncertainties about the management and maintenance effort that will be required), characteristics of soils, long-term stability and the development of vegetation, a pilot study is needed in which a section (for example, a mile in length) is actually constructed. An option would be to set up a USACE – Dutch team of specialists that drafts a detailed design and selects suitable locations, scale and techniques for construction and monitoring. For the location of this experiment, the project team suggests considering an alignment on the border between Lake Borgne and the Gulf, possibly in combination with an accelerated marshland creation pilot.

10.1.2 Marshland stabilization pilot projects

a) Canal infilling pilot project

A pilot is proposed to develop efficient techniques to fill or plug man-made canals in the wetlands. In itself, plugging a canal or filling it in over its full length is not particularly challenging from an engineering point of view. However, the number of canals involved, and the scale of the area, suggests a thorough rethinking of the existing techniques to realize such plugging or filling of canals. A pilot project in which new methods and techniques are tested in the field is suggested before large scale implementation is started.

3) Design copyright Dr. J.W. van der Meer, the Netherlands.

b) Pilot project to increase the effect of fresh water discharge

This pilot aims at optimizing marshland growth and increasing the mixing zone with saline waters. This experiment aims to maximize the effect of water discharges into marshland areas that are already opened up by canals. Areas will be semi-enclosed by low ridge-levees to enhance the flooding effect and residence time of the diverted fresh water. Plugging of canals will be considered to further enhance the effect of freshwater discharge. In order to reduce steep gradients between fresh and saline water, the semi-enclosed area will provide an optimized mixing zone that allows free exchange of water and biota in and out of the semi-enclosed area.

c) Lake segmentation and land formation pilot project

Opened-up lakes in eroded marshland area are marked by increased currents and wave action. This leads to accelerated erosion of marsh edges. In this pilot project (see Figure 18), artificial low ridge-levees, islands and suitably placed oyster reefs will be utilized to divide lakes into segments. This will reduce energy levels but maintain the required flow.

If land-subsidence rates are close enough to background levels and sediment availability is sufficient, marsh growth from existing and new marsh edges should tend to reduce the remaining lake area in a land formation process. This process could be enhanced by additional sediment supply.

10.1.3 Marshland creation pilot projects

The objective of the following pilots is to find promising approaches to marshland creation that are relatively cheap and produce a self-sustaining marsh in the foreseeable future. Requirement for these pilots is that actual and future subsidence rates are low enough to allow sustainable marsh existence by natural or somewhat enhanced growth rates.

a) Accelerated natural fresh water marshland creation pilot project

It is hypothesized that a temporary artificial lowering of the water level to optimal depths for marshland growth will kick-start the recovery of lost fresh water marshes (either using the remaining seed banks, or by means of artificial seeding or planting). This could be combined with hydraulic filling of certain sections to expedite the process (see Figure 20). A yearly cycle of flooding with (if needed with sediment enriched river water) will be implemented to create optimal growing conditions. Step-by-step, the water level will be increased to stimulate as fast as possible marshland accretion, by reducing decomposition of freshly formed organic material, while maintaining yearly flooding cycles, until the present water levels are reached. The slowly increasing water level will reduce the mineralization of newly formed organic soil and therefore maximize the increase of soil thickness. The pilot will research the validity of the hypothesis and will aim to find the optimal mix of water discharge, sediment availability and flooding cycle to attain fastest accretion rates. In principle, a drowned "polder" will be most suitable, where as little as possible new construction is needed to provide suitable control over the hydraulics. Large scale marshland creation could also be seen as a major contribution to carbon and nutrient fixation. The size of a suitable pilot area is estimated at between 20 to 200 acres.

b) Natural salt or brackish water marshland development pilot project

This pilot project is similar to the previous pilot project, but this one has a salt or brackish environment instead of a fresh water system. For this pilot daily water level variations should be allowed according to local tides.

c) Accelerated saltwater marshes development pilot project

A pilot is proposed to study the applicability in the Louisiana coastal area of the traditional Dutch method of salt marsh (in Dutch: *kwelder*) creation, which has been applied in that country for hundreds of years (see Figure 28), with the aim of land-reclamation and shore stabilization. This method is based on the reduction of local sediment losses to longshore sediment transports. This is realized by reducing currents parallel to the shoreline. At the same time, the shoreward transport of sediment due to waves and currents is maintained.

In the Dutch situation, Spartina was planted to fix the freshly deposited sediments. The pilot project will test the validity of the method and optimize the spatial design, including for example the question whether or not straight sections as applied in the Dutch design are appropriate. In the pilot project this method could be combined with the deposition in the study site of dredged fine sediments. The experiment could start with the creation of five to ten parallel low-crested wooden structures to start *kwelder* formation along a one mile stretch of coastline.

Figure 28 Aerial picture showing large-scale marshland ("*kwelder*") creation and stabilization works using low tech measures. The muddy area and marsh vegetation are flooded each tidal cycle (Dutch Wadden Sea, source: Google).

10.2 Recommendations on priority studies

The required investments in flood risk reduction and landscape stabilization measures are substantial. The decision about these investments should ideally be based on sufficiently reliable science and technology. This is where the following recommendations on priority studies play an important role, because for a number of topics follow-up work is needed to more reliably motivate decisions to be made.

These recommendations refer to two important questions:
1. how to derive more reliable answers to the question what flood protection level should be selected for the metropolitan area of New Orleans, and
2. how to improve the reliability of the analysis on storm surge levels and waves, with special emphasis on the effects of vegetation on water levels and waves.

1) Priority study on risk assessment

The risk assessment carried out in this project resulted in a tentative and first order economic optimization of the flood protection level for New Orleans. It is recommended to improve this analysis with a joint effort by U.S. and Dutch specialists. This could be done in the form of further studies with the following components:

1. The defense schemes have to integrate levees and barriers on the one hand, and other types of measures (like wetlands stabilization) on the other hand. In the longer term, the stabilization or (re)creation of wetlands is expected to improve the protection of the areas behind the levees. However, the restoration of wetlands is a relatively slow process that will take decades. The timing of these measures deserves more attention in the risk management analysis.
2. Better and more detailed estimates of costs, surge probabilities and damage are needed. The IPET risk analysis will provide better input data, but this part of the IPET study has not been reported to date. A specific point is the extrapolation of design water levels to higher return periods.
3. The choice for a level of flood protection concerns a societal / political choice. It is recommended that a discussion is started on protection levels and the corresponding decision criteria and that the relevant decision makers and stakeholders are involved.

2) Priority study on the effects of vegetation on surges and waves

The effect of vegetation on water levels and waves remains difficult to estimate. Hence, the reliability of modeling efforts for extreme conditions like hurricanes leaves much to desire. This effect, however, has a direct impact on the hydraulic design parameters for infrastructure, and hence the costs and reliability of that infrastructure. It is highly recommended that priority studies are undertaken at the short term to address the following.

Establishing the effect of different types of wetlands on the surge, wave and wind reduction. The potential is high, but uncertainties are large. Within Delft3D the effect of vegetation is based on parameterized results of detailed numerical simulations of randomly arranged vertical cylinders of various densities and shapes. This also enables a consistent treatment of different types of vegetation (e.g. Cypress versus Spartina). The effect of vegetation is consistently taken into account in both the wave, flow and sediment modules. Under moderate wave conditions the vegetation module has been successfully calibrated for a limited number of vegetation types (e.g. Temmerman et al., 2004, Baptist et al., 2005). This method has all the necessary physics included to account for vegetation effects based on real physical parameters such as density, height and vegetation type. However, in the simulations presented in this report the predicted surge reduction due to the presence of marsh differ a factor of two to four when compared to those reported in literature for other hurricanes.

An optimal utilization of the surge reduction potential of marshland can only be achieved using well-verified and broadly-supported methods and/or models. If the effect can be determined with sufficient accuracy, a sound balance can be made between the effects of hard defense measures such as levees and soft defense measures such as marshland stabilization, and hydraulic design parameters can be determined in a more reliable way. Improvement of the vegetation module is suggested to consist of the following elements, which are aimed at better understanding surge reduction and can be used to improve and validate prediction techniques:

- Initiate laboratory experiments in which the surge reduction potential for various types of vegetation and surge characteristics is systematically investigated.
- Initiate a field measurement campaign with the specific aim to estimate the surge levels across marshland. Deployment of temporary facilities or deployment of teams to estimate surge levels at strategic locations soon after a hurricane could be considered.

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REPORT APPENDICES

A Evaluation criteria

Criteria and indicators for performance

Since the five objectives are formulated on an abstract scale, it is not trivial to see whether or not goals are met by the proposed measures. Therefore 15 sub-goals were added to the five objectives. These are illustrated by numbers 1 thru 15 in Figure 29. From each sub-goal a criterion is derived, which can be used to judge whether a goal is met or not. An indicator for the performance of the measure(s) was assigned to each criterion.

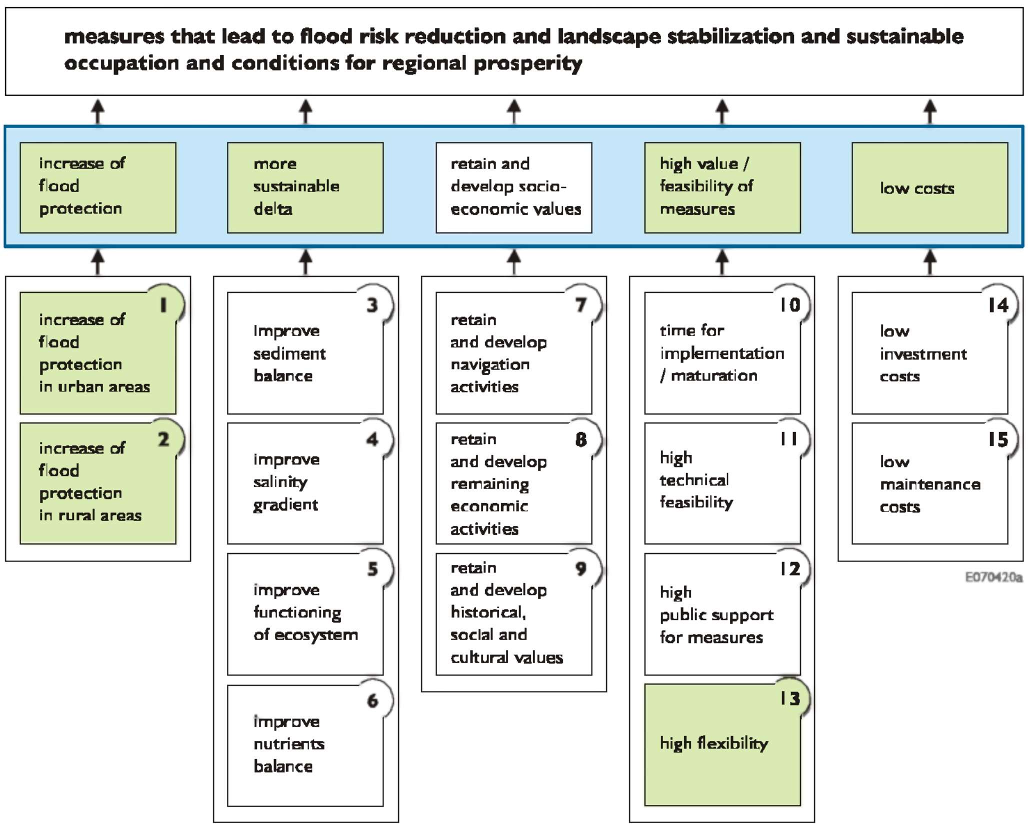

Figure 29 Goals and objectives of the project.

In the following tables, the five main objectives and their 15 sub-goals are translated into a criterion and a performance indicator. Performance indicators have to be evaluated quantitatively when possible, or qualitatively otherwise. Within the Dutch Perspective most of the evaluation will be qualitatively. Most likely, expert judgment will play an important role in deriving the scores for most of the criteria.

Increase in flood protection (Flood protection)		
Sub-goal	***Criterion***	***Performance indicators***
1. Increased flood protection of the urban areas	Protection level urban areas Reduction in flood risk	Flooding probability (%) Reduction in flood risk
2. Increased flood protection of the rural areas	Protection level rural areas Reduction in flood risk	Flooding probability (%) Reduction in flood risk

More sustainable delta (Sustainable Delta)		
Sub-goal	***Criterion***	***Performance indicators***
3. Improve sediment balance	Sediment balance	Qualitative assessment of sediment balance (expert judgment)
4. Improve salinity gradient	Salinity gradient	Presence of fresh water, brackish water and salt water marshes (expert judgment)
5. Improve functioning ecosystem	Ecosystem functioning	Qualitative assessment of ecosystem functioning (expert judgment)
6. Improve nutrients balance	Nutrients balance	Qualitative assessment of improvement of the nutrients balance (expert judgment)

Retain and develop socio-economic values (Socio-economic value)		
Sub-goal	***Criterion***	***Performance indicators***
7. Retain and develop navigation activities	Economic activities	Impact on navigation activities (qualitative)
8. Retain and develop other economic activities	Economic activities	Impact on other economic activities (fisheries, tourism, agriculture and possibly new developments (qualitative)
9. Retain and develop historical, social and cultural values	Presence of historical, social and cultural values	Number of (or potential area with possible presence of) historical, social and cultural values at risk (expert judgment)

High value / feasibility of measures (Feasibility)		
Sub-goal	***Criterion***	***Performance indicators***
10. Time	Time for implementation and time to maturity	Number of years (expert judgment)
11. High technical feasibility	Technical feasibility	Qualitative assessment of feasibility (available materials and techniques, robustness and maintenance aspects
12. High public support	Expected public support	Qualitative assessment
13. High flexibility	Flexibility in implementation of the set of measures	Qualitative assessment of Adaptability and Separability

Low costs (Costs)		
Sub-goal	***Criterion***	***Performance indicators***
14. Low investment costs	Investment costs	Costs ($)
15. Low maintenance costs	Maintenance costs	Costs ($)

Score in general:

++ meets goal completely
+ on the right track
0 neutral
- moves away from goal
-- does not meet goal

Criteria maintained by LACPR

LACPR has developed the following five initial criteria to evaluate the possible strategies for Coastal Louisiana:

1. **Cost effectiveness**: Cost versus amount of risk reduced or cost versus residual risk. Residual risk means damage and likelihood of damage, population at risk and likelihood of exposure.
2. **Robustness**: Plans or measures remain effective under various conditions.
3. **Adaptability**: Ability of measures and plans to be adjusted based on changes in future conditions (flexibility).
4. **Separability**: Ability to perform independently of other measures.
5. **Sustainability**: Ability to balance economic, ecological and social conditions to meet current and projected needs without compromising the ability of future generations to meet additional needs.

This list can be found in the LACPR Interim Report on risk informed planning. No list of criteria is available at present to evaluate measures. However, the Project Management Plan, Enclosure J of the Preliminary Technical Report of the LACPR, indicates the definition of evaluation criteria and performance measures in the proposed content of both the Preliminary and Final Technical Report. Unfortunately, in the actual text of the Preliminary Report no criteria are stated (yet).

Figure 29 also shows the five criteria that USACE maintains in LACPR. This is shown by the green boxes in Figure 29 in the following way:

- **Cost effectiveness** is divided in two criteria; costs and flood protection.
- **Sustainability** can be found directly in the criterion More sustainable Delta.
- **Robustness, adaptability and separability** are incorporated in the criterion Feasibility of the project and Flexibility of the measures.

B Geology

B.1 Introduction

This appendix is mainly based on the paper by Roberts (1997) on the depositional framework of the Mississippi River delta. This paper stresses the cyclic evolution of the delta that is summarized in the *Delta Cycle Concept.* This concept is based on a large body of publications.

The Mississippi River delta plain covers a total surface area of about 30,000 km^2. All Holocene deposits of the Mississippi River have been laid down by a meandering river; this implies that the river discharge did not fluctuate significantly during this period. The Mississippi River has a mean discharge of 15,400 m^3/s and a peak discharge of almost 60,000 m^3/s. The sediment load is 621 million tons/yr; the suspended sediment load downstream of the diversion near Old River, North of Baton Rouge is 146 million tons/yr. The bed load consists of 90% fine sand, the suspended load consists of 65% clay and 35% silt (figures for the lower reach of the river; from Coleman, 1988; suspended load data from Keown et al., 1981, in Wells, 1996). The Atchafalaya River receives 30% of the discharge of the Mississippi River, through the Old River diversion works. The Red River joins the Atchafalaya River downstream of this point, resulting in a total discharge of 6,500 m^3/s and a suspended sediment load of 85 thousand tons/yr (Keown et al., 1981, in Wells, 1996). The sediment discharge of the Atchafalaya River onto the shelf is 220 thousand tons/yr (Roberts et al., 1980). The Mississippi and Atchafalaya Rivers are building out into the Gulf of Mexico which is characterized by mild wave-, current- and tidal conditions, resulting in a river-dominated delta geometry.

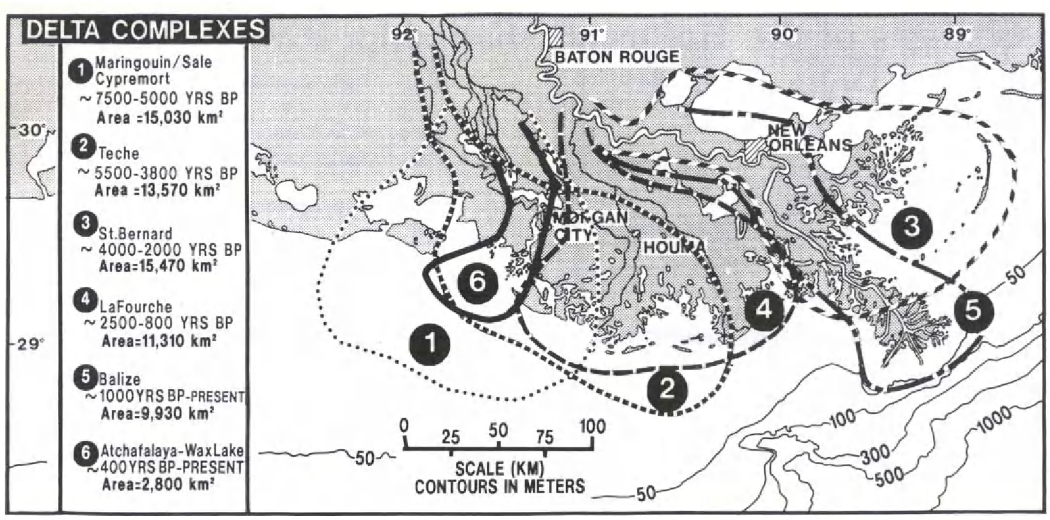

Figure 30 The Mississippi River deltaic plain, illustrating the locations of major delta complexes, including their approximate ages and sizes. (From Roberts, 1997)

Wells (1996) concludes that the demise of the modern Birdfoot delta in the 20th century is probably a result of an inadequate sediment supply (levees preventing overbank flooding and funneling sediment into deep water, sediment trapped by upstream dams, 30% loss to Atchafalaya River) and an inefficient sediment delivery network. This loss of sediment load coincides with the vulnerable state of the Birdfoot delta which is nearing the end of its life cycle. The results of experiments with water and sediment diversions in the Garden Island Bay subdelta (results reported in 1993) suggest that mitigation can only slow down the rate of deterioration but not rejuvenate the dying delta lobe. A recent evaluation of the results from the Carnarvon diversion (Snedden et al., 2007) concludes that the resulting sediment input into Breton Sound is insufficient to offset the present rate of relative sea-level rise in this estuary.

B.2 The Delta cycle

Geological research on the Holocene deposits showed that the present delta plain and the associated barrier islands and submarine shoals along the seaward boundary are the products of cyclic delta building processes. This "delta switching" cycle comprises four steps, (1) rapid progradation of the active delta lobe, (2) switching of the river, leading to abandonment of the active river course, (3) transgressive reworking of the deposits by marine processes, and (4) at the same time building of a new delta lobe at a new position.

Delta building occurs on several time- and spatial scales, resulting in a cascade of "deltas within deltas". From large scale to small scale the following elements can be discerned:

1. the Holocene delta plain;
2. Delta complexes; such as the Marinqouin, Teche, St. Bernard, Lafourche, Balize and Atchafalaya complexes (see Figure 30);
3. Delta lobes, related to the main distributaries of the river within a complex;
4. Subdeltas, related to 2^{nd} order distributaries, and
5. Crevasse- or overbank splays, that result from breaks in the levees of major distributaries.

Delta complexes result from switching of the main course of river which happened every 1000-2000 years. These events produced up to 15,000 km^2 of marshland and sediment sequences on the inner shelf of about 30 m thick. Within a delta complex there can be several individual *(delta) lobes*, built by the major distributaries. Within a delta lobe, *subdeltas* are filling in the shallow embayments between the main distributaries (Figure 31). The sediment sequences they build have a thickness of ~ 10 m (5-20 m); their maximum surface area is about 300 km^2. Subdeltas evolve cyclically, starting with the building of a sediment distribution network and infilling of the interdistributary bay, leading to deterioration of channel efficiency and, consequently, a decline in sediment supply. Since subsidence caused by compaction and dewatering of deposits continues, this eventually results in open water again. This evolution takes 150 to 200 years, see Figure 32. *Crevasse splays* are the smallest morphological element in the Delta Cycle; they have deposition – erosion period of decades, a thickness of meters and a surface area of some km^2.

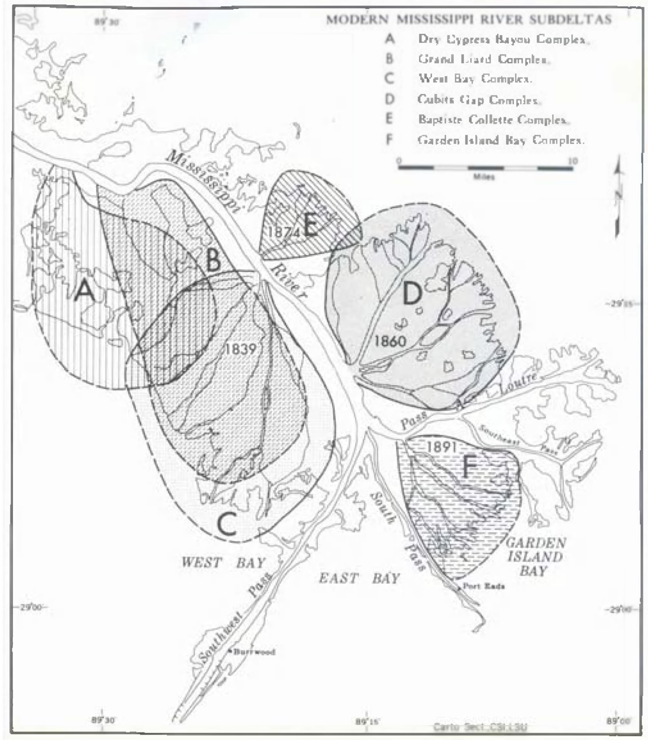

Figure 31 Index map showing subdeltas of the modern Mississippi River Delta. Dates indicate the year of crevasse opening (from Coleman & Cagliano, 1964).

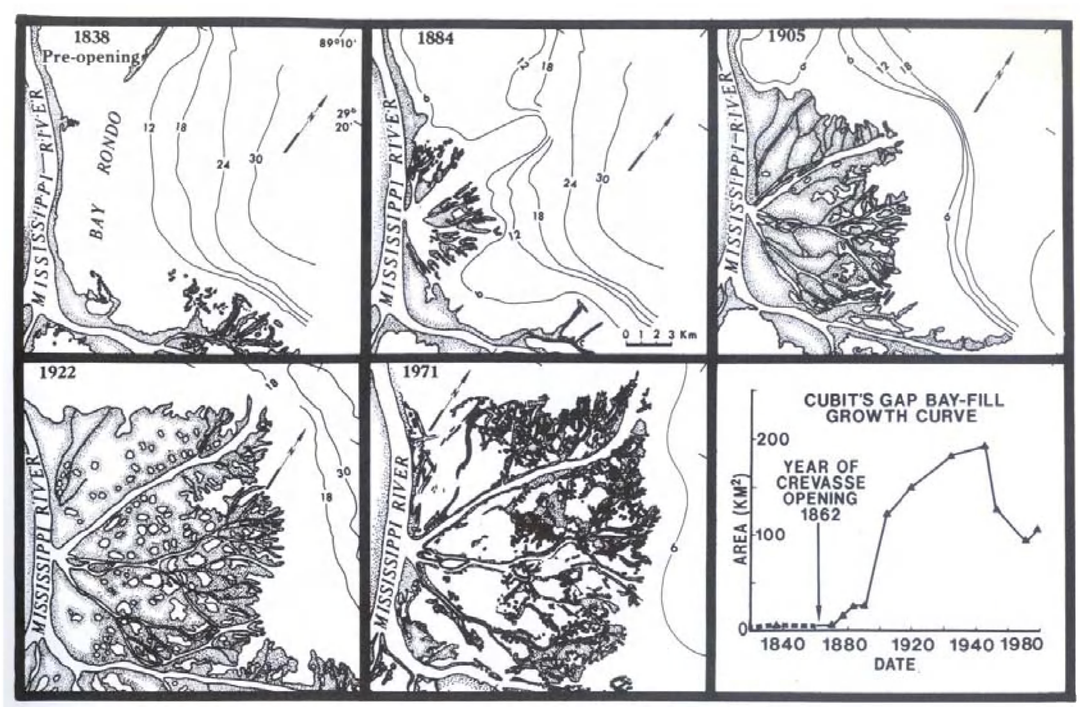

Figure 32 The development of Cubit's Gap, a typical subdelta that is part of the Birdfoot (from Wells et al., 1983). See Complex D in Figure 31 for location of this subdelta.

The Delta Cycle comprises two evolutionary modes: (1) a fluvially-dominated regressive phase of Delta lobe initiation and rapid growth during which the river captures a new course and establishes a channel network, and (2) a marine-dominated transgresssive phase of delta lobe abandonment and deterioration. During the latter phase the channel network is abandoned and the delta lobe becomes sediment starved. This enhances the subsidence of the lobe and causes transgressive reworking of its seaward edge. Erosion of the delta deposits leads to resuspension of fine-grained sediments that are subsequently transported away. The remaining sand, which is only a small portion of the total sediment volume, is reworked into beaches and spits. With ongoing subsidence of the remaining lobe deposits, the sandy beach becomes detached from the marsh, changing them into barrier islands. These islands will eventually disappear, and form a submarine sand shoal offshore of the remnants of the eroded delta lobe. Figure 33 summarizes these different stages in the development of a major delta lobe, including the sedimentary processes and responses. Figure 34 describes both the genesis and the post-abandonement evolution of delta lobes. The post-abandonement evolution can be summarize in a three-stage model, which is based on the geomorphological state of Mississippi delta lobes in different stages of deterioration. The geomorphology of each stage is primarily a result of increasing age since abandonement, acting in concert with subsidence and marine reworking.

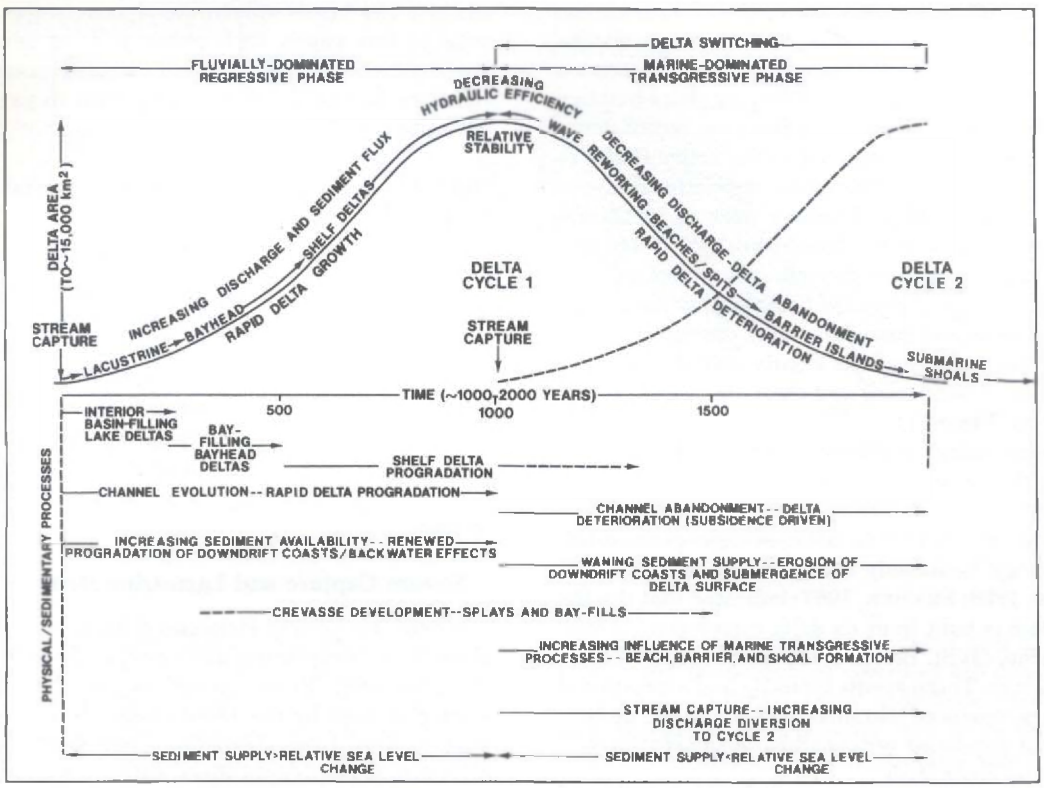

Figure 33 Graphic respresentation of the Delta Cycle stressing processes and responses in both the river-dominated regressive and marine-dominated transgressive phases of development. Note that the duration of the regressive phase of the cycle is much shorter than the transgressive phase (from Roberts, 1997).

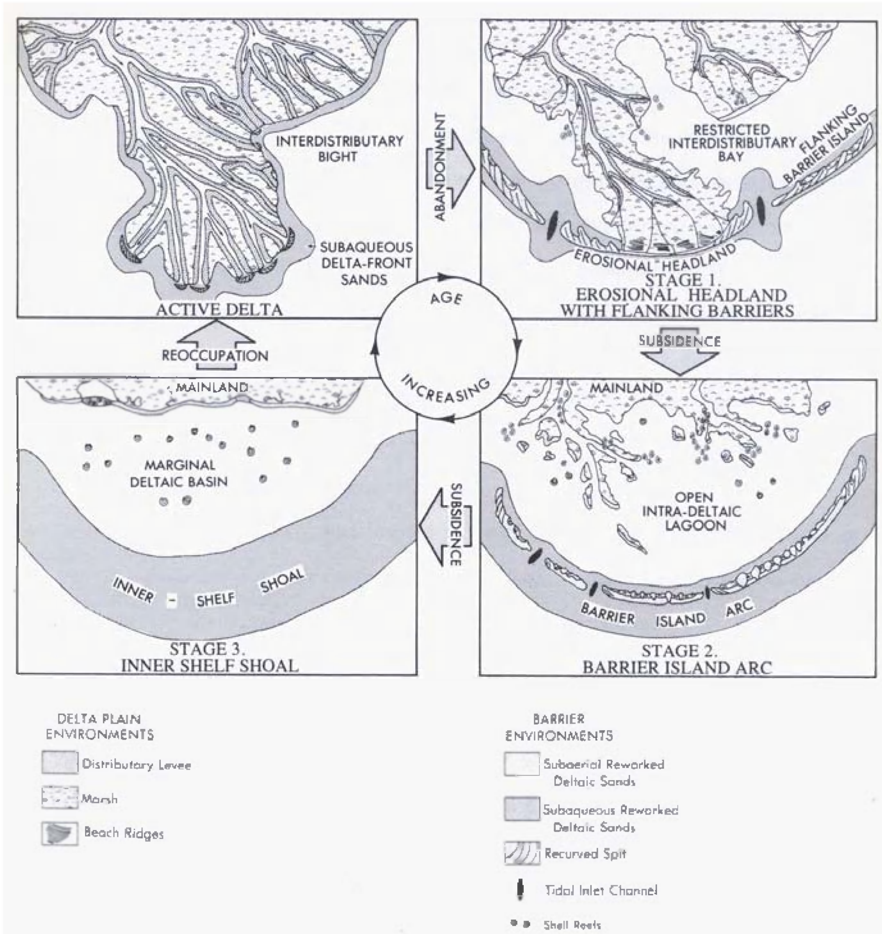

Figure 34 Conceptual model describing the Delta Cycle. The evolution of the Mississippi delta lobes following abandonement can be summarized in a three-stage model. The geomorphology of the subsequent stages "erosional headland", "barrier island arc" and "inner shelf shoal" shows detachment of the sand bodies from the mainland and progressive lowering and finally drowning of these sand bodies. This development is primarily a result of increasing age since abandonment, acting together with subsidence and marine reworking (from Penland & Boyd, 1981; Penland et al., 1988).

B.2.1 Delta cycle, phase 1; delta building

Delta building starts with stream capture and infilling of inland lakes with sediment. After infilling of the alluvial plain, delta formation at the coast starts. With time, these deltas will build out onto the shelf (Figure 34, panel "Active Delta"). At present, the Atchafalaya River is in the phase of building so-called bayhead deltas at the coast (see Figure 35). The Balize or Birdfoot delta is in the shelf-building stage. It has been prograding over the last 1,000 years. The Balize lobe is bounded by the St. Bernard and Lafourche lobes, forcing the Birdfoot to prograde into deep water. Because of the great water depth, the progradation is slow and a thick sediment sequence (from about 30 up to more than 100 m) is deposited. The architecture of the Birdfoot differs from that of other delta complexes that prograded out on the shallow inner shelf. The latter typically prograde very rapidly, develop many elongate and branched distributaries and accumulate a vertical sedimentary sequence that is usually less than 20-30 m thick.

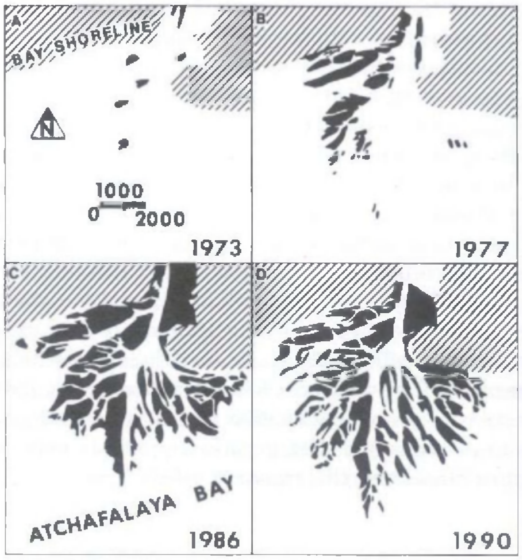

Figure 35 Illustration of the growth of the Wax Lake bayhead delta of the Atchafalaya River (delta complex nr. 6 in Figure 30). (From Roberts, 1997.)

Local reworking of active delta lobes also takes place during progradation, e.g. in bays along distributaries. Abandonment of a distributary will lead to subsidence and eventually marine transgression. Note that this is a small-scale phenomenon! The transgression will result in reworking of channel-mouth deposits into thin beaches (<1.5 m thick) and beach ridges, and oyster reefs growing on drowned levees (Figure 34, panel "Active Delta").

B.2.2 Delta cycle, phase 2; delta abandonment and deterioration

As a delta lobes evolves, its distributaries continue to branch, reducing efficiency of the channel network to transport water and sediment through the system. This progressive hydraulic inefficiency, together with a reduction in gradient as a result of continued progradation, promotes eventual stream capture upriver. When stream capture occurs, the delta eventually shifts from active accretion and progradation to an evolutionary phase dominated by subsidence-driven processes and marine reworking. The state of deterioration of a delta lobe depends on the time passed since the lobe was abandoned; these stages are based on the state of the present-day inactive delta lobes, see Figure 36. They are summarized in the model that is represented in Figure 34 (stages 1 - 3).

Subsidence

Postdepositional dewatering and compaction of the Holocene sediments are the most important components of Relative Sea-Level Rise (RSLR) in the Mississippi River delta. RSLR causes land loss and marine transgression in the delta plain (Kuecher, 1994). At delta lobe scale, subsidence under load, large-scale basinal down-warping and eustatic SLR will contribute to marine transgression. Locally, RSLR has been accelerated by extraction of oil, gas and water, which might have reactivated subsurface faults (e.g. Morton et al.; 2005a,b)

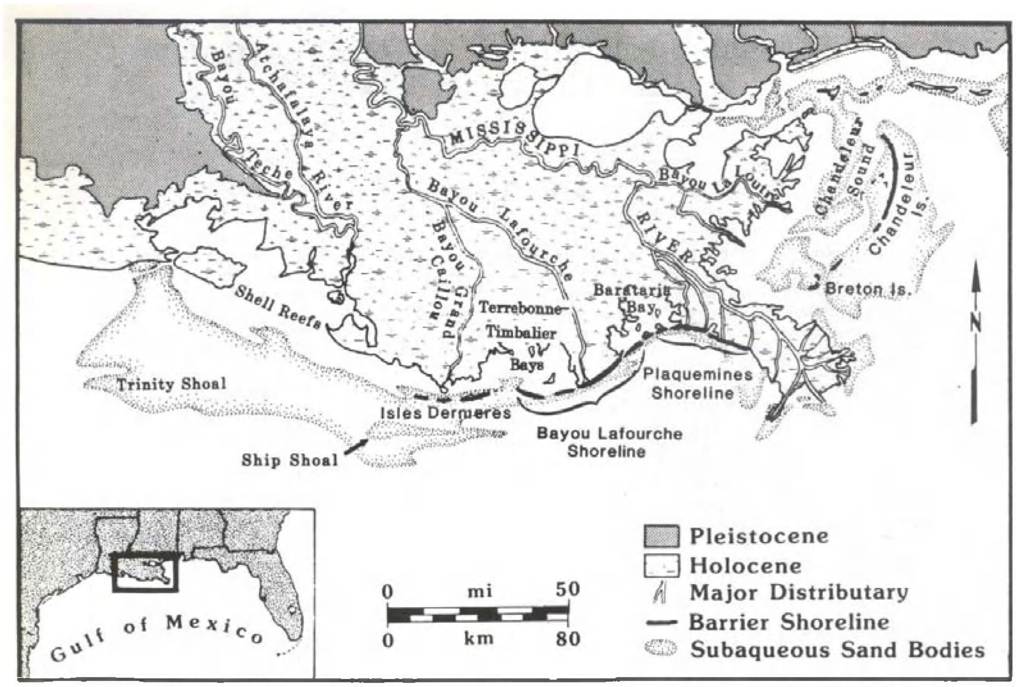

Figure 36 Morphology of the Mississippi River delta. The different shorelines represent different stages of deterioration of inactive delta lobes. The Bayou Lafourche Shoreline is in the "erosional shoreline"-stage, see also Figure 37. The Chandeleur Islands, part of the St. Bernard lobe, are a typical example of a "barrier island arc" (Stage 2). Ship Shoal, a submarine sand sheet, is supposed to be the Stage 3 "Inner Shelf Shoal" associated with the Middle-Holocene Maringouin deal lobe (see Figure 30 for an outline of Holocene delta lobes). (From Boyd & Penland, 1988.)

Since compaction of the Holocene sediments is such a key factor in subsidence, the thickness of Holocene deposits becomes important too: the rate of subsidence increases with the thickness of the deposits.

Consequently, the Birdfoot can be expected to subside rapidly after a significant decrease in sediment supply, caused by its thick sequence of Holocene deposits. This can have large consequences for the pattern and rate of shoreward redistribution of these sediment; even more so when the long distance to the delta plain is taken into account.

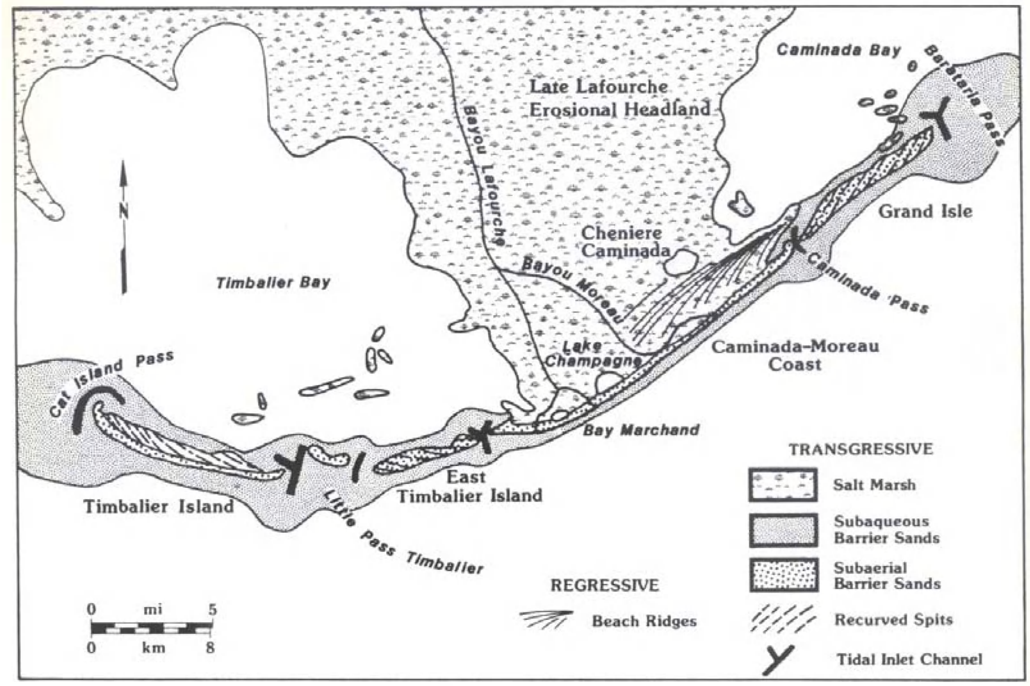

Figure 37 Detailed view of the erosion of the Caminada-Moreau headland of the Lafourche delta lobe. Erosion of the headland causes winnowing of sand from the deposits. This sand is redistributed into barriers, barrier islands and spits. (From Boyd & Penland, 1988.)

Deterioration and erosion of abandoned delta lobes

1) Deltaic headland retreat - beach, spit and barrier island development (Figure 34, Stage 1)

The first stage of subsidence and reworking by waves is erosion of deltaic headlands, which leads to formation of beaches and washover fans. Sand is transported laterally and forms recurved spits. Rapid coastal retreat, together with the growth of bays caused by subsidence, leads to separation of barriers from the delta plain, changing them into *barrier islands*. These barrier islands retreat landward by overwashing and grow sideways by wave-driven longshore transport. With further subsidence of the interdistributary bays the tidal prisms increase, which leads to larger inlets and storage of increasing volumes of barrier sand in ebb- and flood-tidal deltas.

The *Caminada-Moreau headland* of the Lafourche delta lobe (Figure 36 and Figure 37) is in this stage. This shoreline retreated more than 3 km between 1887 and 1988 (McBride et al., 1992), which is about 33 m/yr. It is noted that this headland still receives sediment from Bayou Lafourche and its distributaries.

2) Barrier island arc formation (Figure 34, Stage 2)

With time, the coastline of the deteriorating marsh retreats faster than the barrier islands. The retreat of the marshes is caused by subsidence, lack of sediment input and saltwater intrusion.

The barrier islands migrate shoreward, mainly by wave action. The faster retreating marsh leaves the barrier behind in open water, see Figure 38. The barrier develops into an island arc that is breached and overwashed during storms.

The *Chandeleur Islands* of the St. Bernard lobe (see Figure 36 for location) represent this stage of development. This island chain is about 75 km long and 100-200 m wide. It retreated between 1.5 m/yr in the South and 18 m/yr in North over the period 1855-1989 (McBride et al., 1992). The land loss over this period was 7.6 ha/yr.

3) Submarine shoal formation (Figure 34, Stage 3)

As a result of continued subsidence and reworking by waves, a barrier island chain will finally drown. By that time, the major part of the remaining marshlands that were once related to it will have disappeared and are replaced by a shallow marine embayment. The submarine shoal remaining on the shelf is the final stage of delta lobe evolution.

Ship Shoal, a 50 km long, 5-12 km wide and 4-6 m thick sand body SW of the Isles Dernieres (see Figure 36 for location), is a good example of this stage. This shoal has an asymmetric cross-section, with a much steeper landward slope than its seaward slope, which indicates landward migration. Historic bathymetric data suggest a landward movement of 7-15 m/yr.

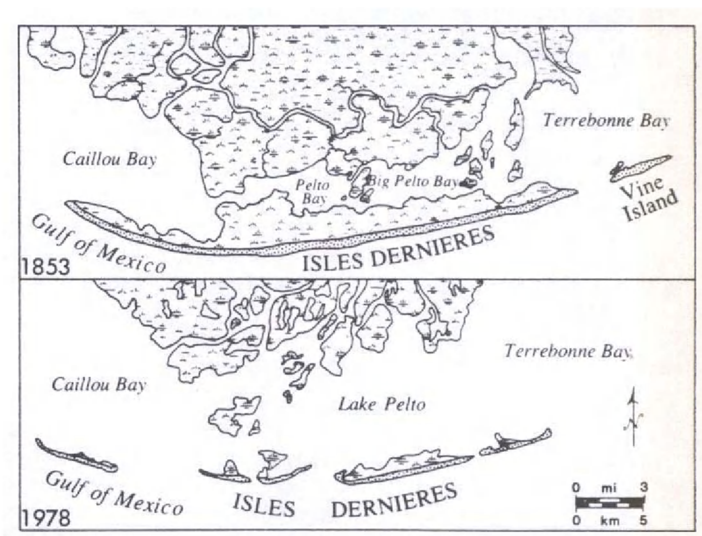

Figure 38 Shoreline changes in the Isles Dernieres clearly illustrate the transition from a Stage 1 to a Stage 2 barrier shoreline between 1853 and 1978. During this 125 year period the mainland shoreline retreated over 4.3 miles (7 km). The erosional headland retreated landward over 0.6 miles (1 km), underwent submergence and the Isles Dernieres fragmented into four islands. The difference in retreat rate led to widening of Lake Pelto. (From Boyd & Penland, 1988.)

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C Ecosystem

C.1 Subsidence rates, land loss and land gain

Gonzalez and Törnqvist (2006) discuss the contributions of land subsidence and sea-level rise, both constituents of relative sea-level (RSL) rise, on the drowning of wetlands and barrier islands in coastal Louisiana. In most large deltas, subsidence involves a shallow component driven by compaction of mostly Holocene strata, and a deep or 'tectonic' component caused by flexure and failure of the lithosphere due to sediment loading, growth faulting, and related processes. However, along the U.S. Gulf Coast, glacio-isostasy associated with the Laurentide Ice Sheet, also contributes to subsidence. In addition, human interventions in coastal Louisiana have intensified the subsidence problem locally: artificial drainage has increased compaction rates of Holocene sediments and subsurface fluid extraction has accelerated compaction of pre-Holocene strata.

Gonzalez and Törnqvist argue that land subsidence as well as eustatic sea level rise will negatively affect coastal Louisiana in the near future. Which process will have the upper hand depends strongly on location. Future (accelerated) sea-level rise plus long-term background rates of subsidence will have a relatively larger impact on areas with thin Holocene sediment covers. In contrast, compaction-driven subsidence will be a comparatively greater player in those sections of the Mississippi delta with a thick Holocene succession.

A long-term RSL record indicates a rise of 0.55 m over the period 600-1600 AD (Figure 39A), which is 0.55 mm/yr. The role of compaction of Holocene strata is minimal in this data set, and the record tracks the interplay of eustasy, isostasy, and tectonism (see Gonzalez & Törnqvist, 2006, for more information). The long-term rate of RSL rise reported here is an order of magnitude lower than the lowest subsidence rate reported by the nearby leveling data (see e.g. Shinkle & Dokka, 2004).

The background rate of subsidence of the north central Gulf Coast can be established from the Pensacola, Florida, tide gauge, which is situated in a tectonically relatively stabile area. This subsidence is the difference between the Pensacola record (~2.1 mm/year; Figure 39B) and the most recent estimate of the rate of global sea level rise for the twentieth century (~1.7 mm/year; from Church & White, 2006), which is approximately 0.4 millimetre per year. The tide gauge record at Grand Isle, Louisiana (Figure 39B), located in the central Mississippi delta that undergoes rapid, compaction-driven subsidence of 9.4 mm/yr, is shown for comparison.

Historical subsidence rates have been calculated from elevation changes at benchmarks, which are periodically resurveyed by the National Geodetic Survey (Figure 40).

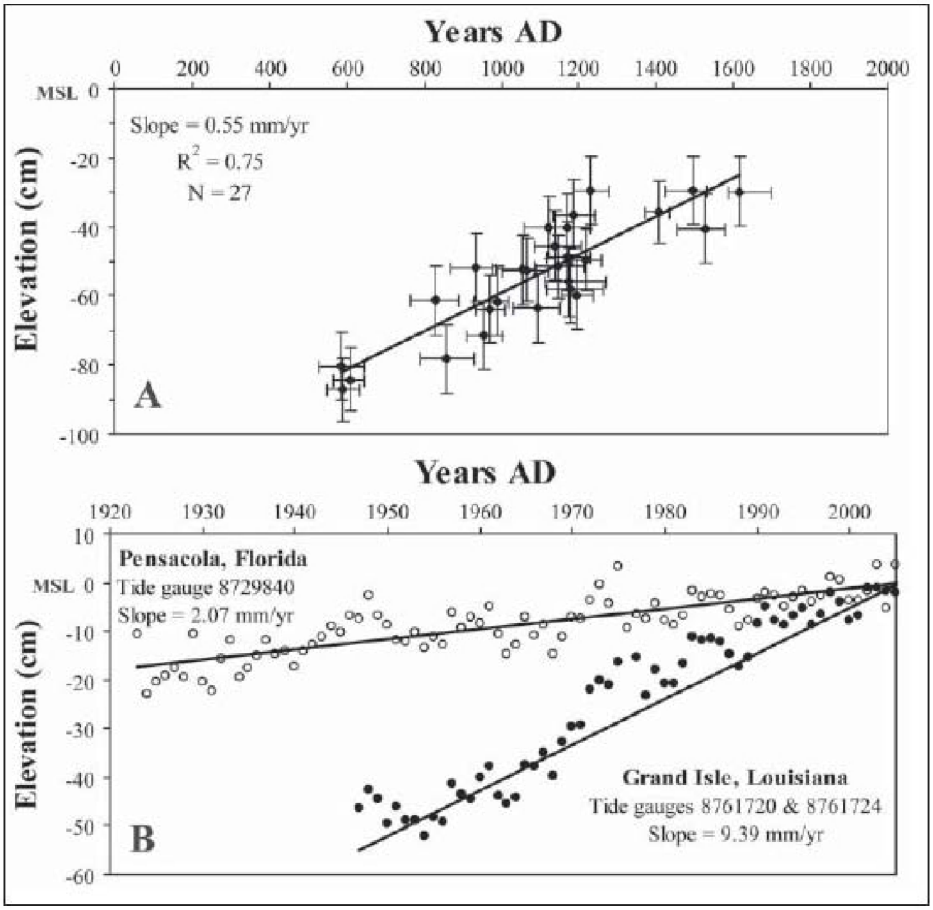


Figure 39 (A) Long-term trend of relative sea level rise for the period 600 to 1600 A.D. The data set contains 27 sea level index points and records approximately 55 cm of relative sea level rise. MSL is present mean sea level. (B) Trend of relative sea level rise for two selected tidal gauges normalized to present mean sea level. Data were obtained from the U.S. National Oceanic and Atmospheric Administration's National Oceanic Service Center for Operational Oceanographic Products and Services. From Gonzalez and Törnqvist (2006).

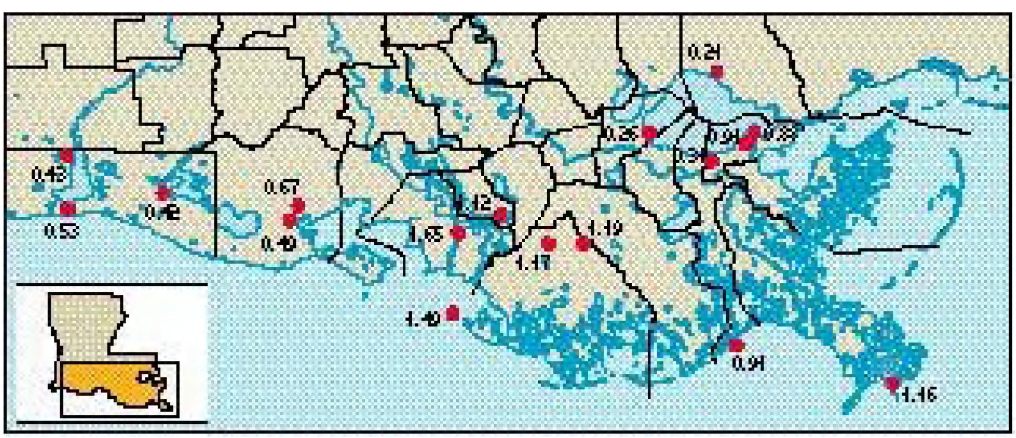


Figure 40 Coastal Louisiana subsidence rates, centimeters per year. Copied from http://biology.usgs.gov/s+t/SNT/noframe/gc138.htm

Impact of hydrocarbon production and faults

Analysis of leveling data from surveys in 1965, 1982, and 1993 along Louisiana Highway 1 between Raceland and Leeville shows that (1) subsidence rates were substantially higher near producing fields and faults than between the fields, and (2) subsidence rates accelerated between the first and second periods of measurement. In this sub-region subsidence rates between 1965 and 1982 ranged from 1.6 to 12.0 mm/yr and averaged about 7.6 mm/yr, whereas between 1982 and 1993 they ranged from 8.2 to 18.9 mm/yr and averaged about 12.1 mm/yr. (From Morton et al, 2006.)

Land Loss

Bernier et al. (2006) conclude that total wetland loss in the Louisiana delta plain is about 250 km^2, or about 50% of the 1956 land area. Analysis of land- and water-area changes for the combined study area (Figure 41) reveals a pattern of increasing land-area loss from the 1950s through the late 1960s, rapidly accelerating land loss in the 1970s, and short-term fluctuations between land loss and land gain from the 1980s to present. Net water area varied by as much as 10% between observed high- and low-water conditions since 1983 based on satellite data (Landsat Thematic Mapper). The derived wetland-loss curve (Figure 41) shows a rapid increase in wetland-loss rates from the late 1960s to 1970s. Wetland-loss rates during this time period were two to four times higher than the pre-1970s rates (Figure 42). In contrast, average wetland-loss rates since the 1980s are of similar magnitude to the pre-1970s rates.

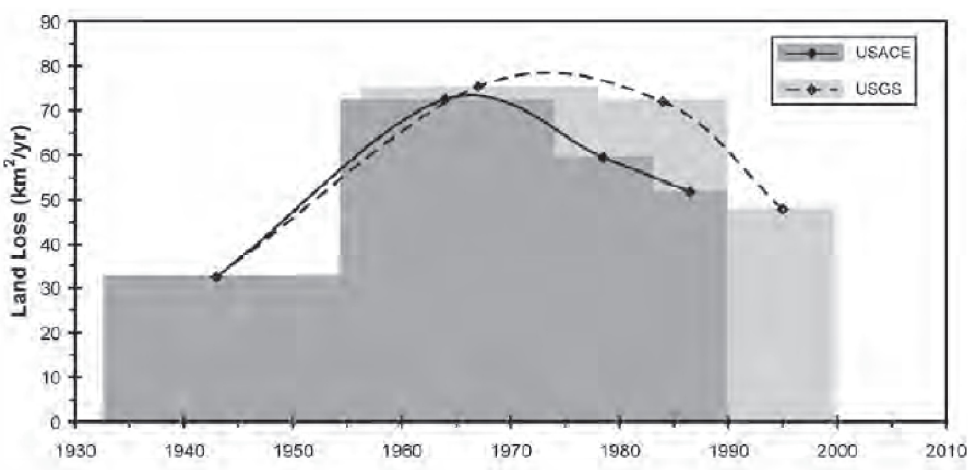


Figure 41 Land-loss rates, Louisiana delta plain, 1932-2000. Data from the U.S. Army Corps of Engineers (USACE; Britsch and Dunbar, 1993) and the U.S. Geological Survey (USGS; Barras et al., 2003). Copied from Bernier et al. (2006).

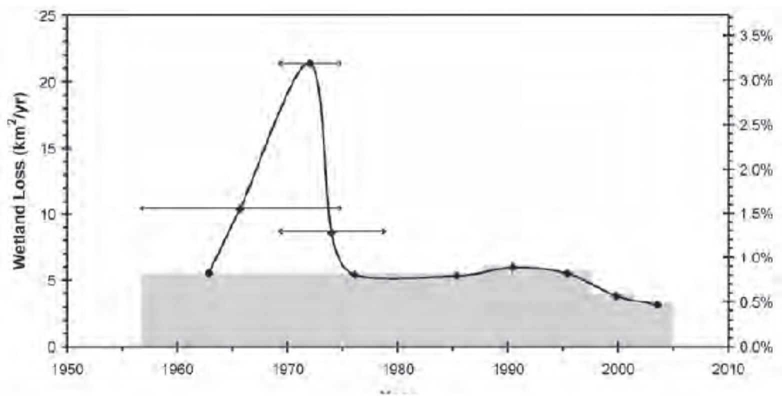


Figure 42 Rate of wetland loss for the combined study area from 1956 to 2005. The post-1983 rates were calculated from Landsat TM imagery acquired on dates for which the daily, previous day, and 3- and 7-day running average water levels at the Grand Isle, Louisiana tide gauge (NOS #8761724) were within one standard deviation of the mean water-level trend line. Peak wetland-loss rates are two to four times higher than the pre- and post-1970s background rates.

Land gain

Freshwater marshes are the primary sites of marshland succession, as new land is produced in an expanding delta lobe. Freshwater marshes occur in an actively accreting, sediment-rich, high-energy riverine environment. Sediment introduction and water level are strongly seasonal, with spring floods and late summer low-water periods. Though spring floods are the rule, expansion of the delta is episodic. In the Atchafalaya basin, for example, expansion occurs only in years when river discharge exceeds about 7,000 cubic meters per second (Figure 43).

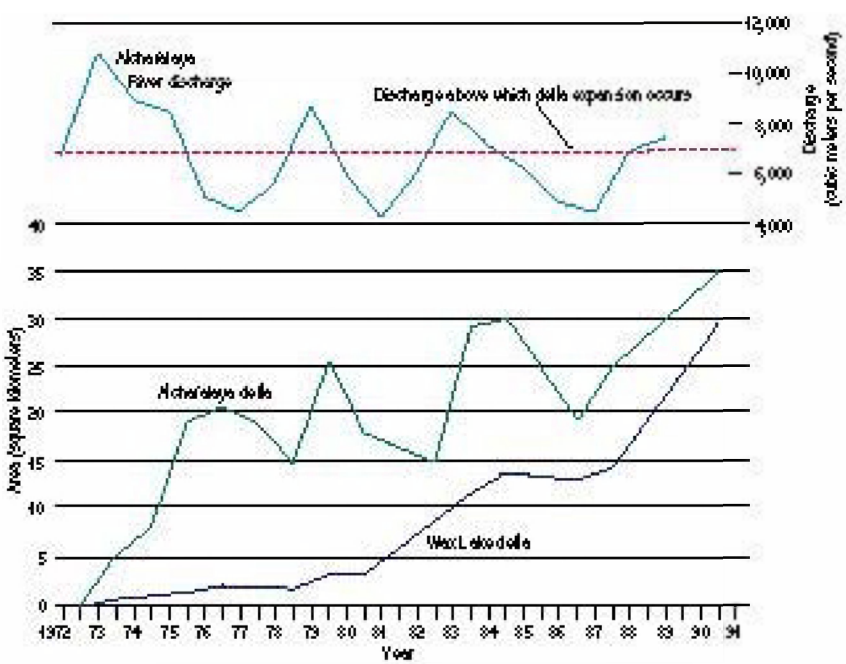


Figure 43 The relationship of growth of the Atchafalaya and Wax Lake deltas to river discharge (copied from http://biology.usgs.gov/s+t/SNT/noframe/gc138.htm).

Between 1972 and 1991, 65 km^2 of marshland (and much subtidal areas became more shallow) was formed. The same process of crevassing is active in the present "Birdfoot"- delta although a lot of sediment is continuously lost to the deeper part of the bordering Gulf of Mexico.

C.2 Ecosystem functioning and living resources

Cyclic processes

This information has been adapted from information made available though the internet (especially http://biology.usgs.gov/s+t/SNT/noframe/gc138.htm)

The only active deltaic areas on the coast today are the Balize ("Birdfoot") delta at the mouth of the Mississippi River and the actively expanding Atchafalaya River delta. Within the Balize delta, much of the heavy sediment load of the Mississippi River is entrained by levees and navigational structures and is deposited in deep water on the edge of the Continental Shelf. At present, erosional processes far outweigh land formation processes over the Mississippi delta as a whole.

The cyclic geological development of the Louisiana coast leads to plant associations or communities that are determined by the stage of development or degradation of each delta lobe (Gagliano and Van Beek 1975; Figure 44). Following a period of rapid wetland formation during the progradational phase of a delta lobe, a longer period of lobe degradation follows the shift of the river to another location. Overlapping natural environments develop and decline as the lobe ages. The sequence begins with a shallow open bay into which the river begins to pour sediments. Infilling of the bay results first in subaerial mudflats, which later become freshwater marshes and swamps (Figure 45). The natural levees along the major distributaries are elevated by sediment deposition during the largest floods and form a skeletal network of high ground that becomes terrestrial habitat amid the wetlands and lakes.

As the delta lobe expands and the river's course is canalized, portions of the lobe that receive little direct freshwater input come under the influence of marine forces, and freshwater marshes slowly change to brackish and then to saline marshes. The river abandons the lobe slowly over many years, and the system becomes progressively more saline. The compaction of recently deposited sediments and the loss of a mineral sediment supply begin a period of net subsidence, during which time the land surface gradually sinks beneath the water, the plant cover dies, the substrate disperses, and the area reverts to a shallow bay. At the marine interface, reworking of the shoreline by waves, longshore currents, and storms forms beaches and headlands that become detached from the mainland when the interior marshes are lost. Thus, a barrier island system is one of the last expressions of a degrading delta lobe. Research has shown that habitat diversity changes with age of a delta lobe with a maximum diversity occurring during the middle of the destructional decay phase. In this stage the landscape pattern has increased to maximum complexity, creating more and more habitat types. Of a total of about 16,000 km^2 of wetlands in Louisiana, marshes occupy about 10,000 km^2 and forested wetlands about 6,000 km^2. Of this 6,000 km^2, about 600 km^2 are shrub-scrub (USGS, 1990) (Figure 46).

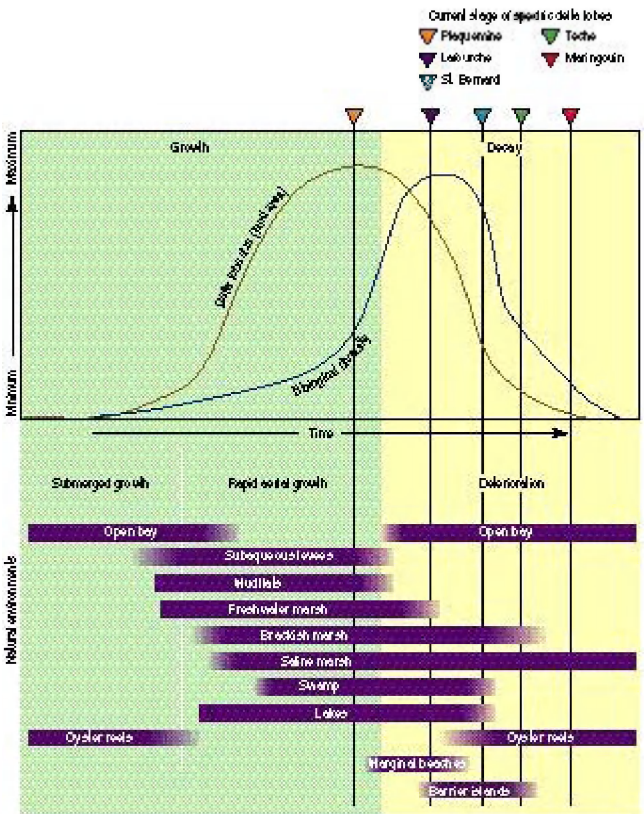
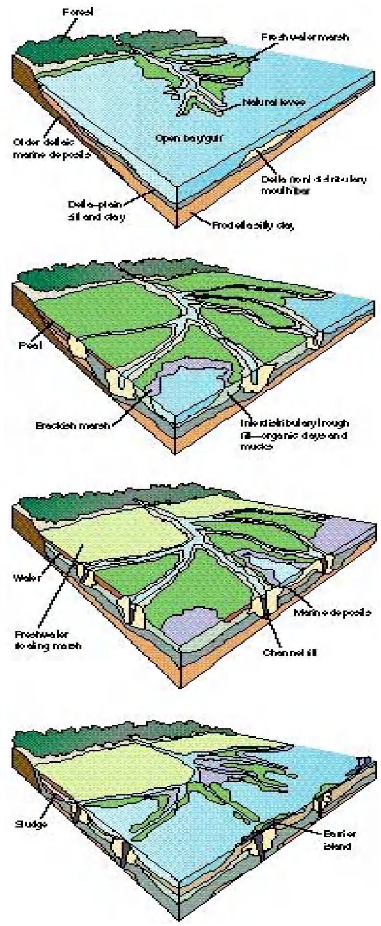
Figure 44	Figure 45
	

Figure 44 Graphical depiction of the growth and decay of a delta. Habitat and biological diversity peak in the early to middle stage of the decay phase. © Houston Geological Society. Figure copied from http://biology.usgs.gov/s+t/SNT/noframe/gc138.htm

Figure 45 Sequence of growth and decline of a delta lobe

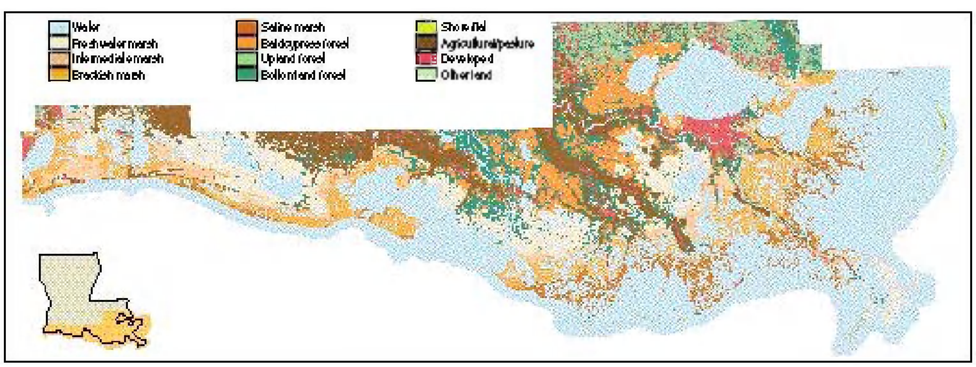


Figure 46 Map of major coastal habitats of Louisiana, 19881990 (data from U.S. Geological Survey, National Wetlands Research Center data base).

Landscape

This information has been adapted from information provided by the Barataria Terrebonne Estuary Program and other sources that were available though the internet.

The natural landscape of the Mississippi delta is characterized by a number of estuarine systems that are separated in space, but are connected form the land side by the flow of Mississippi water through its tributaries. Form the seas side, the tide moves back and forward along the coastline and provides Mississippi outflow water mixed with Gulf water to each estuary. Going from East to West at least four major estuarine systems can be identified, namely the Pontchartrain basin, Barataria and Terrebonne estuaries, Atchafalaya influence area and the Chenier plains. This structure is a result of the dynamic development of the major outflows of the Mississippi through time covering almost the complete width of the coastline of the state of Louisiana (700 km). Going from North to South, the flat land gently slopes toward the sea, producing a 100-200 km deep deltaic plain bordering the coastline. The landscape is dominated by ridge features, that have been deposited by tributaries or old outflows of the Mississippi River. Ridges are in general not higher than 6-9 m above sea level but are the highest points in the landscape and as such have been crucial as unique habitat and suitable location for agriculture and habitation. This landscape, where fresh and saline waters have been mixing, rich in nutrients and silt has been and is a great source of productivity that has been utilized by many species and has attracted man for thousands of years. The landscape has been, is and will be dynamic, meaning that erosive and accreting processes will be counteracting each other with different results in different periods and locations. What is water can become land, what is land can become water and vice versa. Also there will be and have been transitions between fresh and saline environments as a consequence.

Biotopes from fresh to salt

Salinity gradients and inundation frequencies are dominant factors controlling the biotopes that are found in the estuarine systems. The most fresh biotopes are bottomland and ridge hardwood forests and freshwater swamp forests. Hardwood forests are dominated by ash, hackberry, oak and maple trees. They are an important nesting grounds for bald eagle and migratory songbirds. The swamp forests occur in areas that are more frequently flooded by fresh river water. Here the bald cypress and moss-draped tupelo are dominating trees. Its waters are rich in crawfish. Nesting birds here are heron, ibis and egrets. If land is even lower, trees disappear and marsh biotopes dominate.

Marshes are divided into four "zones" going from fresh to salt, with subtle transitions in between. *Fresh marshes* are home to the most diverse vegetation and fauna of the area. Vegetation is characterized by maiden cane, bulltongue and spikerush. Typical animals are frogs, ducks, alligators, turtles, muskrats, mink, otters, egrets, herons and hawks. Fresh marshes can form large floating surfaces on lakes, with thicknesses of many meters. *Intermediate marshes*, with some input of saline water have a different vegetation and fauna, that can resist a little salt. This is the prime nursery habitat of brown shrimp, blue crab, gulf menhaden and other commercially and recreationally valuable species. More influence of salt results in the formation of brackish marshes, flooded with moderately salt water, where wire grass and salt grass start to dominate. This area is the area were high densities of blue crabs, shrimp, speckled trout and redfish are found. Dominating mammals are raccoons, mink and otters. The *salt marsh*, located most close to the sea is regularly flooded and is dominated by oyster grass. Here the same aquatic species are found, however sometimes in other stages of their lifecycle, while migrating between the estuary and the Gulf.

The coastal edge is formed by a chain of barrier islands, consisting of fine sand, forming beaches backed by low dunes. Beaches and dunes are popular nesting and foraging areas for many birds such as gulls and pelicans. Migratory shorebirds and songbirds frequent these barrier islands. The sandy soil provides habitat for unique shrub vegetation, the submersed shallow sandy bottoms on leeward sides provide exceptional feeding grounds for many fish species. Behind the barrier islands, the bathymetry is dominated by shallow water, dissected by a number of tidal passes and channels. These natural and man-made channels are the main conduits of salt water entering the estuarine systems (Figure 47).

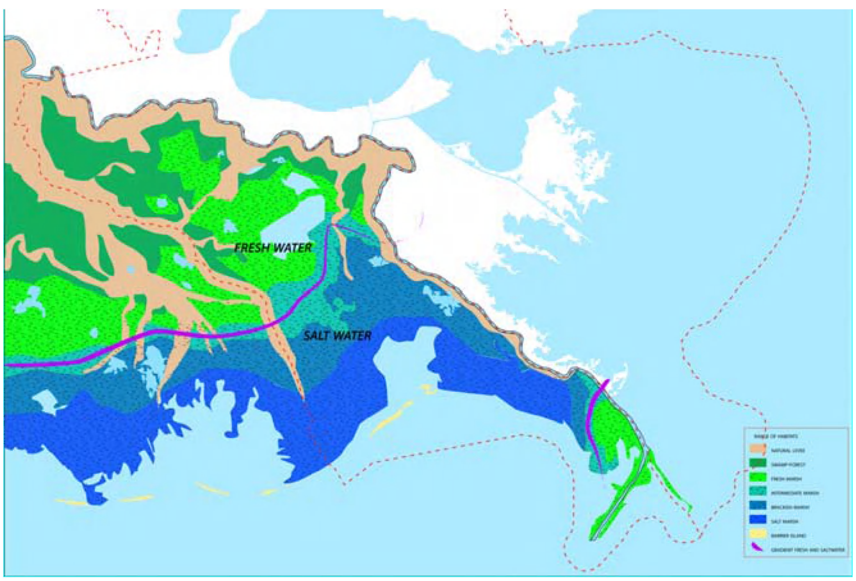


Figure 47 Biotope zoning in Barataria-estuary (source: adapted from data provided by Barataria Terrebonne National Estuary Program)

The researchers working on the CLEAR modeling project (Twilley, 2003) proposed a concept to clarify the transition between biotopes based on changes in inundation and salinity. Note that transition routes often include open water formation. Figure 48 depicts the main idea.

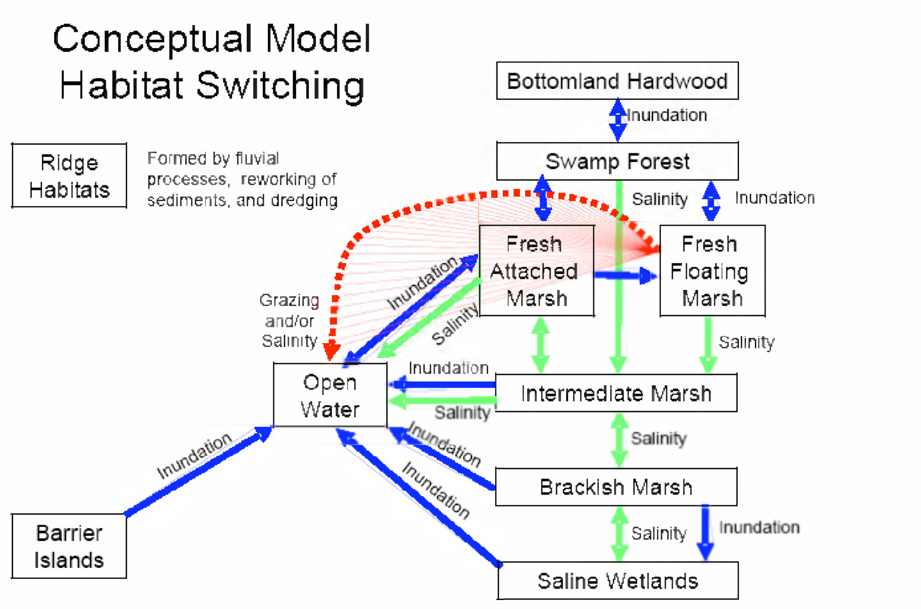


Figure 48 Concept of biotope switching processes in the Mississippi delta plain (Twilley et al, 2003). Note that grazing is also a factor leading to open water formation.

Key species

The North American Flyway passes directly over the Louisiana coast. More than 5 million migratory waterfowl spend the winter in the Louisiana marshes. Millions of neo-tropical birds utilize the area, while they cross the Gulf of Mexico.

Many animal species depend upon marsh and forest biotopes for their reproduction, nursery and food. Important biotopes have been reduced in area (for instance more than 200,000 acres of hardwood bottomland forest have been converted into agricultural lands after the 1950's. Much larger areas have been drained and converted before this period. This has reduced habitat area for the Louisiana black bear, making it a rare species. Special programs have been put in place more recently to protect the key species American bald eagle and the alligator. Populations seem to recover somewhat in the last decades.

The massive and continuing marsh losses (about 50 km^2 each year, losses have been starting before the 1930's, about 600 km^2 from 2005 Hurricanes Rita and Katrina alone) have reduced habitat area, but this is not yet clearly reflected in declines in fish and wildlife populations that depend on marsh habitat such as white and brown shrimp, blue crab or top-predators such as fish eating birds (osprey, bald eagle, pelican species). It is hypothesized that the availability of productive fresh marsh edges is compensating loss of marsh area, for the time being.

Fish and shellfish production

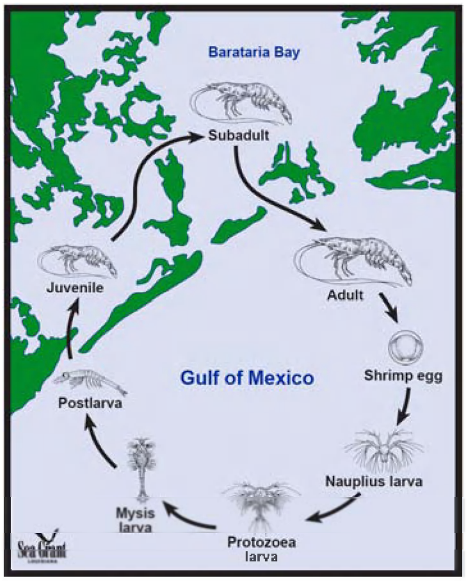


Figure 49 The life cycle of a shrimp, Elizabeth Coleman et al, 1999. Louisiana Sea Grant College Program, LSU, Baton Rouge, LA 70803. About 98% of Gulf fish species depend on wetlands for reproduction. http://www.pulitzer.org/year/1997/public-service/works/1-1/

Important species are oysters, shrimps and crabs, bay anchovy, Atlantic croaker, red drum (redfish), spotted sea trout, largemouth bass and catfish. Oyster harvesting is a long term economically important activity. Oyster biomass seems to be stable. Oyster filtration capacity could be linked to water quality if densities are sufficiently high. Oyster habitat is optimal when salinities are not very high and not too low, fresh water input needs to be significant to make oyster grow in abundance.

Growth is dependent on salinity, temperature and sufficient phytoplankton production. Oyster habitat improvement is an important aspect of oyster management. The shrimp's lifecycle is linked to the estuarine systems (nursery) and the Gulf proper (reproduction). See Figure 49. Its catch is the largest and most valuable fishery in Louisiana.

Production seems to be stable but is influenced by salinity, water temperature and tidal action. In total there are more than 200 species of finfish occurring in the estuarine systems. Anchovy and croaker are the two most abundant fish species and therefore an important part of the estuarine and coastal food chains. Red drum is an important recreational species, just like the largemouth bass. Catfish is sustaining both recreational and commercial fisheries. The latter two species are limited to the fresh parts of the water systems. Louisiana shrimp, crab and oyster production provide 26% of the total catch (by weight) in the lower 48 states of the U.S. This fishery provides jobs for 40,000 citizens of the state. Total annual catch, including fish, is worth about $400 million and ranks as the second state considering fishery production. Compared to the Netherlands situation, shellfish catch in 2005 (mainly mussels and some oysters) had a market value of about $150 million. The value of the "raw" produce was about $60 million).

When all Gulf fisheries over all states are combined, 200,000 workers in the sport and commercial fishing industries have an economic impact on the regional economy estimated at more than $5 billion. Fishery production is steadily decreasing. Practically all main commercial species are overfished or on the brink of overfishing. (Information derived from http://www.pulitzer.org/year/1997/public-service/works/1-1/).

Agriculture

Agriculture is dominated by sugarcane growing. In better drained places, soy bean, pecan, wheat and corn is grown. Many former soy bean fields have been converted to pasture lands after dramatic drops in price. It has been experienced in the area, that flooding with salt water of agricultural land, will make it unsuitable for cropping for up to ten years. Fertilizers used in agriculture are enriching waters in the estuarine systems. This has been resulting in blooms of (toxic) algae in lakes, that can affect survival and productivity of fish, crabs, shrimps and filter feeders such as oysters. Pesticides such as atrazine, that is used to combat weeds, are washed out into the groundwater, lakes and channels. This is causing elevated concentrations in drinking water close to or exceeding toxic limits. Run-off of fecal coliform bacteria is regularly limiting the harvestability of shellfish such as oysters, due to ensuing health risks.
Mercury accumulation is presently limiting the consumption of some fish species. It has been reported that breeding success of for instance local pelican colonies could be influenced subsequently by this kind of pollution. Sugar cane growing and cattle raising produce an annual value of about $300 million (in Barataria Terrebonne Estuary System).

Other resources (oil, gas)

The Louisiana coastal zone had rich resources in natural oil and gas. The production of oil and gas has decreased about a factor 4 between 1990 and 2001. Oil production has been moved to offshore, where large reserves are exploited. The oil industry has developed a lot of refining and chemical infrastructure in the coastal area, to provide a link between oil production sites and inland transport networks. Inshore production value was about $1 billion in 2001. This coastal network transports 30% of the nation's gas and oil supply. 80% of U.S. offshore production is transported through the Louisiana coastal zone. 50% of the U.S. refinery capacity is located in this area. The exploitation of these resources has influenced the landscape considerably. Many channels have been dredged through the marshes to access drilling stations and enable construction of pipe lines. This has changed water circulation and salinity gradients in many areas of the delta. Accelerated subsidence rates have been linked to oil and gas extraction (a proven impact of natural gas extraction is in the Dutch Wadden Sea of the Netherlands where the seabed subsided at places about 30 cm after gas extraction in a period of about thirty years).

Main issues

Pollution (oil, chemicals, nutrients)
The nutrient load being discharged by the Mississippi has produced a regular hypoxia in the Gulf of Mexico, killing all non-mobile species and some fish every summer season. The area of the "dead zone" is about 21,000 km^2. It stretches along the entire coast of Louisiana. This nutrient load is produced by intensive agriculture practices upstream in the Mississippi basin. In some years, the "dead zone" enters the nearshore shallow waters, killing many animals. Large scale restoration of the lost filtering function of fresh, brackish and salty wetlands for Mississippi River water will help reduce this phenomenon. Yearly, about 3,000 oil or chemical spills are recorded along the Louisiana coastline by the Coast Guard Marine Safety Office. See also *http://www.pulitzer org/year/1997/public-service/works/1-1/*

Changed water circulation and salinity cause biotope switching

Construction of shipping channels has promoted the intrusion of saline water into formerly fresh parts of estuaries. The MRGO canal brings saline water into Lake Pontchartrain, causing considerable mortality of local fauna and flora. The Houma shipping channel and channels dredged for oil exploration have the same effect. Salt marsh erosion is allowing saline waters to flow further into estuaries and is now threatening the drinking water quality of people living in the Southern parts of the bayous. Switching between biotopes is caused by the same processes. Large-scale infrastructure parallel to the coast such as highways and railways has disturbed the normal flow of water. This has caused changes in the health of existing biotopes that have become either too fresh or too saline, or have experienced changes in inundation regimes.
Known from historical times, massive oyster reefs in front of the coastal zone have now disappeared because of changes in water discharge and salinity gradients.

Oyster squeeze

The best-known mollusk in Louisiana estuaries is the eastern oyster, which has been extensively studied because of its commercial importance. At the seaward end of the estuary, oysters are being pushed inland by encroaching saltwater, which favors oyster predators and parasites. At the landward end of the estuary, oysters are being pushed seaward by pollution from developed areas. Regularly, oyster fishing if closed due to bacterial pollution levels being exceeded. Despite this squeeze, the area of substrate potentially suitable for eastern oyster production is increasing as wetlands degrade, and the area leased for oyster production is also increasing (Condrey et al. 1995).

Saltmarsh subsidence, eat-out and erosion

Compaction of subsoil and sea level rise are important causes of relative subsidence. Oil and gas extraction add an unknown fraction. Saltmarshes and levees get waterlogged and this influences the mortality of species. For instance many oak trees on levees in the Southern part of the delta are now dying or dead. due to waterlogging. Saltmarsh vegetation is sensitive to chemical changes in the subsoil that are caused by waterlogging. In addition, the introduction of an exotic mammal species (Nutria) is causing overgrazing of saltmarshes resulting in mortality. Once a saltmarsh patch has died off, stability is lost and erosion accelerates. An increase in large open water surfaces will allow more waves and higher current speeds. This will further increase erosion.

Hydrocarbon and formation water production

Various studies of induced subsidence in the Gulf Coast region demonstrated that reductions in land elevation can occur either directly above the producing formation or several kilometers away from producing wells. At some of the investigated sites, the locus of subsidence and land loss was controlled by the coupling between reservoir compaction and slip along growth faults that become active when sufficiently large volumes of fluid (oil, gas, formation water) were removed from the subsurface (Figure 50 and Figure 51).

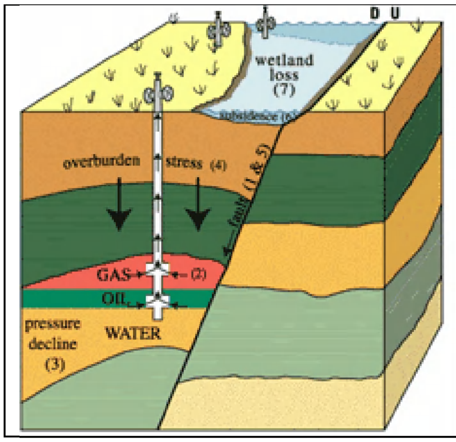


Figure 50 Possible effects of petroleum production. Prolonged or rapid production of oil, gas, and formation water (2) causes subsurface formation pressures to decline (3). The lowered pressures (3) increase the effective stress of the overburden (4), which causes compaction of the reservoir rocks and may cause formerly active faults (1) to be reactivated (5). Either compaction of the strata or downward displacement along faults can cause land-surface subsidence (6). Where subsidence and fault reactivation occur in wetland areas, the wetlands typically are submerged and changed to open water (7). Figure is not to scale. D, down; U, up. (copied from Morton et. al., 2006).

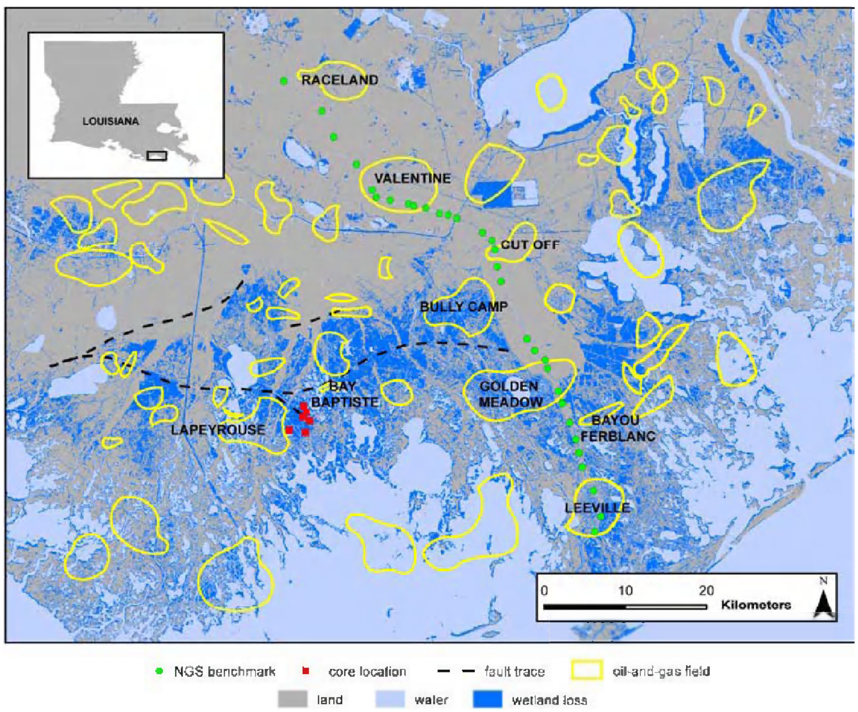


Figure 51 Map of South Louisiana showing data sets near and along Louisiana Highway 1 between Raceland and Leeville, including locations of benchmarks along Louisiana Highway 1 (green circles), oil and gas fields, wetland losses, and cores from the Madison Bay study area (red squares). Fault projection from Kuecher and others (2001); wetland losses from Morton et al. (2005); outlines of producing fields modified from Morton and Purcell (2001). (copied from Morton et. al., 2006).

Rates of wetland loss in the 1990s and early 2000s were slower than when the wetlands collapsed between the 1960s and 1980s. The deceleration in rates of wetland loss, which corresponds with the rapid decline in hydrocarbon production, could signal a reduction in the underlying rates of subsidence (Figure 52 and Figure 53).

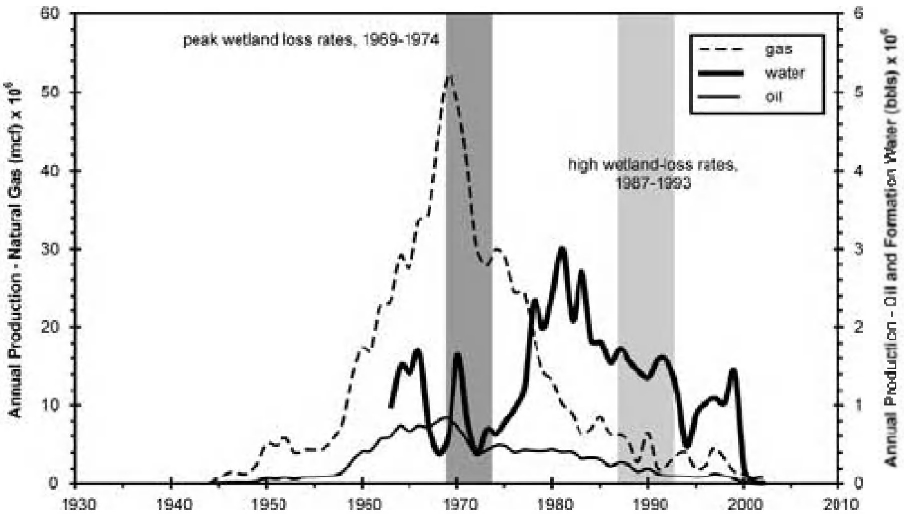


Figure 52 Cumulative hydrocarbon production in the Lapeyrouse and Bay Baptiste Fields, Louisiana from 1944 to 2002. Compare with production history with changes in wetlands observed in air photos at nearby Madison Bay. Production data from the Louisiana Department of Natural Resources and the PI/Dwights PLUS Database (HIS Energy 2003). Wetlands began rapidly disappearing after the field begain rapidly producing large volumes of hydrocarbons in the 1960s. Wetland loss generally slowed when hydrocarbon production rates declined. Wetland loss also was rapid in the late 1080s and early 1990s following a peak period of formation water production. Copied from Morton et al. (2006).

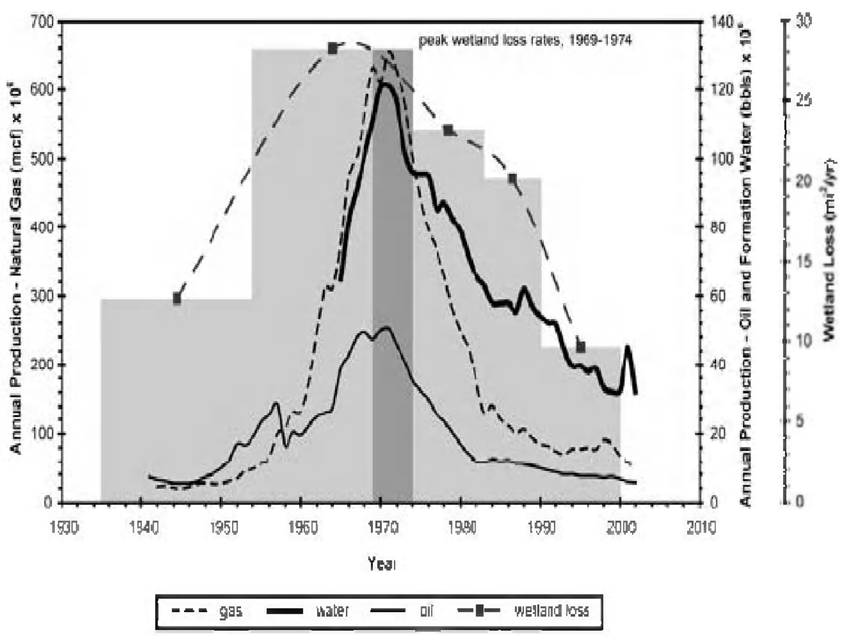


Figure 53 Composite histories of fluid production from oil-and-gas fields and wetland loss in South Louisiana. Production data from the Louisiana Department of Natural Resources and the PI/Dwights PLUS Database (HIS Energy 2003). Wetland loss values were determined by Britisch and Dunbar (1993) and John Barras (unpublished data). These historical data, integrated across the delta plain, show close temporal and spatial correlations between rates of wetland loss and rates of fluid production. Copied from Morton et al. (2006).

Impact of canal construction

Canals currently comprise about 2.5 percent of the total coastal surface area in Louisiana and the percentage has been increasing with time. Historically, canals have been dug for drainage and access. Today the greatest share of canalization is attributed to the oil and gas industry (see Figure 54). In 1984, 70 to 80 percent of the coastal management permits issued for canals were for oil and gas activities. The primary reasons for the myriad of canals in the Louisiana coastal zone include navigation, pipeline routes, and access to drilling sites. Although dredging canals has only directly converted 2.5 percent of the wetlands to open water, their impact is much greater. Spoil banks composed of the material dredged from the canals tend to smother adjacent marshes, converting wetlands to uplands, often interrupting natural hydrologic processes, and blocking the distribution of sediment. Canals oriented perpendicular to water flow tend to impound water and reduce sediment availability, and ponding of water can drown a marsh. Canals parallel to water flow tend to lessen freshwater retention time and allow greater inland penetration of saltwater. Researchers such as Turner et al. estimate that as much as 90 percent of Louisiana's land loss can be attributed to canals. (after EPA-230-02-87-026, Saving Louisiana's Coastal Wetlands, April 1987).

A relationship between canal density, salinity intrusion and marsh loss rate was found. Turner et al. (1982) found that in places where canal density was zero, marsh loss was always less than 10% of the total loss and was usually nearly zero. This finding indicates that if there were no canals, the marsh loss rate would be less than 10% of the present rate. The area actually dredged out of the marsh for a canal is less than 10% of the total loss. The rest of the loss is attributed to indirect effects of circulation disruption by the canal and its spoil deposits, unintended impoundment of wetlands, and saltwater intrusion into freshwater wetlands (Turner 1987; Turner and Cahoon 1987). (after http://biology.usgs.gov/s+t/SNT/noframe/gc138.htm)

The levees created by the spoil banks not only alter the natural hydrological flow, but can also block migration of aquatic organisms. Because the canals are deeper than the surrounding wetlands, they allow larger predators to enter areas inhabited by juvenile fish. Marked declines in fish catch by some Louisiana commercial fishing industries have been noted as a direct result of predation and loss of migratorial passageways (Reed, 1994, 1995).

Tides enter and leave through the canals at a greater velocity than through undisturbed marsh, resulting in erosion and widening of the banks. Annual increases in canal width range between 2 to 14% (Craig et al. 1979). Saline water travels up the canals, invading deep into freshwater territory, causing vegetation to die and creating open water where dense vegetation previously existed.

In an undisturbed system, nutrient-laden sediments would naturally flow through the wetlands and be utilized for primary production. Now canals reroute it to lakes and ponds, causing an increase in eutrophication. Canals are, therefore, directly linked to loss of wildlife habitat, and to the decrease in the effectiveness of the marsh as a natural water purifying system (Craig et al. 1979). After Leanne Lemire http://horticulture.coafes.umn.edu/vd/h5015/97papers/lemire.html.

Figure 54 Canals dug in Louisiana's coastal marshes for oil and gas drilling and production operations.

After a three-year (1991–1993) field investigation Wang (1997) found that deposition of sediments on intertidal marshes was influenced by man-made canals that alter the hydrologic regime in the upper reaches of the tidal channel. Bryant and Chabreck (1998) reported the influence of impoundment on marsh growth. They found a clear relationship between flooding regime, sediment load, growth of root biomass and bed level increase.

Canal damage remediation techniques

After: Lemire, L. Backfilling canals to restore Louisiana wetlands.
(http://horticulture.coafes.umn.edu/vd/ h5015/97papers/lemire.html).

Five main solutions are listed and discussed by the author to remediate canal damage.

1) Controlled Diversion: One proposed mitigation technique was to allow USACE to divert some of the Mississippi River water into a controlled area, creating a new delta. This diversion could create more wildlife habitat and could potentially improve fisheries. This would require prior planning, operational experience and ongoing management. Although the cost and efficiency would have been low, there was a great deal of concern regarding the concentrations of heavy metals and pesticides in both the water and sediment. This potential project was put on hold pending further investigation.

2) Reuse of Spoil: A 5-year research project was conducted by USACE to reuse material from spoil banks. Some suggestions included deposition as a substrate for wildlife habitat, beach renewal, restoration of bare ground, road construction material and sanitary land filling. The study concluded that spoil material used as a biologically productive substance could be effective and the results could be accurately measured. Although this alternative could be used as a post-remedial action, it would not halt the ongoing loss from continued dredging and canal building.

3) Regulatory Controls: Regulatory controls have the advantage of affecting the entire coastal zone area. It requires builders comply with standardized practices. Controls suggested include (1) standardizing the depth of canals and requiring companies to backfill them once they were no longer in use, (2) prohibiting new canal construction, (3) minimizing new canal construction by the use of existing canals, (4) plugging pipeline canals with earthen or shell dams (plugs) wherever possible, (5) no new wetland impoundments, (6) avoiding or eliminating residential development on wetlands, and (7) reserving spoil material to build new marshes. While these methods would not eliminate past damage, but further wetland destruction would be halted.

4) Saltwater Intrusion Remediation: Remediation efforts have been suggested to reduce the impact of saltwater intrusion. Impoundment or semi-impoundment by constructing low levees with spoil material close to the marsh edge will limit water exchange. Little is known about this technique's long-term effectiveness. Impoundments do not allow for fish migration. Studies have also shown that hurricanes have a more devastating effect on impounded areas than on natural marshes. A second suggestion was to divert freshwater into the marshes to reduce salinity. A third option to restore the natural hydrology of the wetland system was to permanently close some canals, and to install locks in navigation channels.

5) Backfilling Canals: The most important of the five mitigation techniques was backfilling of the canals. In one study, 33 canals that had been abandoned by the oil industry were backfilled. The backfilling process consisted of bulldozing spoil banks back into the canals. Removing spoil from banks to encourage re-vegetation, and restoring the canal depth to its natural state. After backfilling was completed, return visits were routinely done. Sediment deposition and loss was measured, as was canal depth and width (Turner et al., 1994).

The cost of this backfilling project was in the range of $1,200 to $3,400 per hectare. In contrast, building of the original canals were constructed at an average cost of $25,000. Other positive aspects of this technique were that costly equipment was not required and there was no further on-site management required. Once backfilling was completed, the area was left for natural processes to take their course.

The results of backfilling have been effective. Although some canal delineation is still discernible, the edges of the spoil banks are becoming more irregular. Re-vegetation is occurring on spoil banks, although if the elevation was too high, there was a change in species. Dendritic drainage patterns have reestablished and have begun to revert back to their natural hydrologic flow, especially in areas where no plug was in evidence. Where plugs were intact, wildlife and fish habitats were created but did not allow for migratory aquatic species. In addition, deposition of sediments and nutrients were not apparent.

Some of the most significant factors that influenced the success of the backfilling project was the canal length and whether or not sufficient amount of spoil material was returned to the canal. These factors were directly related to the experience of the dredge operator. Putting the correct amount of spoil material back in the canal without gouging the marsh or causing the marsh elevation to be too high or too low, was a key factor. Because there are so few skilled operators, it was difficult to get consistent results.

Backfilling as a restoration technique to manage abandoned canals is easy, cost effective and does not require further on-site management. The area becomes re-vegetated, and erosion is halted. The natural hydrology is restored and fish and wildlife become more abundant. As more abandoned canal sites become available, more opportunities will be available for future wetland restoration.

Backfilling canals to restore Louisiana wetlands

Canals have been built for access and transport of oil, which has been extracted from the coastal area. One restoration technique being utilized is backfilling of canals once they have been abandoned by the oil companies. Results of a series of backfilling experiment were reported by Neill and Turner (1987) and Turner et al. (1994). Plugged canals contained more reestablished marsh and much greater chance of colonization by submerged aquatic vegetation compared with unplugged canals. Complete reestablishment of the vegetation was not a necessary condition for successful restoration. In addition to providing vegetation reestablishment, backfilling canals resulted in shallow water areas with higher habitat value for benthos, fish, and waterfowl than unfilled canals. Spoil bank removal also may help restore water flow patterns over the marsh surface.

C.3 Toward reduction of land loss

Planned and implemented measures for curtailing wetland loss

The possible options for curtailing wetland loss are numerous. They include diverting freshwater and sediment into the marshes; changing the course of the Mississippi River; modifying patterns of water and sediment flow to the marshes; maintaining wetlands artificially; restoring the barrier islands; and shifting away from the types of canals, channels, and levees that have destroyed wetlands to alternative transportation and flood protection strategies that have less adverse environmental impact. More information can be found in EPA document EPA-230-02-87-026.

Barrier island restoration using dredging spoils

Thus far the most extensive land loss has occurred in the Barataria basin and around Terrebonne Bay in an area South of New Orleans and West of the Mississippi. Not surprisingly, the barrier islands protecting this region have deteriorated to an alarming extent and are in need of restoration. The Isles Dernieres barrier island chain, which protects Terrebonne Bay, is one of the most rapidly deteriorating barrier shorelines in the United States and for the most part is unable to perform its shore protection function. Chain breakup has resulted both from major storm actions and from the loss of nourishing sediment from the natural system. Whiskey Island, a representative part of the Isles Dernieres chain, lost an average of 31.1 acres (12.6 ha) per year from 1978 to 1988.

One source of new sediment for restoring the Isles Dernieres chain is Ship Shoal. In April 2004 the Minerals Management Service of the U.S. Department of the Interior issued an environmental assessment dealing with the issuance of noncompetitive leases for using outer continental shelf sand resources from Ship Shoal to replenish the coast and barrier islands. This assessment considered the effects on sensitive coastal and near-shore resources of the mining of approximately 14 million cubic yards (11 million m^3) of outer continental shelf sand. The processes evaluated would use either a trailing suction hopper dredge or a cutterhead suction dredge to place the sand either on barrier islands for restoration or into temporary storage for later use as a construction material.

Ship Shoal is a submerged remnant of an ancient barrier island arc that lies about 10 miles (16 km) South of the Isles Dernieres chain. The shoal is about 31 miles (50 km) long and 3 miles (5 km) wide, with a relief up to 12 feet (3.6 m). The water between Ship Shoal and the barrier islands is no deeper than about 32 feet (9.7 m), and for most of the way its depth is less than 20 feet (6 m). This would hamper the use of large hopper dredges and large transport barges. Coastal engineers will have to decide between long-distance pumping in a 10 miles (16 km) pipeline with booster stations and some combination of hoppers, barges, and shorter pipelines.

Concepts for Large-scale Restoration in Coastal Louisiana Using Long Distance Conveyance of Dredged Material

After: Reed, D.J., 2004. Concepts for Large-scale Restoration in Coastal Louisiana Using Long Distance Conveyance of Dredged Material. Report based on a Technical Workshop organized by USEPA in October 2004. http://www.epa.gov/earth1r6/6wq/ecopro/em/cwppra/b_dupont/long_ distance_conveyance12_04.pdf

Natural process solutions, such as diversions, would introduce new sediments into the system, but gradually over many years. Larger diversions would dramatically alter the salinity regime of the basins. There are also concerns regarding the fate of nutrients introduced with the river waters and the potential for eutrophication and perhaps harmful algal blooms. The introduction of new sediments into the estuarine basins could also be achieved through long-distance pipeline conveyance of dredged materials. A workshop held in October 2004 focused on the conveyance technology and clarified for many in the Louisiana restoration community that the movement of dredged material many miles across the coast to areas of need was technologically feasible. Concerns remained, however, regarding the use of large quantities of dredged material to create functional marsh habitat on a large scale (i.e., thousands of acres).

C.4 Timeline of recent restoration activities

This timeline was copied from info made available on the web of the Northeast-Midwest Institute http://www.nemw.org/louisiana.htm.

Below a timeline is given of events establishing and implementing restoration activities in Coastal Louisiana since 1993:

The Louisiana Coastal Wetlands Restoration Plan, 1993

The Louisiana Coastal Wetlands Conservation and Restoration Task Force, as mandated in the Breaux Act, completed the "Louisiana Coastal Wetlands Restoration Plan." The Plan provided a comprehensive approach to restore and prevent the loss of coastal wetlands. Using a basin planning approach, a number of needed projects are identified and the implementation of major strategies is called for, such as the abandonment of the present Mississippi River Delta, multiple diversions in Barataria, reactivation of old distributary channels, rebuilding barrier island chains, seasonal increases down the Atchafalaya, reversal of negative hydrologic modifications, and controlling tidal flows in large navigation channels.

A Long-term Plan for Louisiana's Coastal Wetlands, 1993

S. M. Gagliano and J. L. van Beek for the Louisiana Department of Natural Resources completed "A Long-term Plan for Louisiana's Coastal Wetlands." The Plan provided for comprehensive offensive and defensive strategies to be carried out in two 25-year phases. Key elements of the Plan included the establishment of a "Hold Fast Line", reallocation of Mississippi River flow with the establishment of phased subdeltas, estuarine management and an orderly retreat seaward of the "Hold Fast Line", and succession management of freshwater basins landward of the "Hold Fast Line." Volume two listed possible sources of funding for plan implementation.

Barataria-Terrebonne National Estuary Program, 1993

The Management Conference of the Barataria-Terrebone National Estuary Program generated a list of 254 potential actions that would help the Program achieve it's twelve goals. Of these, fifty-one were being developed through the Program.

A Long-term Comprehensive Management Plan for Coastal Louisiana to Ensure Sustainable Biological Productivity, Economic Growth, and the Continued Existence of its Unique Culture and Heritage, 1994

Dr. van Heerden completed a "Long-term Comprehensive Management Plan for Coastal Louisiana to Ensure Sustainable Biological Productivity, Economic Growth, and the Continued Existence of its Unique Culture and Heritage." The Plan attempted to simulate natural delta growth processes by creating river diversions and reestablishing former distributaries and restoration of Louisiana's barrier islands.

An Environmental-Economic Blueprint for Restoring the Louisiana Coastal Zone: The State Plan, 1994

The Governor's Office of Coastal Activities' Science Advisory Panel Workshop completed "An Environmental-Economic Blueprint for Restoring the Louisiana Coastal Zone: the State Plan" as directed by the Wetlands Conservation and Restoration Authority (State Wetlands Authority), under Act 6. The report provided a long-range blueprint for restoring Louisiana's coastal wetlands, which included several key provisions. The most important of these were: (1) diverting Mississippi River water and sediments into key locations; (2) restoring, protecting, and sustaining barrier islands; and (3) modifying major navigation channels to reduce saltwater intrusions and storm surge entry.

Scientific Assessment of Coastal Wetland Loss, Restoration and Management in Louisiana, 1994
Dr. Boesch published "A Scientific Assessment of Coastal Wetland Loss, Restoration and Management in Louisiana." The report assessed the then-current restoration approaches and wetland loss processes, and provided scientifically-based recommendations to improve restoration efforts. It determined that the Breaux Act was off to a good start, but that (1) region-wide strategies needed better integration with small-scale ones, (2) better technical and policy review was needed, (3) private land rights should be balanced with greater public interests, and (4) financing for large-scale introduction of alluvial materials should be obtained.

Sierra Club Legal Defense Fund petition the U.S. Environmental Protection Agency, 1995
Leading a group of 17 stakeholders, the Sierra Club Legal Defense Fund petitioned the U.S. Environmental Protection Agency and the Governor of Louisiana to convene a management conference under Section 319 of the Clean Water Act. In coordination with other agencies, the U.S. Environmental Protection Agency responded by initiating an exchange of scientific knowledge and public information through a series of workshops and symposia. Conferences held in New Orleans, Louisiana and Davenport, Iowa conveyed information on the dynamics and effects of hypoxia, links to nutrient loads from the Mississippi River System, and management activities under way in the basin. Soon after, the Environmental Protection Agency convened meetings of high-ranking federal officials to start a policy dialogue and asks the White House Office of Science and Technology Policy to conduct what would become an assessment of hypoxia in the Northern Gulf of Mexico.

Louisiana Coastal Wetlands Conservation Plan, 1997
As authorized in the Breaux Act, the U.S. Army Corps of Engineers, U.S. Fish and Wildlife Service, and the U.S. Environmental Protection Agency completed the "Louisiana Coastal Wetlands Conservation Plan." In order to achieve no net loss of coastal wetlands due to development activities, the plan recommended actions including public education, innovative technology development, and landowner assistance.

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 1997
The federal workgroup dealing with nutrient issues in the Mississippi River/Gulf of Mexico region was broadened to include state and tribal officials and given a new name -- the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force.

Coast 2050 initiative launch, 1997
At the urging of the Coalition to Restore Louisiana, state and federal efforts launched "The Coast 2050 Initiative" to arrive at an overall vision and strategic plan for coastal restoration in Louisiana. Coast 2050 sought input from local governments and the public for the development of a consensus-based restoration plan in partnership with state and federal agencies. Regional ecosystem restoration strategies and habitat objectives that are judged to be technically sound and publicly acceptable were developed for the entire coastal zone of Louisiana.

Harmful Algal Bloom and Hypoxia Research and Control Act of 1998
Congress enacted the Harmful Algal Bloom and Hypoxia Research and Control Act, creating an interagency task force on harmful algal blooms and hypoxia, mandating both a national

assessment of harmful algal blooms and a national assessment of hypoxia; and calling for an integrated assessment and action plan for hypoxia in the Northern Gulf of Mexico.

The Coalition to Restore Coastal Louisiana releases "No Time To Lose: Facing the Future of Louisiana and the Crisis of Coastal Land Loss", 1999
The Coalition to Restore Coastal Louisiana released "No Time to Lose: Facing the Future of Louisiana and the Crisis of Coastal Land Loss." The publication detailed five fundamental principles that must govern restoration policies in the region, including the expansion of coastal restoration efforts.

Atchafalaya Bay Delta Reevaluation project, 2000
The Atchafalaya Bay Delta Reevaluation project was initiated to address new alternatives for flood control and navigation. The alternatives included re-routing of the navigation channel, opening additional outlets from the upper basin, closing the lower Atchafalaya River outlet for lower river flows and delta management. The study was conducted with close cooperation from local, state and federal resource agencies.

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force Action Plan, 2001
The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force released it's "Hypoxia Action Plan," identifying the programs and tools critical for reducing nitrogen-loading to the Mississippi/Atchafalaya River Basin and the Gulf of Mexico.

Terrebone voters pass a quarter-cent sales tax, 2001
Terrebone voters passed a quarter-cent sales tax to help pay the local share of the planned $719 million hurricane-protection system. The local tax was estimated to raise roughly $4.5 million a year for the project. The state promised to match every dollar raised locally in order to pay for costs not covered by the federal government.

Legislative audit criticizes Louisiana Department of Natural Resources, 2004
A legislative audit criticized the Louisiana Department of Natural Resources' division that oversees the coast for not doing a good enough job of ensuring that wetlands development is mitigated. The Department asked lawmakers to strengthen the department's enforcement and permitting rules.

Local government officials and business leaders push Congress, 2004
Local government officials and business leaders pushed Congress for the Morganza-to-the Gulf hurricane-protection system, which aimed to protect Terrebonne from hurricanes, and the Third Delta Conveyance Channel, which would channel fresh water from the Mississippi River to ailing local wetlands.

C.5 Summary of findings on wetlands

- The cyclic geological development of the Mississippi Delta is the driver of a cycle of habitats and biodiversity at each location in the Delta, spanning many millennia. Nothing lasts forever. All lobes are at present in the high biodiversity, slow "deterioration-phase" of this cycle. The Atchafalaya delta is an example of the natural fast growth-phases as part of the same cycle.

- Long term relative subsidence is estimated between 2-7 mm/yr. Main causes are compaction, sea level rise, fault activation and post glacial land subsidence. Compaction rates are highest in the youngest deposits.
- Historic subsidence rates are measured at 12 mm/yr in the Mississippi Delta with increased rates between 1960-1990's up to 30 mm/yr. As main new cause for subsidence oil and gas extraction is identified.
- At present subsidence rates (and marshland loss) seem to have slowed down again. This is suggested to be linked to depletion of hydrocarbon resources and therefore the gradual end of oil and gas production in the area.
- Marshland accretion rates are measured at 7-13 mm/yr, at least half of this accretion is from locally produced organic matter. Regularly flooded marshes accrete the most rapid and contain highest anorganic fractions. 1,000 gr sediment can result in 1 cm/m^2 vertical marshland accretion. Natural accretion is therefore able to cope with long term subsidence rates and a little extra.
- Marshes close to streams and canals receive the highest sediment loads and therefore sustain higher accretion rates than backmarshes. High sediment loads produce increased nutrient availability and therefore also sustain higher productivity.
- Canal formation is considered as one of the most important causes of marshland loss. Canal formation has altered hydrodynamics. If this caused changed flooding frequencies, marsh accretion has been affected. Nutrients are flushed to the sea without being taken up in marshland vegetation. Fresh marshes are flooded less, because water is channeled more effectively toward the sea. Marshes in tidal areas could be flooded more frequently.
- Opening up of marshes is increasing erosion by increasing wave fetch and current speeds. Increasing flooding depth and frequency could compensate a little, by importing more sediment for marsh accretion.
- In addition, marsh browning disease and overgrazing by an exotic rodent is reducing marshland areas further.
- Main restoration options collected from various authors to restore marshlands in open water areas and broken marsh with few spoil banks are marshland creation and marshland nourishment. One could:
  - Enhance local sediment import and stabilization at the edge of open water areas in order to restore marshland horizontal extension.
  - Use long-distance pipeline conveyance of suitable dredged materials (fine fractions) to provide kick-start of marsh creation especially in combination with channel infilling.
  - Create river diversions in order to restore the hydrology and long-term marsh nourishment, but too large changes in salinity or salinity variations could conflict with dominant uses (such as oyster culturing) and could induce marsh mortality, leading to open water formation.
  - Create subtidal barriers consisting of coarse materials to reduce fetch and storm surges, explore the possibility to combine this with protective oyster reefs.

   - Restore or create new shorelines to enhance the success of marsh nourishment and marsh creation in the leeward-areas. This can help to reconstruct salinity gradients inshore.
   - Create or restore islands to provide further reduction of fetch and restoration of bird breeding habitat.
   - Provide piped sediment to areas where sediment is needed, without providing an overdose of fresh water or saline water.
- Main remediation actions to compensate marshland loss caused by canals are:
   - Plugging, isolating or backfilling of canals to restore hydrologic and salinity gradients
   - Restoration of regular flooding to restore natural accretion rates by breaching of spoil banks.
   - Manage rodent populations and marshland burning.
   - Restore hydrology of impounded areas (for instance areas sealed off artificially by levees, by railway or roads).
   - Use remaining spoil banks and other higher elevation features to stabilize adjacent marshes and to create wooded habitats and conduits for sediment-transport conveyance channels.

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D Hydraulics and Morphology

Preface

The project activities in the framework of hydraulics and morphology are based on exploratory simulations with Delft Hydraulics' hydrodynamic and morphodynamic process based model Delft3D (http://www.wldelft.nl, Lesser et al., 2004). Although this model is one of the most advanced engineering tools of its kind, comprehensive modeling exercises as were carried out in the IPET and LACPR projects were beyond the scope of the present project. Instead, the model was utilized to investigate various measures for hurricane surge reduction and delta restoration strategies at reconnaissance level. This implies a first order screening of measures and strategies to enable a selection of promising concepts which will require further detailing in follow-up studies.

Various model schematizations were used to investigate the measures. The hurricane surges were investigated by considering the wind and pressure fields derived from Hurricane Katrina. Constant river discharges were used to investigate the sediment distribution in the delta for delta restoration measures.

The modeling approach in the current project has the following limitations:

1. The models were applied with a limited calibration.
2. A deterministic modeling approach was followed based on Hurricane Katrina. Modifications that were considered involved an increase of the windspeeds to Category 5 and a translation of the hurricane track to estimate worst-cases for the Barataria and Pontchartrain basins.
3. In many simulations wave effects were excluded.
4. The effect of marshland on wave and surge reduction was determined with a method which has not been tested for hurricane conditions.
5. Morphodynamic simulations were based on an average river discharge and sediment load. Furthermore, wave and wind effects were ignored.
6. The models were run in depth-averaged (2DH) mode.

Section D.1 gives a general overview of the characteristics of the Mississippi delta regarding discharges and sediment load. In Section D.2 various surge reduction measures are investigated. Section D.3 describes the effects of delta restoration strategies on the stability and creation of marshland, the effect on the overall sediment balance and salinity gradients. Finally Section D.4 contains a technical description of the applied Delft3D model.

D.1 Mississippi River flows and sediment loads

The Mississippi River discharges the headwater flows from about 41 percent of the contiguous 48 states. On a long-term daily basis, discharges in the Mississippi River average 540,000 cfs (15,400 m^3/s). The peak discharge is approximately 2,120,000 cfs (60,000 m^3/s).

Following the disastrous Mississippi flood in 1927, the federal government began building levees in earnest to protect the Mississippi Delta, including New Orleans. Oil and gas development in the region added to the problem as exploration companies built canals across the delta for building drilling platforms and for routing pipelines. Shipping canals for better access to the Port of New Orleans further disrupted the natural processes in the delta. Silt that once replenished the delta, nourishing the of marsh grass, flowed straight into the Gulf of Mexico.

Suspended sediment concentrations in the river decreased markedly between 1950 and 1966. Since that time the observed decrease in the suspended sediment load has been minimal. Long-term suspended sediment loads in the river average 400,000 tons per day; they have ranged from an average of 1,576,000 tons per day in 1951 to a still considerable average of 219,000 tons per day in 1988.

Studies by the USACE (e.g. Keown et al., 1981) indicate that the suspended sediment load of the Mississippi River has decreased substantially during the last 20 years, especially the larger-grain-sized sediments (sands). Causes of these changes include:

1. the construction of reservoirs in Mississippi River tributaries (especially upper Missouri River tributaries, sources of most of the coarse sediments);
2. improved soil conservation practices (i.e., less topsoil erosion);
3. the mining of pointbar (river) sands for construction and industrial usage; and
4. the dredging and land disposal of riverine sediments. The net effect of this upstream sediment use is to reduce the amount available for deltaic sedimentation, natural nourishment of barrier beaches, and transport into marshes by floods and tidal currents. The decrease in grain sizes has also reduced the land-building potential.

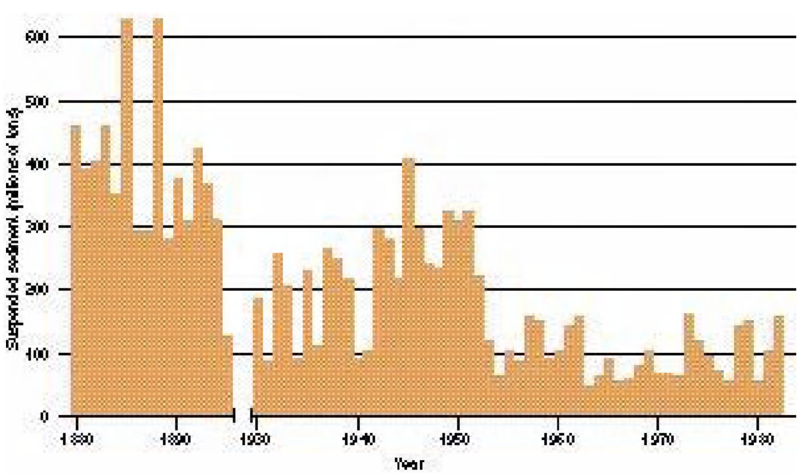

Figure 55 Historical record of the suspended sediment load of the Mississippi River at New Orleans (Kesel 1987). Historical period = before 1900, pre-dam period = 1930-1952, and post-dam period = 1963-1982. http://biology.usgs.gov/s+t/SNT/noframe/gc138.htm

D.2 Protection of New Orleans for different Delta scenarios

Introduction

Within this topic two parallel approaches are followed. With a realistic model of the Mississippi Delta a number of measures representing different delta configurations (present, pessimistic and optimistic) were investigated to illustrate the role the delta has in the protection of the hinterland. This approach is referred to as the "prototype modeling approach". The other approach, the so-called "schematic approach", is aimed at providing insight into the contribution of the different components of a delta (e.g. barrier islands, marsh) to spatial and temporal surge level distributions. The following sections describe the set-up and results for both approaches.

Prototype modeling approach

Two delta configurations and two hurricane paths were investigated. The delta configurations are a delta with vegetation and without vegetation (the size of the delta was not modified). Two hurricanes were investigated: Hurricane Katrina with winds taken from the H*Wind dataset (NOAA website), and a hurricane with wind speeds similar to Hurricane Katrina but with a path that was shifted 0.5 degree Westward, to investigate a possible funnel effect in the Barataria basin. The latter hurricane wind fields were generated with the WES model (UK MetOffice).

The effect of vegetation

The maximum surge levels for Hurricane Katrina are shown in Figure 56. Notice that only tide, wind and pressure effects are included. The effect of locally generated wind waves will result in a further increase in surge levels. From the plots it is apparent that the effects on surge levels in the vicinity of New Orleans is relatively small. The most noticeable difference can be seen in the marshlands East of the Birdfoot, where the vegetation causes an additional surge due to extra set-up. Further upstream along the banks of the Mississippi River, the surge is somewhat reduced by the vegetation.

The effects of vegetation in the area East of Lake Pontchartrain (Waveland) and to the West of the river (Barataria Basin) are minor.

Hurricane path at 0.5 degrees Westward

Shifting the hurricane path 0.5 degree Westward results in an expected increase in surge levels in the Barataria basin, whereas Eastward of the Birdfoot surge levels have reduced (Figure 57). Now the effect of the vegetation is more pronounced. Although maximum surge levels are higher with the vegetation the surge intrusion distance has reduced significantly and the surge levels at the levees near New Orleans are reduced by 30 to 50%.

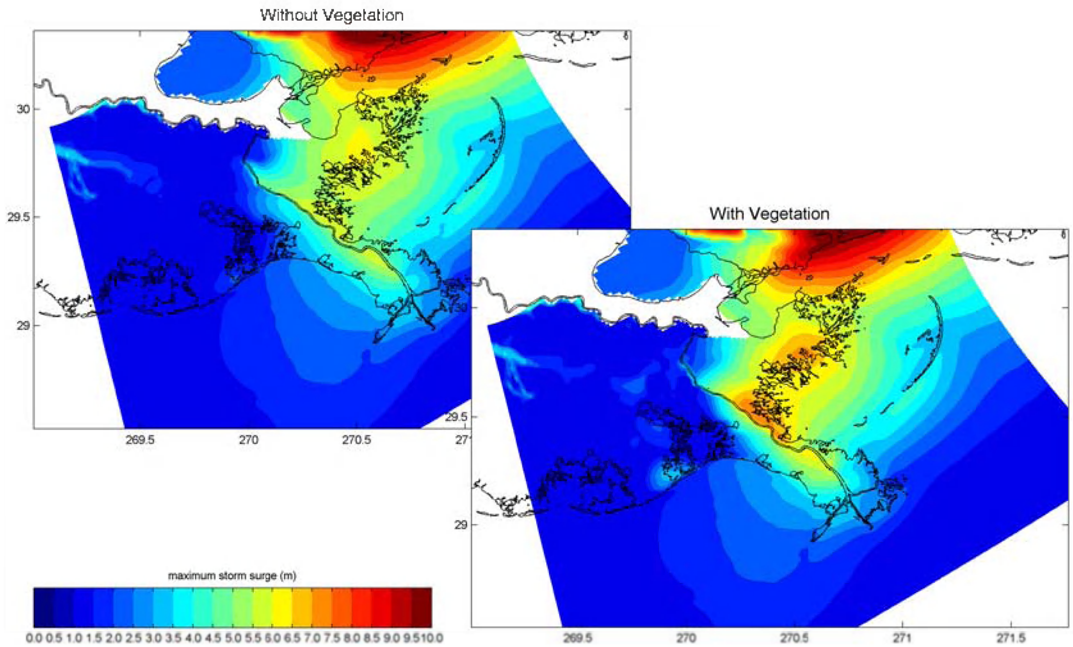

Figure 56 Maximum surge levels for Hurricane Katrina with and without vegetation (m).

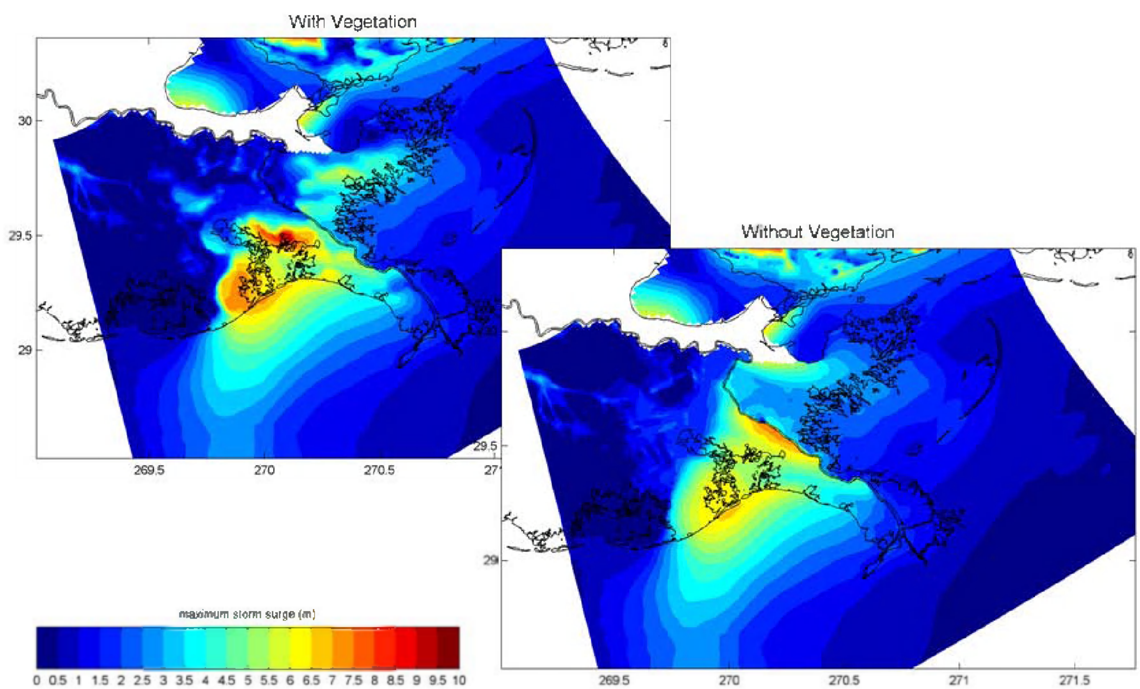

Figure 57 Maximum surge levels for Hurricane Katrina shifted 0.5 Deg Westward with and without vegetation (m).

Schematic approach

Two types of schematic Delft3D model simulations were used to investigate the storm surge during a hurricane landfall. For the first type of simulation, a simple model of a straight coast was generated. For the second type, a schematic representation of the Mississippi Delta including the Birdfoot was used.

Straight coast

In the schematic approach the storm surge during a hurricane landfall at a straight coast was investigated in a number of simulations. The model domain of the schematic model is shown in Figure 58. Figure 59 shows the cross-shore profile. A large shallow plateau with a width of 50 km and a depth of 1.0 m is situated in front of the coast line. To the South the bottom drops to a maximum depth of 100 m with a slope of approximately 1 in 500. The initial water level in the model was set at 0 m. The imposed hurricane was based on Hurricane Katrina (wind speeds up to approximately 150 knots) and the hurricane path was from South to North through the center of the domain.

The schematic model of the straight coast is used to qualitatively investigate the effects of vegetation, funneling and barrier islands.

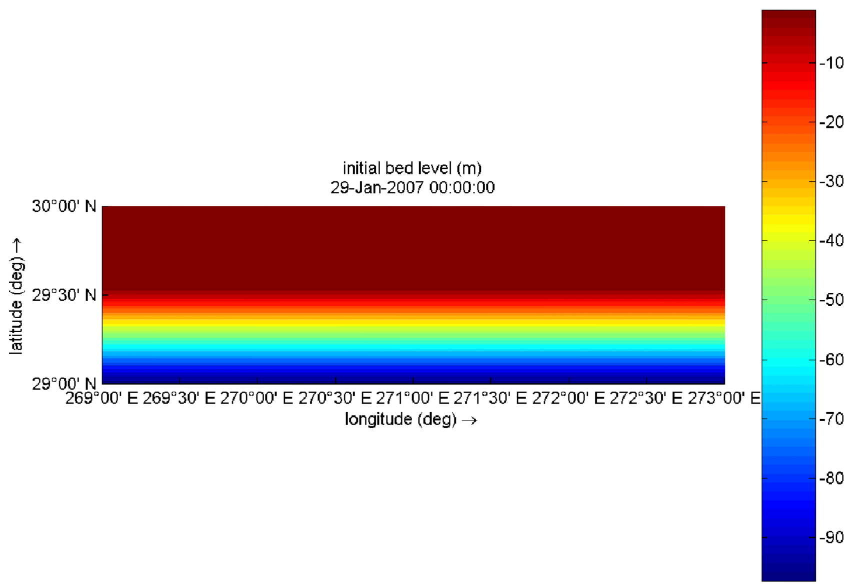

Figure 58 Schematic bathymetry for the straight coast case.

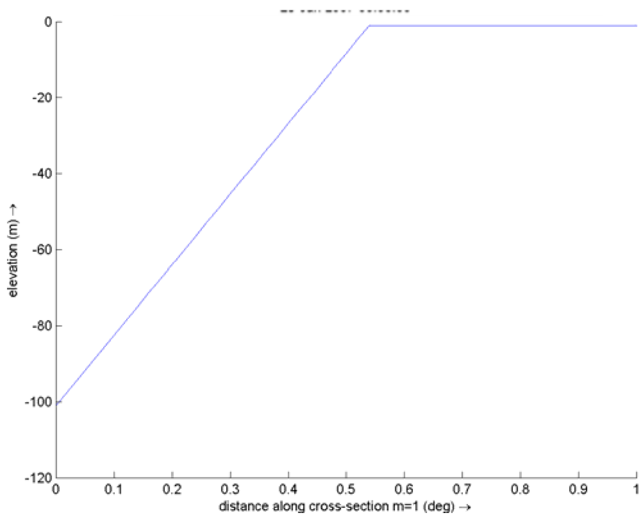

Figure 59 Cross-shore profile for the straight coast case.

A set of five Delft3D hydrodynamic simulations have been executed: 1) reference simulation and investigating 2) the effect of vegetation, 3) funnel effect, 4) barriers islands at MSL +3 m, 5) barriers islands at MSL +10 m. The maximum surge levels are summarized in Figure 60. The following conclusions are drawn from this investigation:

1. The storm surge in the reference simulation reaches a maximum height of approximately 11 m. This height is comparable to the maximum observed storm surge at landfall during Hurricane Katrina.
2. Vegetation (Spartina) has been introduced in the model over the entire shallow plateau. This increases the storm surge just South of the plateau to some extent, but it drastically reduces the storm surge at land fall. A similar effect could be seen in the results of the prototype modeling of Hurricane Katrina (see also Figure 56). The effect however is now much larger. This is most likely due to the fact the vegetation now covers a continuous and much larger area, whereas in the prototype modeling, only grid cells that were situated above mean sea level contained vegetation.
3. A large levee has been inserted in the center of the model in order to create a funnel effect during hurricane landfall. Figure 60 shows that this effect has the potential to increase surge levels significantly. In this case, the surge levels are increased with approximately 20 percent. The extent of the funnel effect probably depends also on the angle of incidence of the hurricane path with the coast line.
4. In two of the simulations, a row of barrier islands at the edge of the shallow plateau was included. The barrier islands are each 12 km long seperated by 8 km wide inlets. In the first simulation, the height of the islands was set at MSL +3 m, whereas in the second, the height was set at MSL +10 m. The aim of this distinction was to investigate whether overwashing of the islands (which can only occur in the first simulation with relatively low barrier islands) adds to the maximum storm surge levels. The barrier islands appear to cause a lowering of about 1 m of the maximum storm surge at land fall. Overwashing of the islands does not seem to affect water levels at landfall, but it does causes an increase of storm surge levels just landward of the barrier islands.

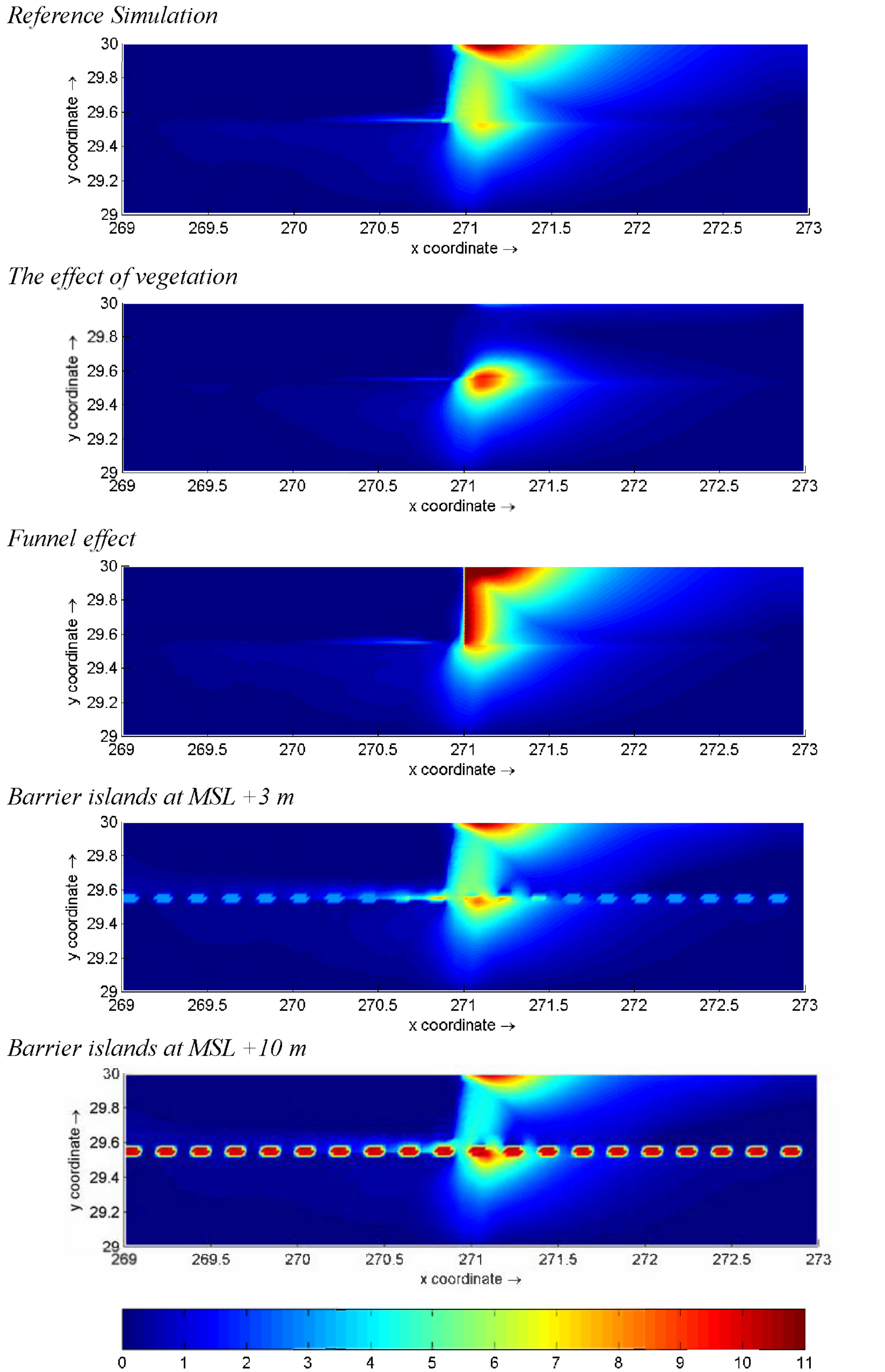

Figure 60 Maximum water levels (m) for various schematic delta configurations

Schematic Mississippi Delta

The dimensions of the delta in the schematic model are similar to those of the real Mississippi delta. The model was clockwise rotated by approximately 45 degrees for practical purposes. Furthermore, it does not contain Lake Pontchartrain. Figure 61 shows the bathymetry of the schematic model. The figure also shows the position of a number of locations at which time series of water levels are generated. The dashed lines indicate the position of two cross-sections at which maximum storm surge levels are extracted from the model output. The effects of vegetation are included in all simulations in this paragraph unless specified otherwise. The thick green line in Figure 61 indicates the area in which vegetation (uniformly distributed spartina grass) is present in the model. The blue and red line indicate the hurricane tracks that were considered. Vegetation is implemented in the Delft3D model by acting as a sink in the momentum equation. It should be noted that the Delft3D vegetation module has never been validated in areas of this size or in situations with hurricane surges.

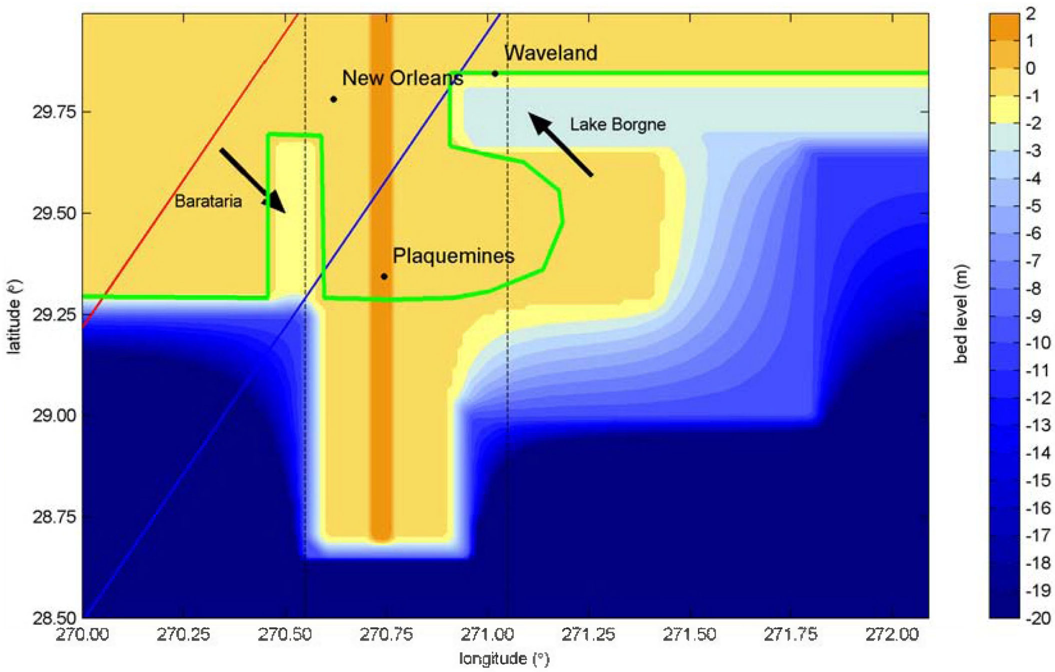

Figure 61 Schematic model Mississippi Delta. Area inside green line indicates presence of vegetation, red and blue lines indicate hurricane tracks. Dashed lines indicate the cross-sections utilized in the interpretation of results.

The model has been applied to investigate the relative effects on storm surge levels of a number of measures in the Barataria and Pontchartrain basins:

Barataria Basin (West of the Mississippi River):

- Vegetation in Barataria Basin
- Levees in Barataria Basin of different height
- Closing barrier islands Barataria Basin
- Increasing vegetation area in Barataria Basin

Pontchartrain Basin (East of the Mississippi River)

- Closing gaps between Chandeleur Islands
- Filling up Lake Borgne

A Category 5 hurricane with a track (see blue line in Figure 61) and propagation speed similar to Hurricane Katrina has been used to investigate the effects of the different measures East of the Birdfoot. An identical hurricane wind field and pressure drop is used to investigate the interventions West of the Birdfoot, except that the eye of this hurricane is shifted 0.5 degrees to the West (see red line in Figure 61). This shift has been applied in order to achieve a significant storm surge in the Barataria Basin (West of the Mississippi). Hurricane Katrina itself did not cause a large storm surge here.

Vegetation in Barataria Basin

Figure 62 shows the computed maximum water levels along the Western cross-section (see Figure 61) for simulations with and without vegetation.

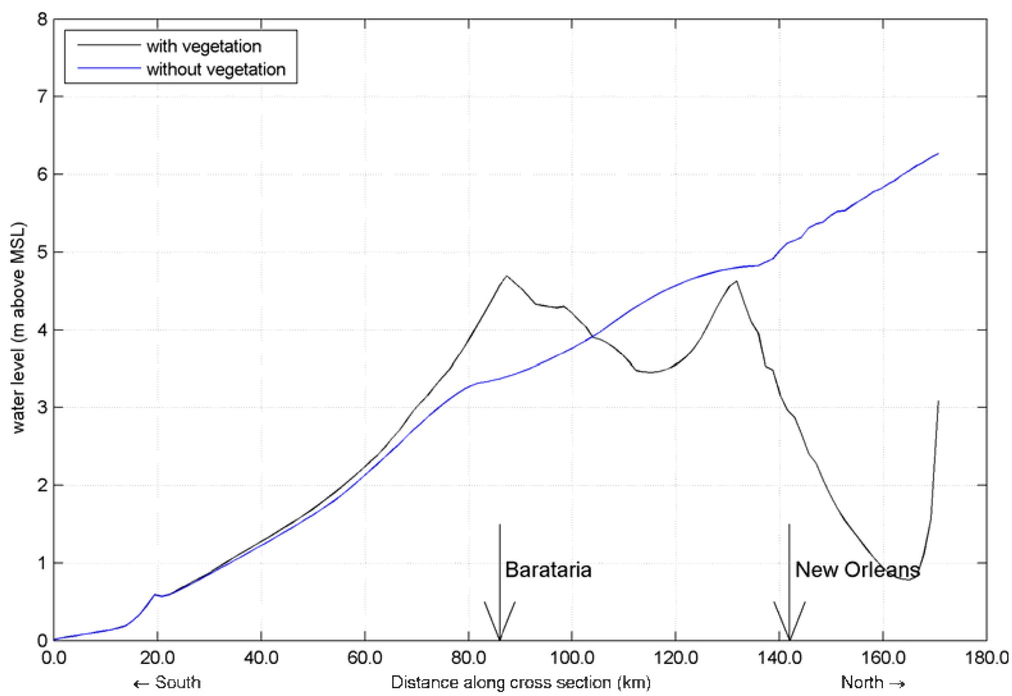

Figure 62 Maximum surge levels with and without vegetation along Eastern (Barataria) cross-section.

It appears that marshlands are very effective in reducing storm surge levels in the Barataria Basin near New Orleans. Whereas the maximum surge level without vegetation keeps on increasing in Northward direction, the levels with vegetation drop significantly close to New Orleans. It should however also be noted that an additional surge (negative effect) is present over about 20-30 km before the surge is actually reduced compared to the case without vegetation. The reduction landward of the maximum additional surge is in the order of 1 m reduction per 5 km marshland (about 1 foot per mile). This reduction is about a factor 2 – 4 larger than those observed for Hurricanes Rita and Andrew (Day et al., 2007). It illustrates the large uncertainty in the estimation of surge reduction by marshes. Especially the type of marsh will have a major impact on the surge reduction rate, healthy fresh water marsh will consist of cypress trees of considerable height compared to salt water marsh with relative low elevation. Although the state of knowledge on this aspect does not warrant any firm quantitative statement it is thought that the positive effect of healthy fresh water marsh lies within the range of predictions presented here.

Levee in Barataria Basin

Figure 63 shows the position of a levee that was built into the model. The green line indicates the area in which vegetation (spartina grass) is present in the model. The effectiveness of levees with crest heights of MSL +2 m, MSL +4 m and MSL +8 m was investigated. The model runs were all carried out with vegetation in the Barataria Basin.

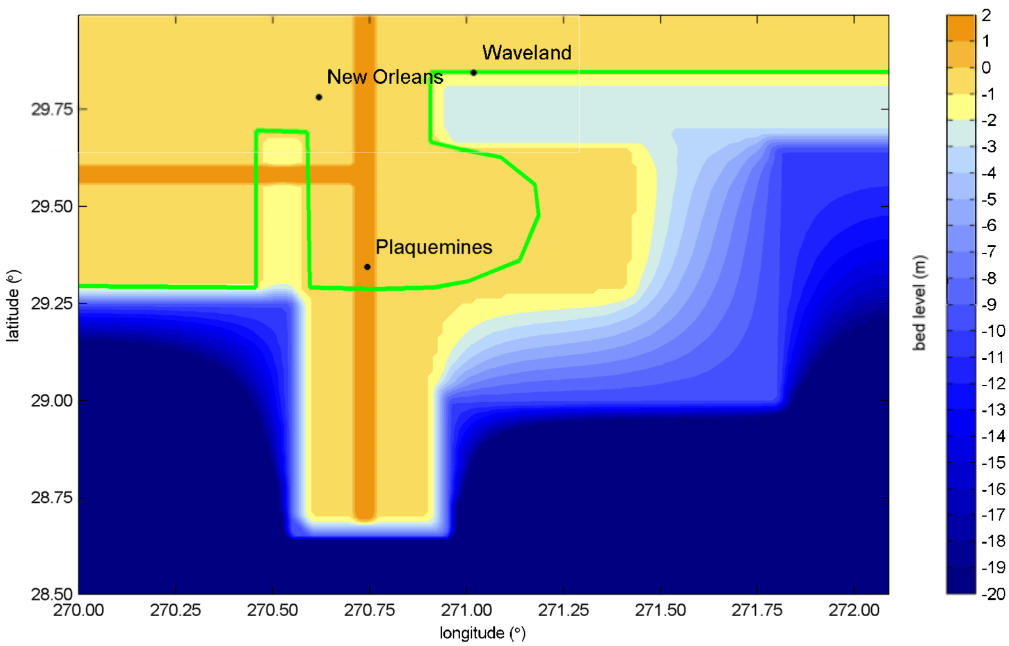

Figure 63 Position of levee across the Barataria basin.

Figure 64 shows maximum surge levels throughout the duration of the storm for the simulation for the reference case (i.e. no levee in the Barataria Basin). The maximum storm surge level in this case at New Orleans is approximately 3 m.

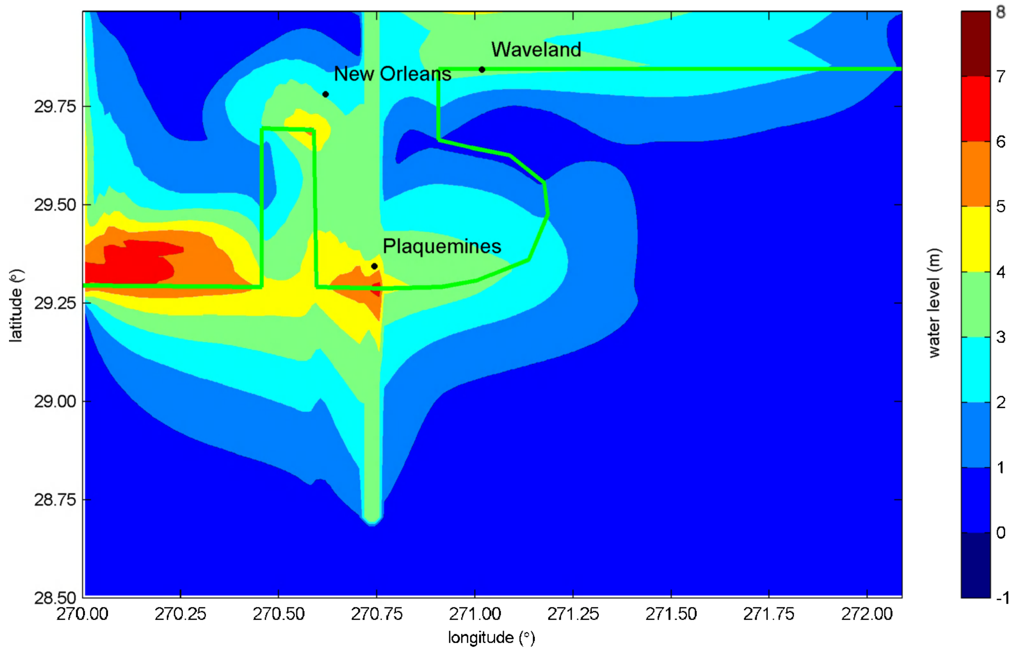

Figure 64 Maximum storm surge levels for reference case.

Figure 65 shows maximum surge levels throughout the duration of the storm for the simulation with the levee crest at MSL +4 m. The levee causes a strong decrease in surge levels to the North. Close to New Orleans, the maximum surge level is now less than 1 m (a reduction at New Orleans of approximately 2 m with respect to the simulation without a levee). However, at the seaward side of the levee, a build-up of surge levels can be seen. The increase in maximum water levels here is approximately 3 m.

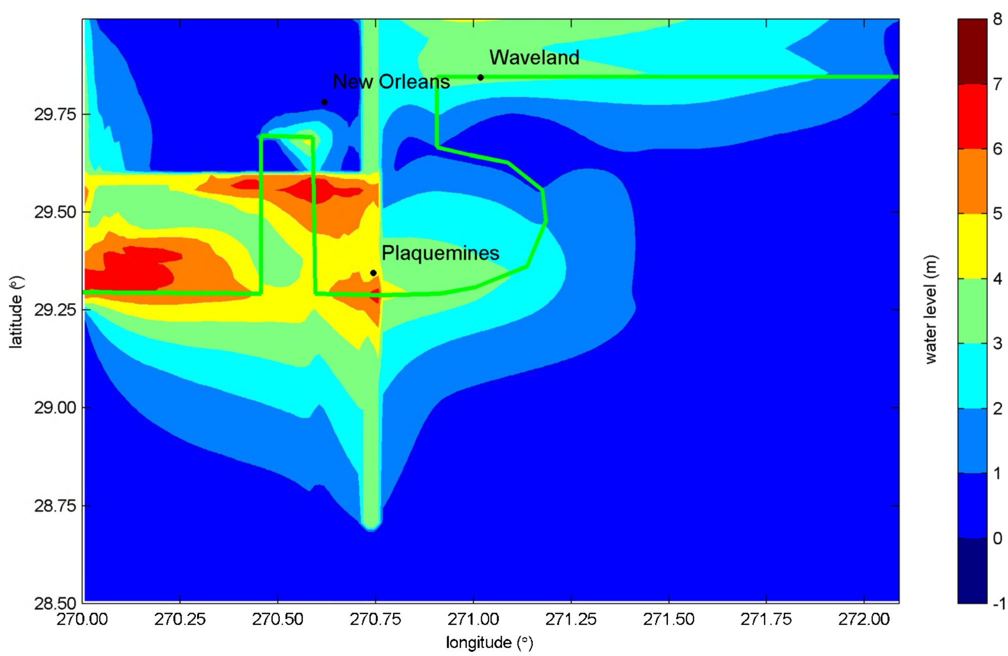

Figure 65 Maximum storm surge levels with levee crest at MSL +4 m

Figure 66 shows maximum water levels along the Western cross-section (see Figure 61) for the different levee heights.

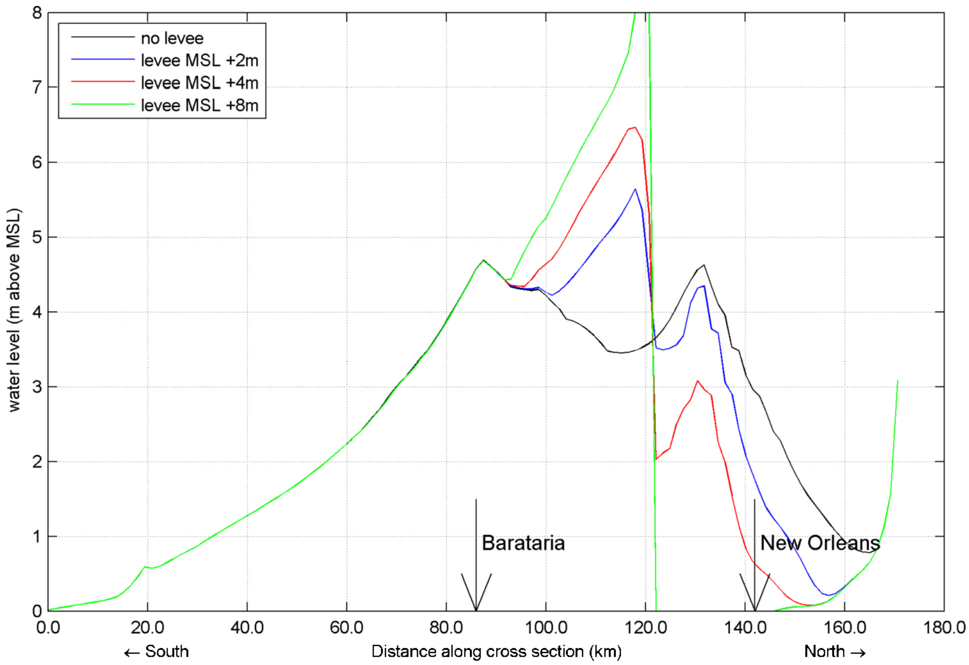

Figure 66 Maximum storm surge levels for different levee crest heights along Eastern (Barataria) cross-section

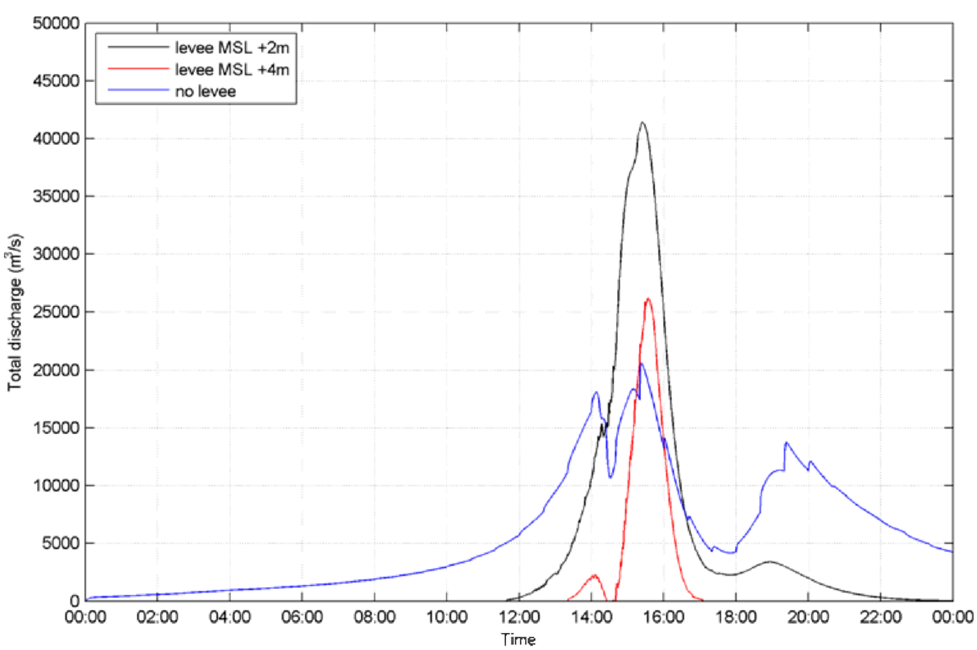

Figure 67 Discharge over levee for different levee crest heights

Figure 67 shows the total discharges over the levee. The 8 meter levee did not overtop and is therefore left out of the figure. The cumulative volume of water that flows over the 2 m levee amounts to approximately 60% of the volume without any levee. In case of the 4 m levee, this volume is reduced to less than 20%.

It appears that a levee in the Barataria Basin can be an effective measure in reducing surge levels near New Orleans, where the 4 m high levee appears to be relatively more effective than the 2 m levee. The highest levee (MSL +8 m) is non-overtopping in the present model set-up.

Closing barrier islands Barataria Basin

Figure 68 shows maximum water levels when the gaps between the barrier islands South of the Barataria Basin are completely blocked off. The islands in this simulation have been made infinitely high. No water from the Gulf of Mexico can therefore enter the basin. It appears that closing of the Southern side of Barataria would be a very effective measure in reducing surge levels near New Orleans. Figure 69 shows the maximum surge levels along the cross-section. This increase of water levels at New Orleans is solely caused by wind set-up of water inside the Barataria Basin. This surge is reduced to less than 1 m, due to the fact that the volume of this water body is limited

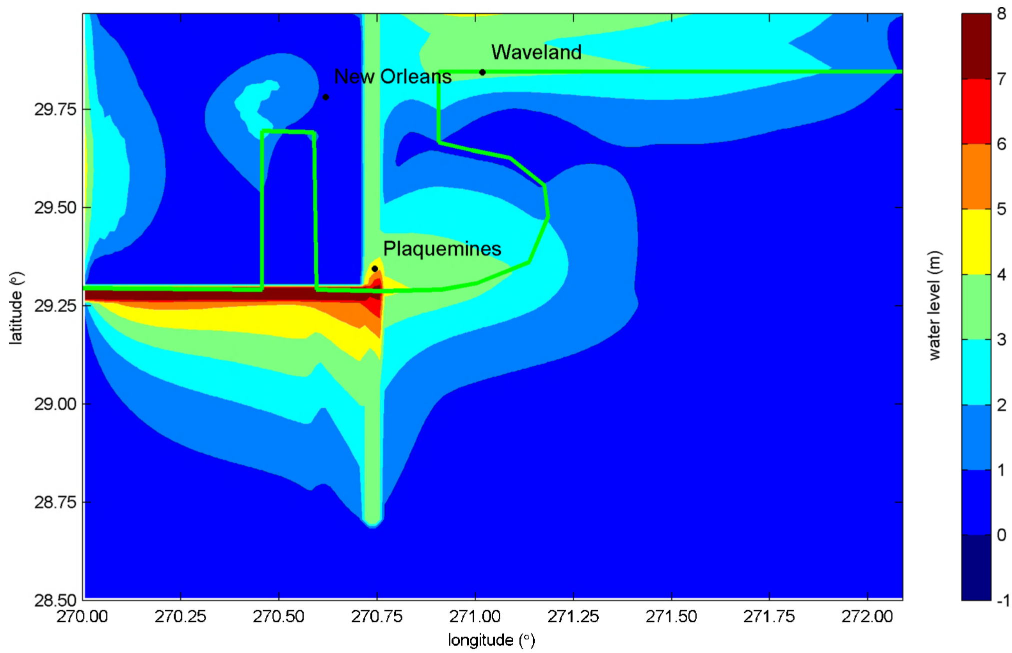

Figure 68 Maximum surge level after closing the barriers South of Barataria

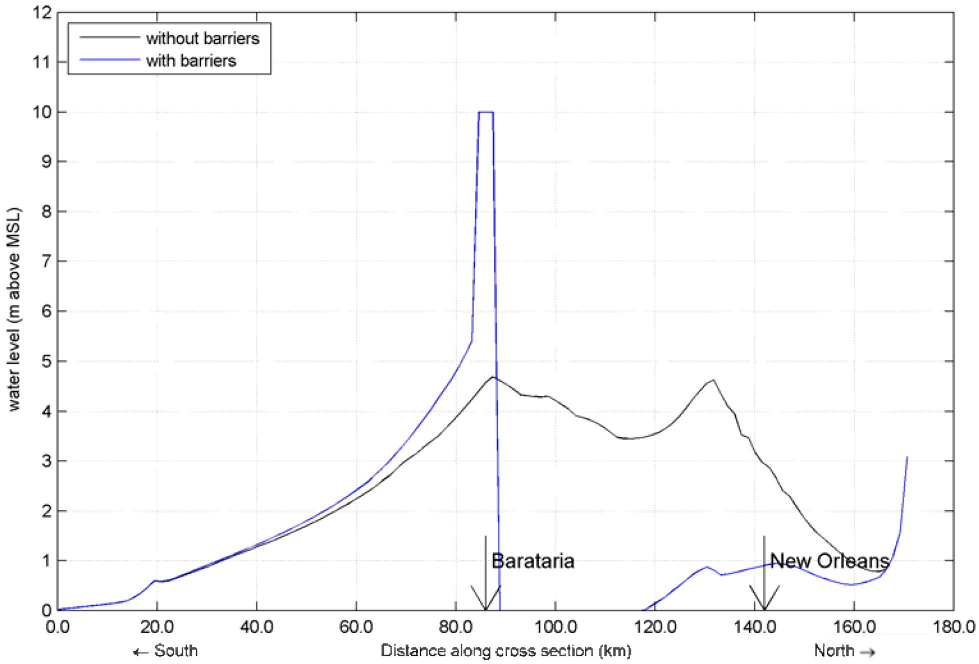

Figure 69 Maximum surge level after closing the barriers South of Barataria along Eastern (Barataria) cross-section

Increased vegetation area in Barataria Basin

Another simulation was carried out in which the vegetation was extended to the deeper part of the Barataria Basin. Figure 70 shows the outline of the vegetated area (green line) and the maximum surge levels. The maximum surge levels along the cross-section are shown in Figure 71. According to the model, the extended marshlands have a large impact on surge levels in the basin, effectively reducing the surge near New Orleans to zero.

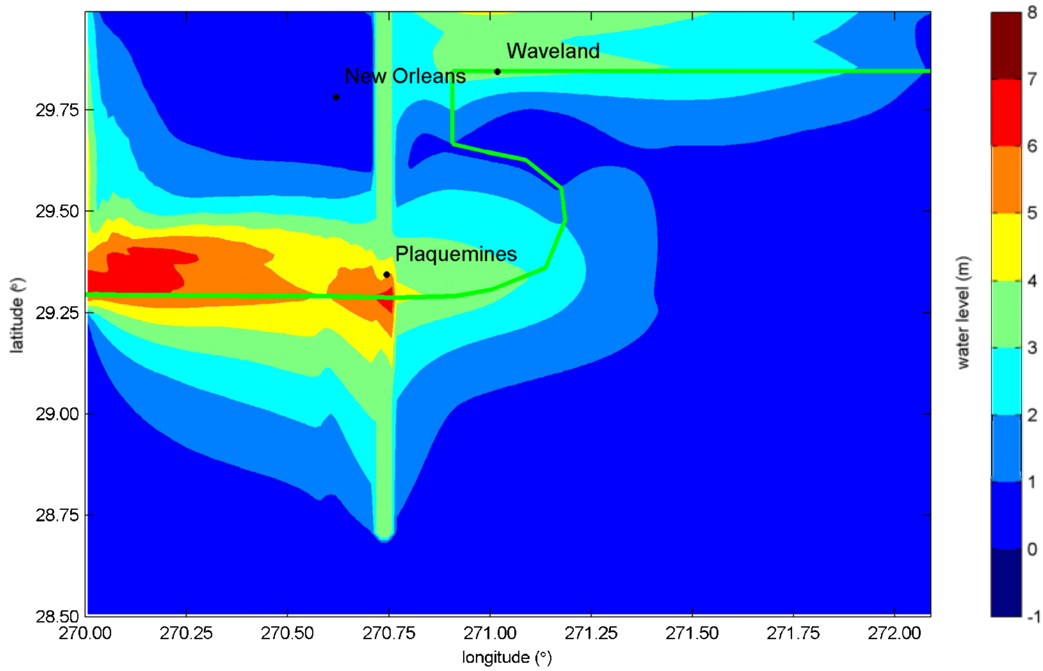

Figure 70 Maximum surge levels with extended vegetation in Barataria Basin

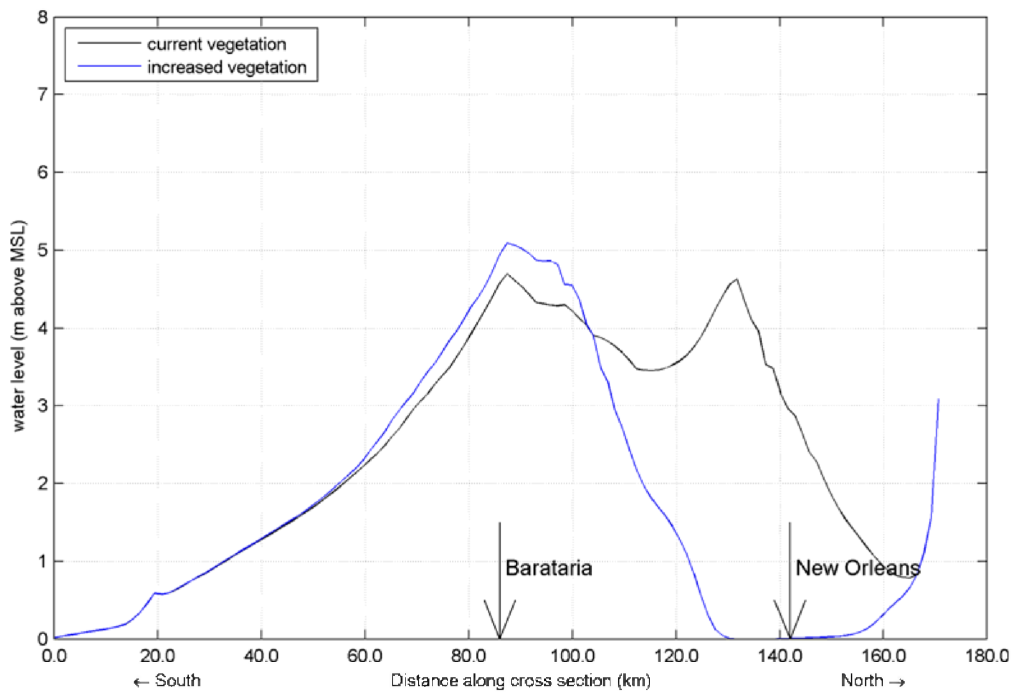

Figure 71 Cross-section of maximum surge levels with extended vegetation in Barataria Basin

Closing off Chandeleur Islands

Two surge reduction measures were investigated at the Eastern side of the Mississippi River. The first was the option to completely block off the area along the Chandeleur Islands. Figure 72 shows the maximum surge levels East of the Mississippi River for the "present" situation. The maximum surge levels after the Chandeleurs are blocked off are shown in Figure 73. Although blocking the Chandeleurs significantly reduces the maximum water levels along the marshlands East of the river, the effect closer to the Mississippi/Louisiana coastline is much less. This can be explained by the fact that there is still a large volume of water behind the Chandeleur Islands. The surge near Waveland appears to be mostly a local effect, caused by wind set-up in Lake Borgne. Figure 74 shows the maximum surge levels along the Western cross-section. This too shows that the storm surge at Waveland is hardly influenced by closure of the Chandeleurs.

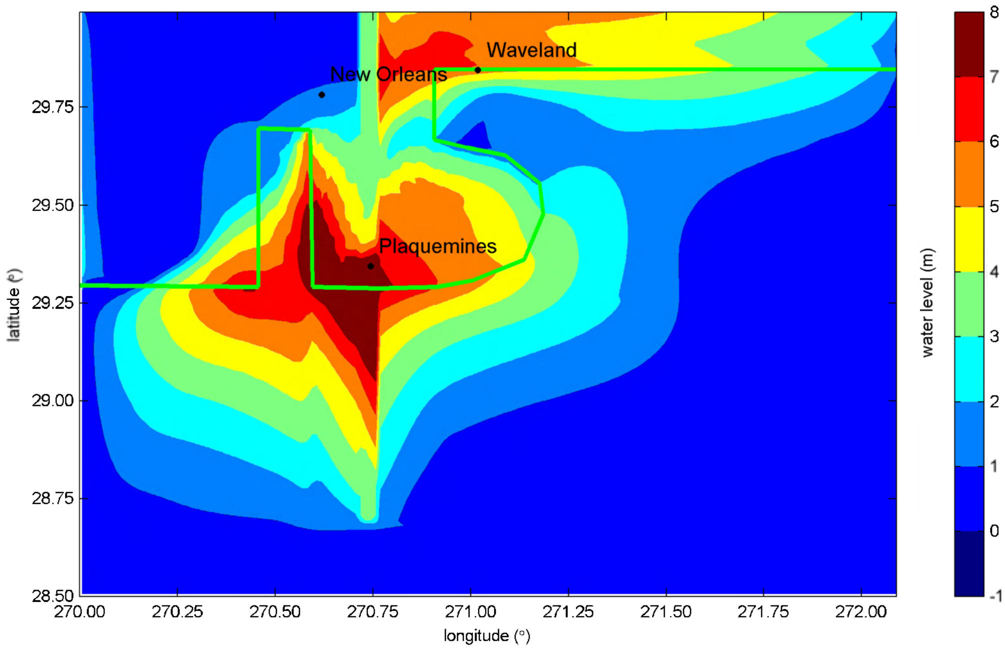

Figure 72 Maximum surge levels reference (present) situation

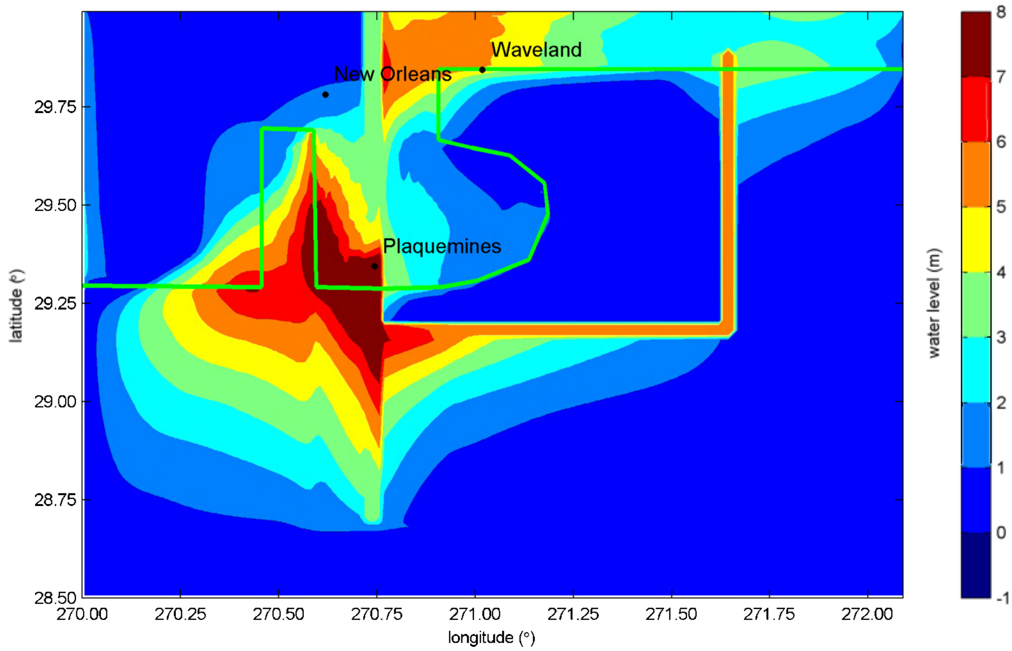

Figure 73 Maximum surge levels after closing off Chandeleur Islands

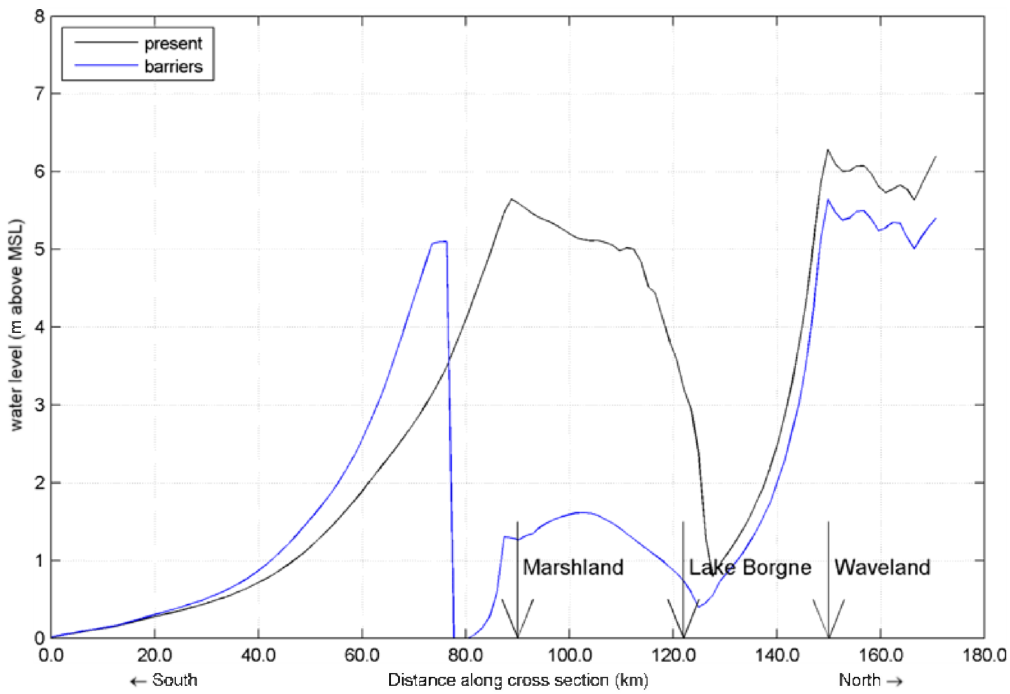

Figure 74 Maximum surge levels after closing off Chandeleur Islands along Western (Pontchartrain) cross-section.

Vegetation in Lake Borgne

From the previous simulation it was concluded that the surge near Waveland was mostly a local effect of wind set-up in Lake Borgne. An effective way of reducing the surge could be to fill up

Lake Borgne and restore the marshlands in that area. The effects of this measure are shown in Figure 75 and Figure 76. Surge levels near Waveland are now reduced with more than 5 m.

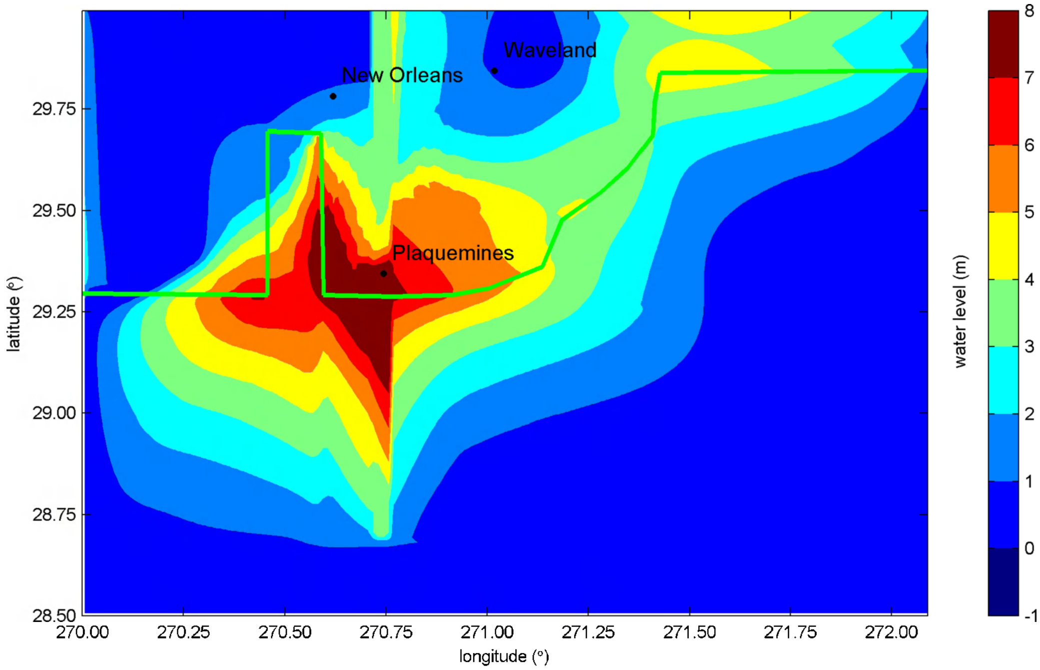

Figure 75 Maximum surge levels with vegetation in Lake Borgne

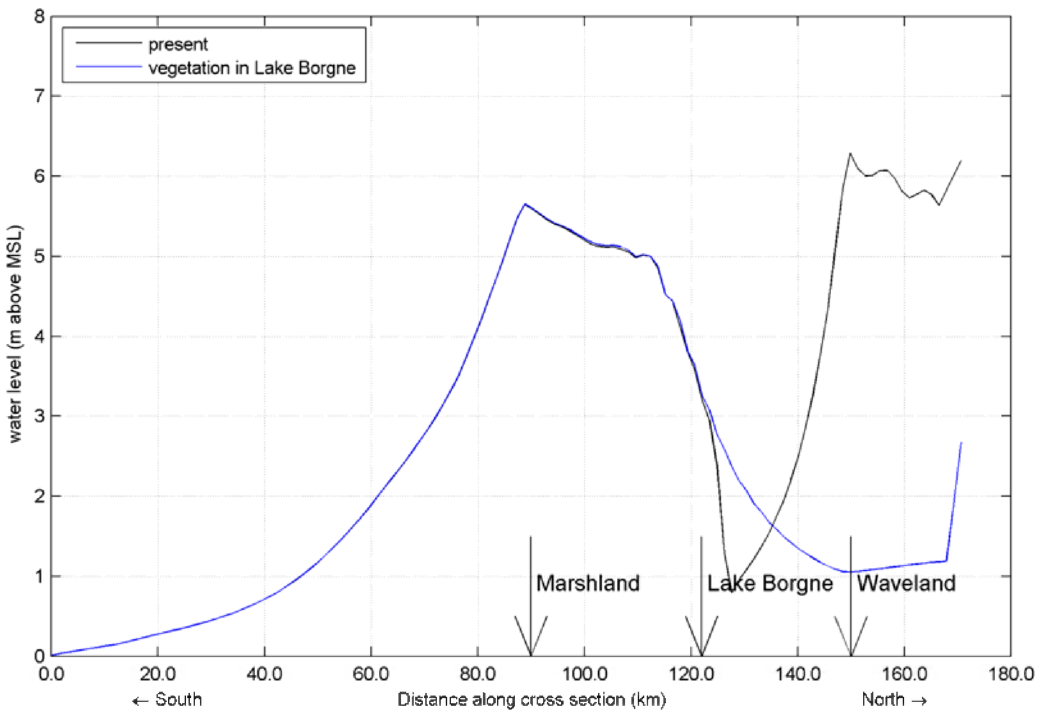

Figure 76 Maximum surge levels with vegetation in Lake Borgne along Western (Pontchartrain) cross-section.

Storm surge barriers in Rigolets and Chef Menteur passes

A number of simulations have been carried out to determine the effects that storm surge barriers in the Rigolets and Chef Menteur passes would have had during Hurricane Katrina. For this purpose, an existing Delft3D model that covers the entire Gulf of Mexico, as well as Lake Pontchartrain, the Rigolets and the Chef Menteur passes in sufficiently high detail has been used. The wind field for these simulations was taken from the H*Wind dataset (NOAA web site) and converted to the proper Delft3D format. The pressure fields were then computed using the Holland (1980) wind model.

The model is able to reproduce observed water levels in Lake Pontchartrain with reasonable accuracy. The initial 2-3 foot increase in water levels in the lake, caused by inflow from Lake Borgne due to strong Easterly winds in the days prior to Hurricane Katrina, could not be taken into account in the applied model set-up.

The model results show that the peak water level observed in the lake close to New Orleans was largely a result of local wind set-up in the lake. The large inflow of water (through the Chef Menteur and Rigolets passes and over the narrow land bridge between the passes) due to the storm surge in Lake Borgne, that caused a further increase of mean water levels in the lake, only occurred several hours after the eye of the hurricane had passed. It did therefore not significantly influence the peak water level near New Orleans that was observed around 1400 UTC.

Simulations were carried out for the present situation, a configuration in which a high levee was constructed over the land bridge and a configuration with both the levee on the land bridge and storm surge barriers in both the Rigolets and Chef Menteur passes. Figure 77 shows a snapshot of the surge levels during Hurricane Katrina and Figure 78 shows the computed water levels in the middle of the lake and near New Orleans (indicated by arrows in Figure 77) for the three configurations. The figure shows that neither the levee nor the barriers in the passes would have had a significant impact on the peak water level that occurred at 1400 UTC. The simulations also show that the storm surge barriers would have been able to prevent the mean lake level increase that occurred after 1800 UTC (compare the blue lines with the black and red lines in Figure 77). In the configuration with only levees on the land bridge, this increase would still have happened. This indicates that the largest portion of the water volume that entered the lake after 1800 UTC flowed through the passes. It should be noted that storm surge barriers in the passes would have been able to prevent the initial mean water level increase of 2-3 feet in the lake prior to the storm, thereby probably also reducing the peak water level at New Orleans with 2-3 feet.

It is very well possible that storm surge barriers could prevent flooding around Lake Pontchartrain in other hurricanes. The hydrodynamics of a hurricane storm surge in the Mississippi Delta are highly complex, and, strongly dependent on maximum wind speeds, propagation speed and angle of approach of the hurricane and the radius of maximum wind speed (among many other factors). It does however seem that building a levee on the land bridge will be much less effective in reducing the inflow into Lake Pontchartrain than the construction of storm surge barriers in both passes.

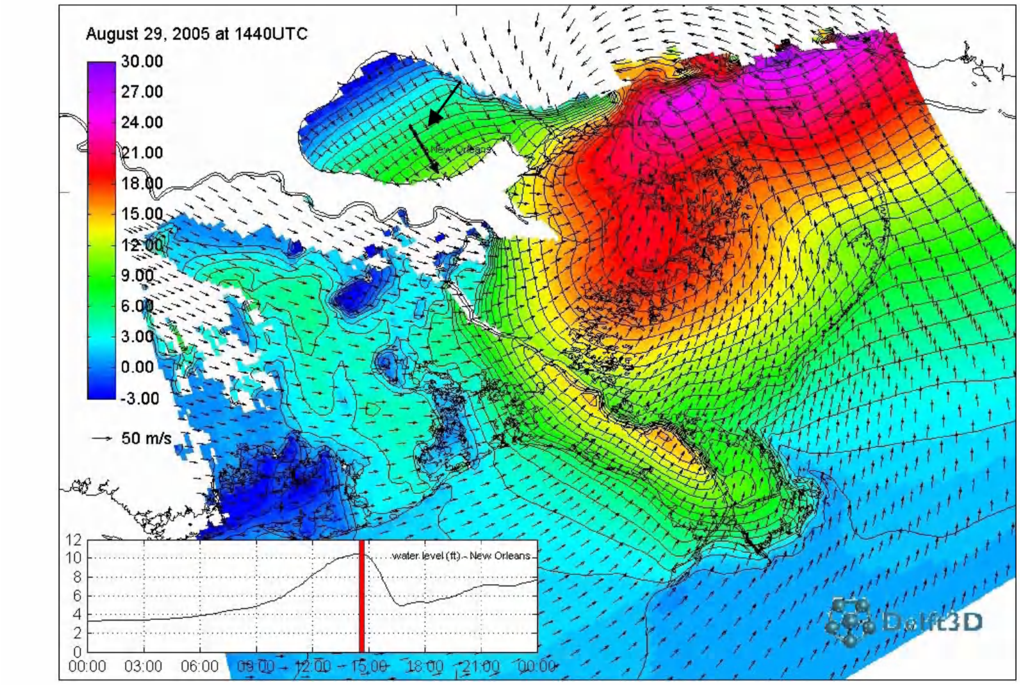

Figure 77 Overview of surge levels (levels in feet) for Hurricane Katrina, location of monitoring stations used in next figure are indicated by black arrows.

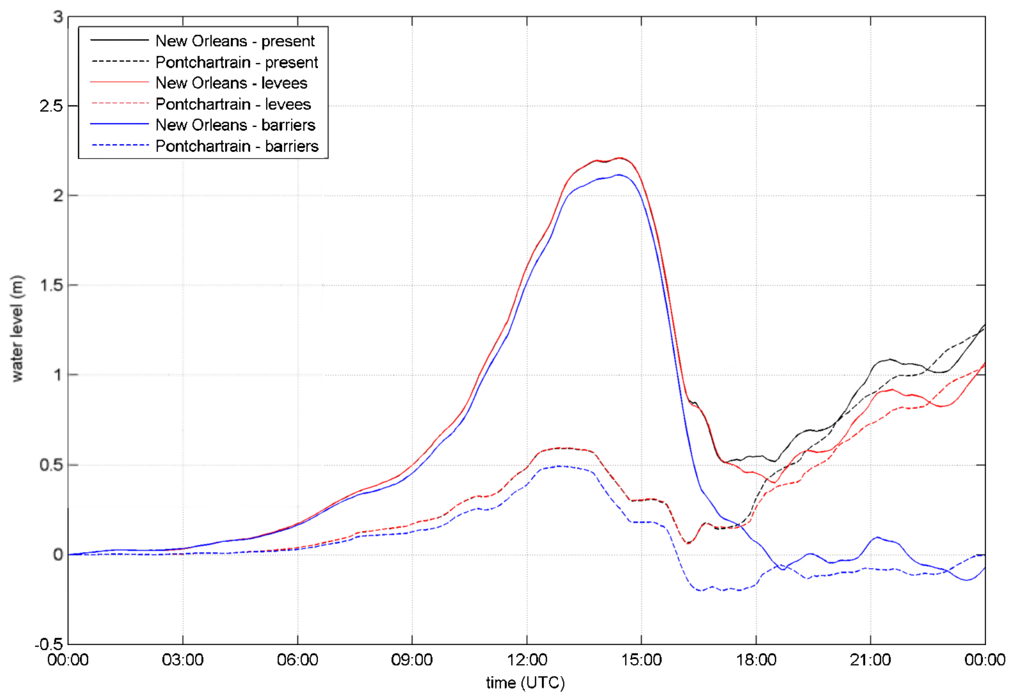

Figure 78 Water levels near New Orleans and in the middle of lake Pontchartrain for different barrier configurations.

D.3 Modeling sediment transport

Exploratory Delft3D simulations were carried out in which sediment fluxes and salinity levels have been determined for the present situation as well as for a number of delta restoration measures. To evaluate the effectiveness of these measures, the model results were primarily used to assess the accumulation of sediments in the Barataria and Pontchartrain basins and the effects on salinity gradients in the Mississippi delta. The simulations were carried out using the same model as for the storm surge predictions in the previous section (more information on the model can be found in Section D.4).

The river discharge was set to 20,000 m^3/s (approx. 700,000 cfs) with a sediment concentration of 0.25 g/l. This yields a yearly sediment load of 200 million tons of sediment which is in agreement with recently observed sediment loads from the Mississippi River. In these simulations, only the fine (cohesive) sediment fraction has been taken into account. Wind and wave effects were ignored. Apart from the 10 year morphodynamic simulation for the present situation, which serves as a reference, the deposition of river sediment has been investigated for the following measures:

- Narrow (1 km) and deep (15 m) diversion channels South of Plaquemines (over a period of 10 years)
- Wide (5 km) and shallow (5 m) diversion (over a period of 2 years)

The simulations cover a period of one month (two spring-neap cycles). The use of a morphological acceleration factor allows the scaling of bed level changes (deposition of river sediment) to a longer period. In the first two simulations, this factor was set to 120, which yielded a total morphological time of 120 months (10 years). In the third simulation, the factor was set to 24 (2 years). The initial salinity is set to 31 ppt throughout the entire model domain.

Present situation

Figure 79 shows the thickness of the deposited river sediment after 10 years for the present situation. It appears that most of the sediment settles relatively close to the river mouth, thereby contributing to the continuous expansion of the Birdfoot. This can be explained by the fact that tidal currents are small in this area and can therefore not transport the river sediments over large distances. It must be noted again that wind and waves were not taken into account. Although wind and wave driven currents will increase the depositional area, most of the settled sediment will lie beyond the morphological active parts of the delta.

Figure 80 shows the computed salinity at the end of the simulation (i.e. after one month). The small residual (tidal) drift forces the river water mainly West of the bird foot. The extend of the river plume is in the order of 100 km, but may significantly increase or decrease depending on the temporal river discharge, wind and wave conditions. In the depth-averaged (2DH) simulation, the higher density of the sea water ensures that the fresh water plume is pushed against the delta. In reality vertical stratification will occur forming, a "bubble" of fresh water on top of the salt water. Near the water surface this will lead to a larger fresh water plume than shown in Figure 80. However, the model shows the correct qualitative behavior which is sufficient to evaluate the (relative) effects of the delta restoration measures.

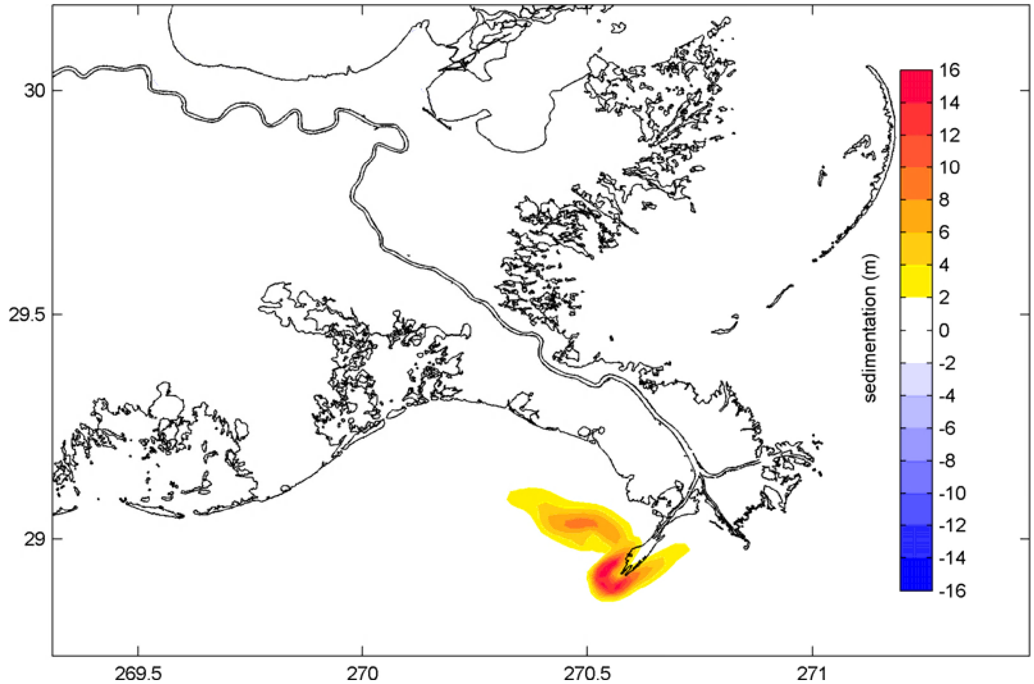

Figure 79 Deposition of river sediments over 10 year in the present situation (m).

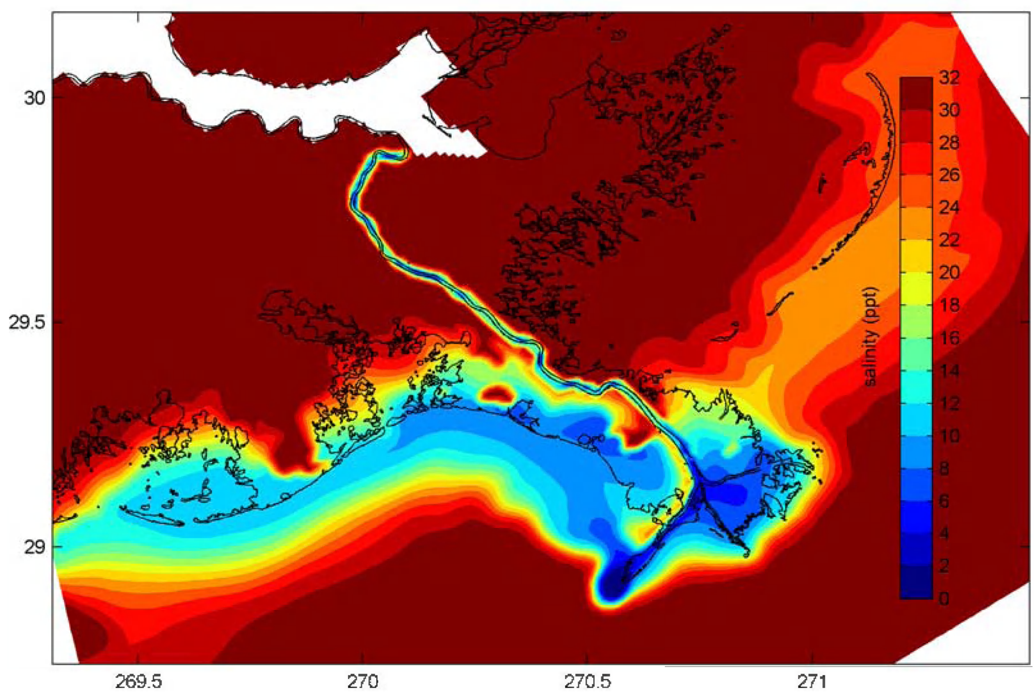

Figure 80 Salinity after one month in the present situation (ppt).

Narrow diversion channels

Figure 81 shows the bathymetry for the measure in which two relatively narrow (approx. 1 km) and deep (15 m) diversion channels have been dredged.

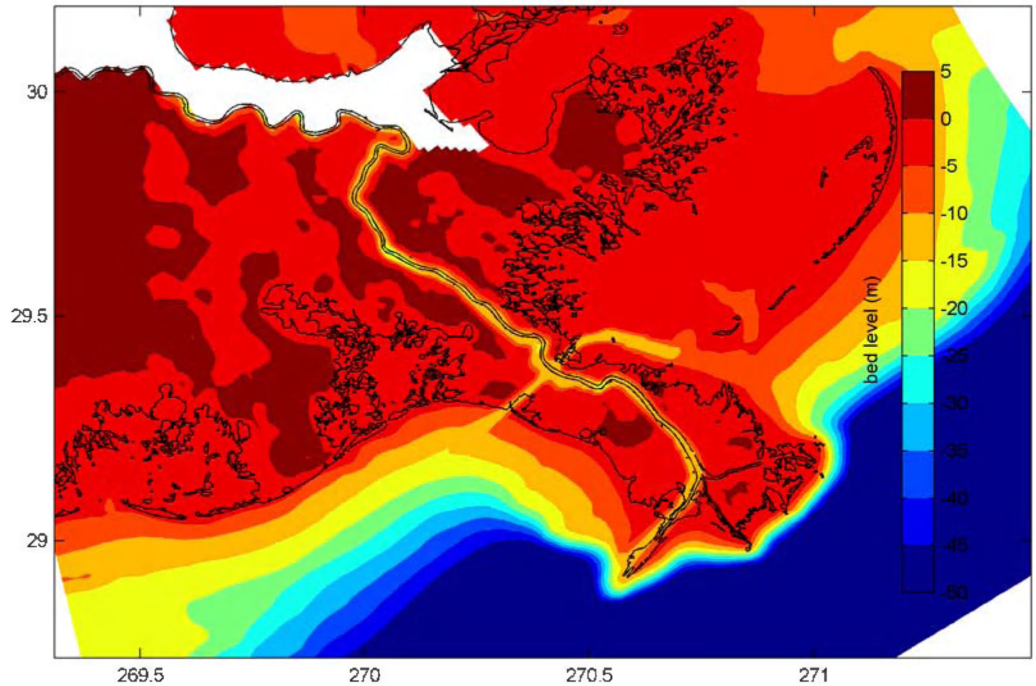

Figure 81 Bathymetry with narrow diversion channels (m).

Strong deposition occurs in the newly dredged channels (see Figure 82), but most of the river sediments are deposited along the banks of the Western diversion channel. It appears that a new branch to the Birdfoot, similar to the Atchafalaya Delta will be formed after the creation of the diversion channels. Strong deposition also occurs in the original navigation channel downstream of the diversion channels. This is caused by the fact that current velocities have been reduced significantly here, as approximately 80 percent of the river discharge now enters the Gulf of Mexico through the diversion channels. The amount of deposited sediments that are now part of the morphological active part of the delta has increased. However, the positive effects on stability of the delta are probably limited and will take decades to centuries to become noticeable. If reconnection of the Mississippi River with the delta would be the primary objective, diversions would have to be constructed well inside the delta (20 to 40 km further upstream than considered here).

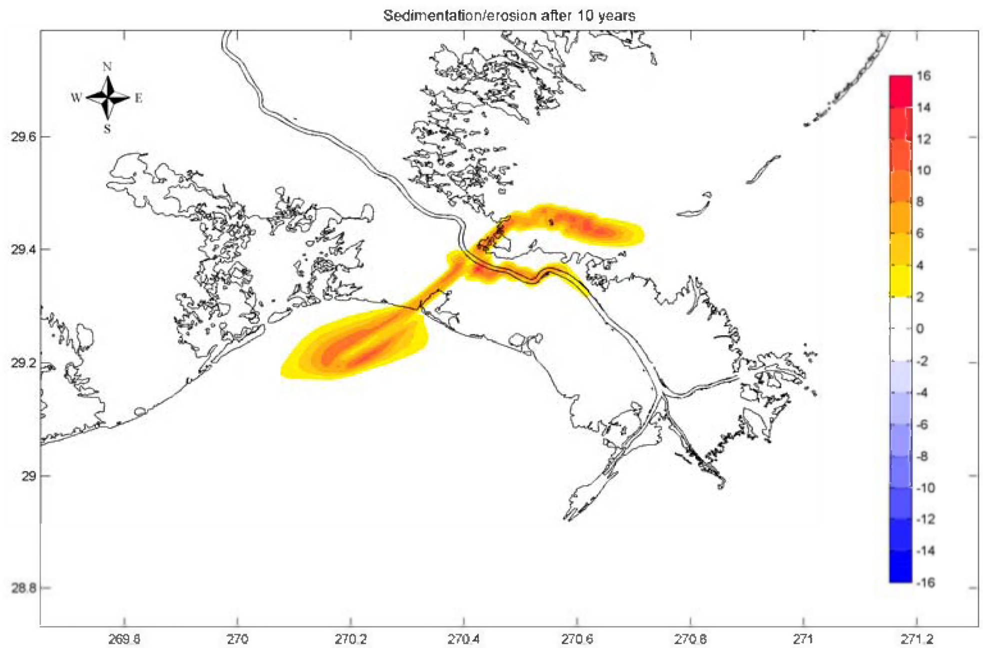

Figure 82 Deposition of river sediments over 10 year with narrow diversion channels (m)

Figure 83 shows the salinity after one month. The dredging of the two diversion channels has caused a large drop in salinity levels in the delta. In both the Barataria and Pontchartrain basins salinity levels have dropped dramatically (compare Figure 83 to Figure 80) which will have a profound impact on local habitats.

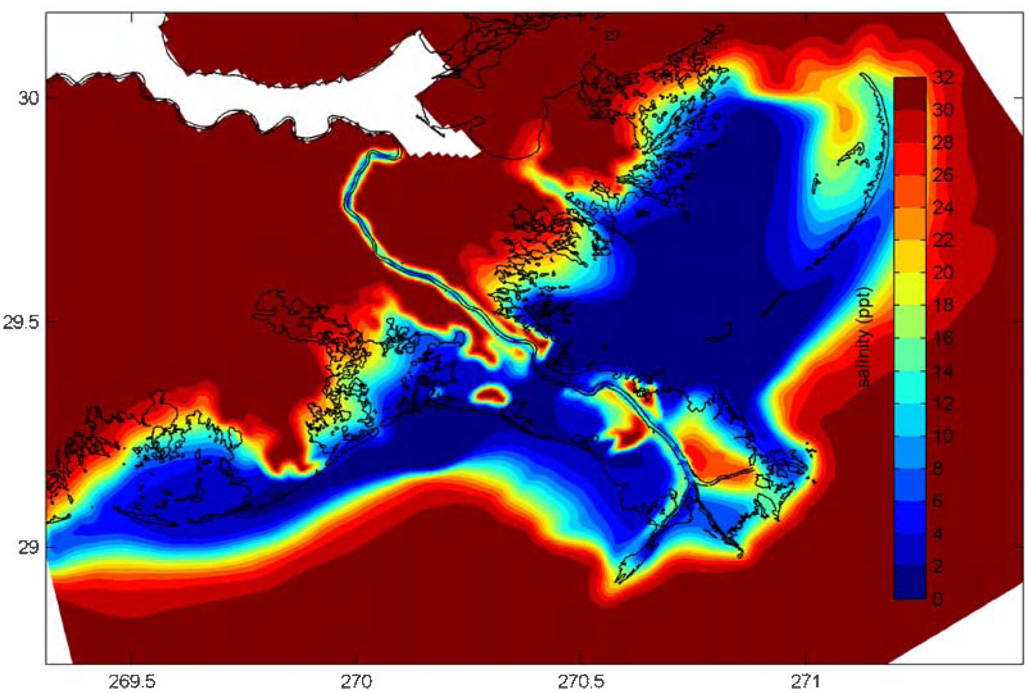

Figure 83 Salinity after one month with narrow diversion channels (ppt)

Wide diversion channels

Figure 84 shows the bathymetry for the scenario in which two wide (5 km) and shallow (5 m) diversion channels have been dredged.

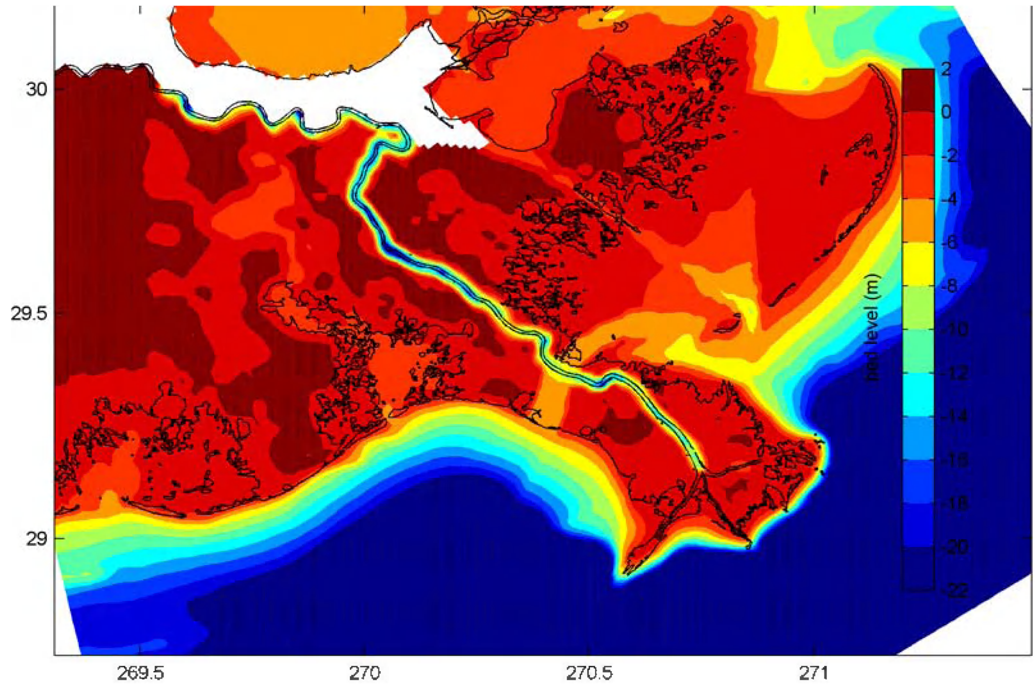

Figure 84 Bathymetry with wide and shallow diversion channels (m)

Figure 85 shows the deposition of river sediments after 2 years. The pattern looks somewhat similar to Figure 82 but the sediment load appears to be deposited closer to the Birdfoot. This is caused by the fact that the current velocities in this scenario are lower than in the scenario with two deep and narrow diversion channels. The underlying reason to study this scenario was to see whether "disconnecting" the Birdfoot would lead to a strong tidal current through the newly dredged channel. It was thought that this current could redistribute sediment in the longshore direction, thereby effectively "nourishing" the delta. However, it appears that there is no significant tidal longshore current. Furthermore, the total volume of sediment that would need to be dredged from the wide channel is so large that this alternative is probably not viable.

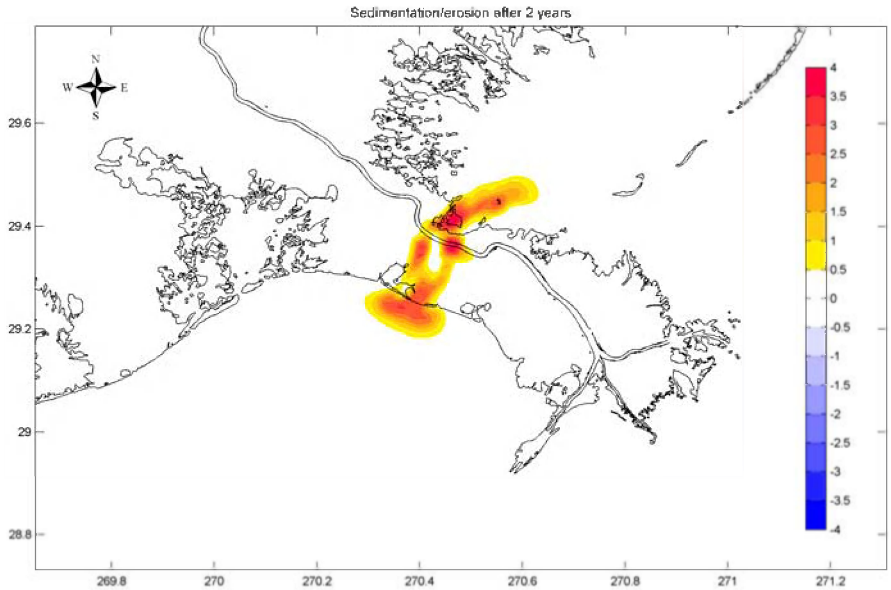

Figure 85 Deposition of river sediments over 2 year in the present situation (m).

Crevassing in Barataria Basin

Additional simulations were carried out to assess the effects of crevassing into the Barataria Basin and into the Lake Borgne area. These simulations were run over a one month period. During the simulation crevassing into the Barataria Basin occurred at 5 locations for the first 10-days. At each location 1,000 m^3/s was "pumped" out of the river. The arrows in Figure 86 show the different crevassing locations. The figure also shows deposition of sediments that were taken out of the river. In total, approximately 1,000,000 m^3 of sediment are deposited during the 10-day crevassing period. Most of the sediments are deposited in the direct vicinity of the crevassing location and the sedimentation is typically limited to less than 5 cm (see the yellow/orange spots in Figure 86). Figure 87 shows the salinity levels at the end of the one month simulation. Almost the entire Barataria Basin has turned from salty/brackish to a fresh water body.

It can be concluded that crevassing has a much larger effect on the salinity distribution than on deposition of sediments in the Barataria Basin. The amount of fresh water that is needed to deposit significant amounts of sediments in the Barataria Basin (thereby countering effects of ongoing erosion and subsidence in the basin) would be so large that the entire basin would be permanently changed into a fresh water lake. This would be in contrast with the aim to restore "healthy" salinity gradients in the basin.

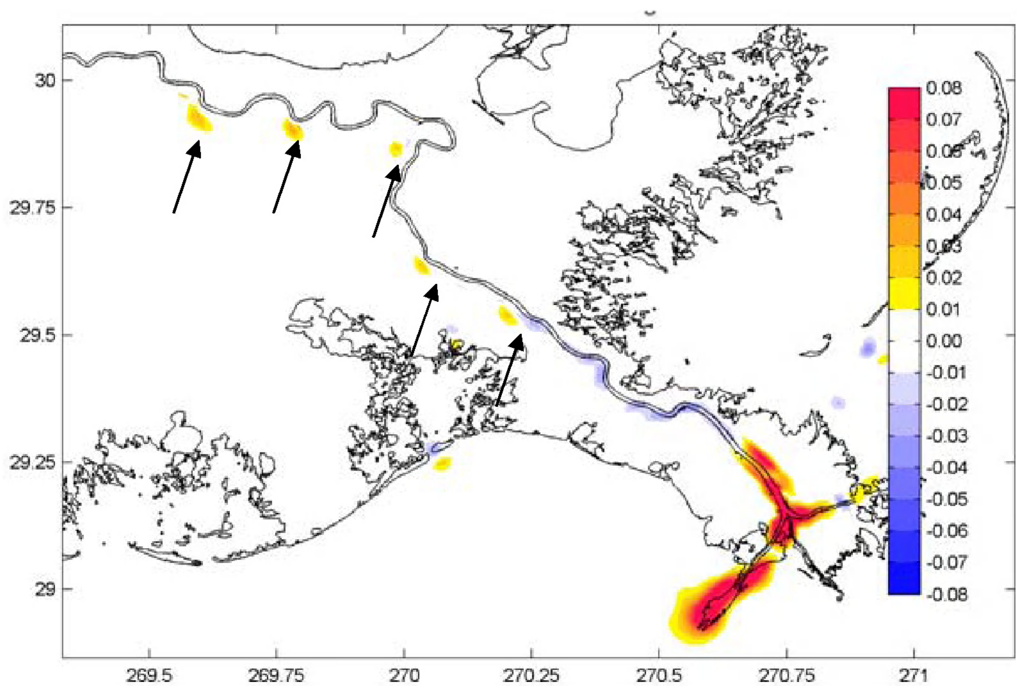

Figure 86 Erosion and sedimentation (m) after crevassing in Barataria Basin

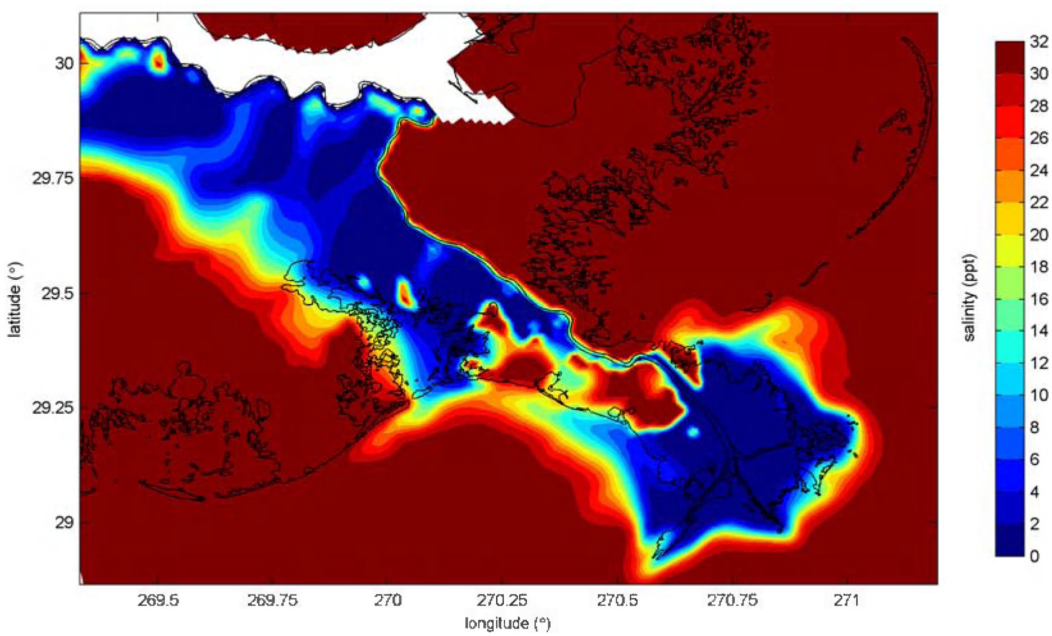

Figure 87 Salinity levels after on month (crevassing in Barataria Basin)

Crevassing in Pontchartrain Basin

The simulation with crevassing to the East of the river was carried out with three crevassing locations. At the most upstream location, 3,000 m^3/s of fresh water are "pumped" out of the river over a 10-day period. At the middle and most downstream location, 2,000 m^3/s and 1,000 m^3/s were taken from the river respectively. Figure 88 shows the deposition levels at the end of the one month simulation. The salinity levels after one month are shown in Figure 89.

The effects of crevassing to the East of the river are similar to those of crevassing in the Barataria Basin. Here too, the amount of fresh water that is needed to deposit significant amounts of sediments would be so large that a large area East of the Mississippi would be permanently changed into fresh water.

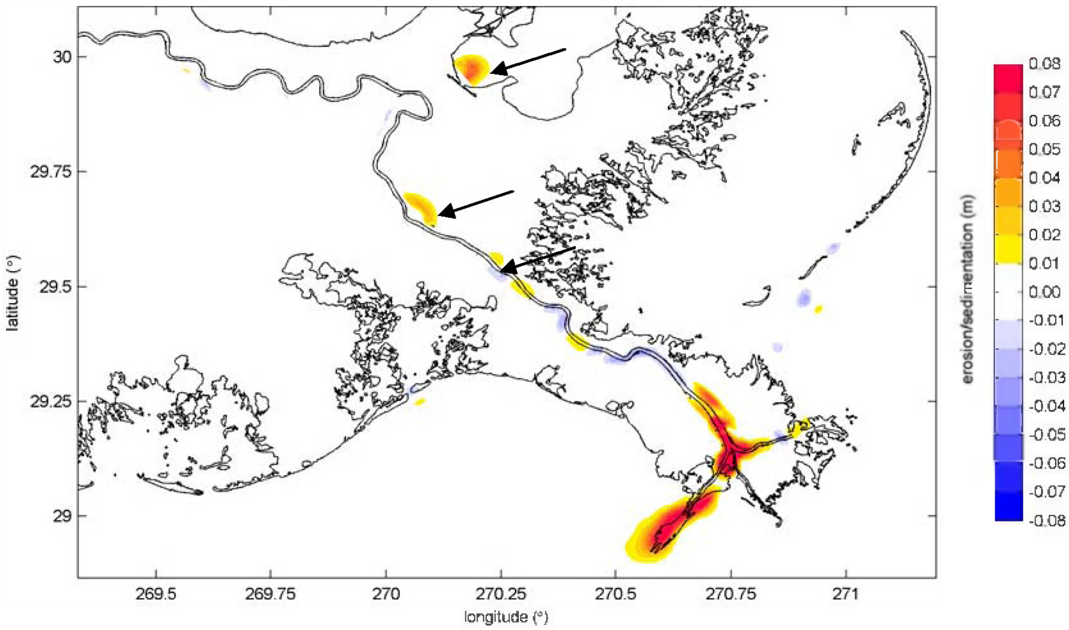

Figure 88 Erosion and sedimentation (m) after crevassing in Lake Borgne

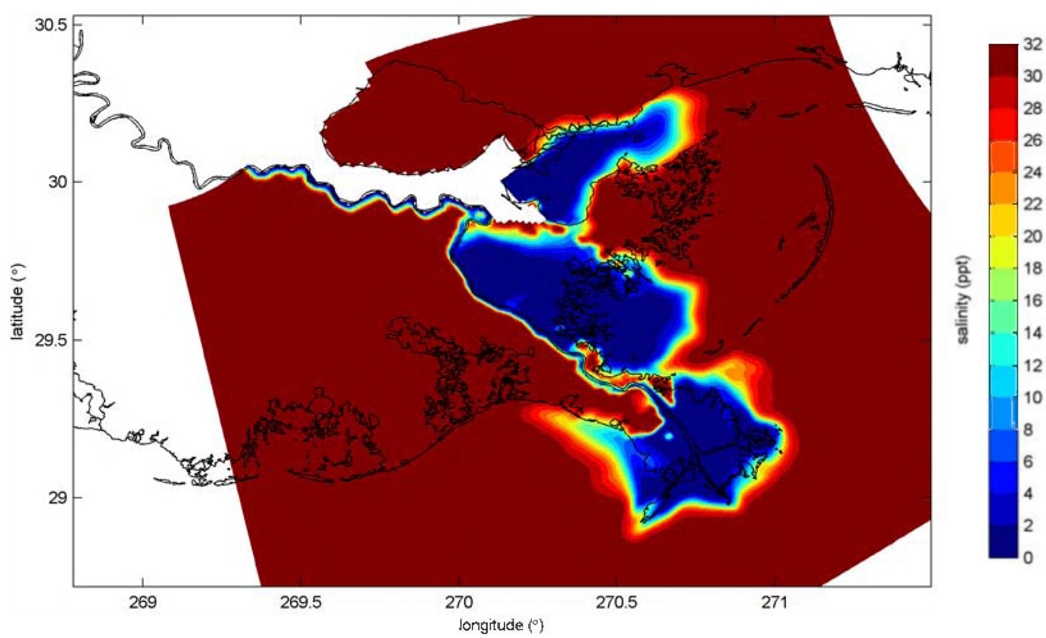

Figure 89 Salinity levels after on month (crevassing in Barataria Basin)

D.4 Modeling

The Delft3D model grid consists of a curvilinear grid with approximately 23,000 active grid cells. The bathymetry for the model has been obtained by interpolating the bathymetric data from a detailed ADCIRC model onto the computational grid. Figure 90 shows the model bathymetry.

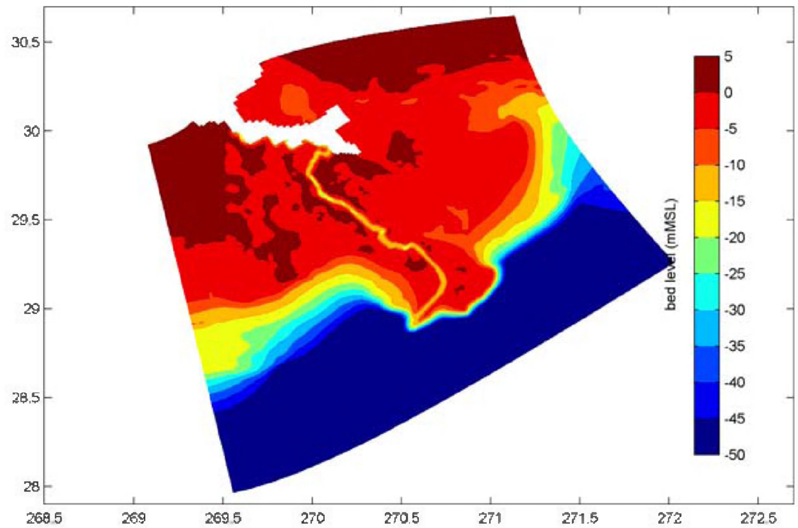

Figure 90 Model bathymetry (m)

Figure 91 shows the computational grid itself. The horizontal grid spacing varies from 500 m to 2 km.

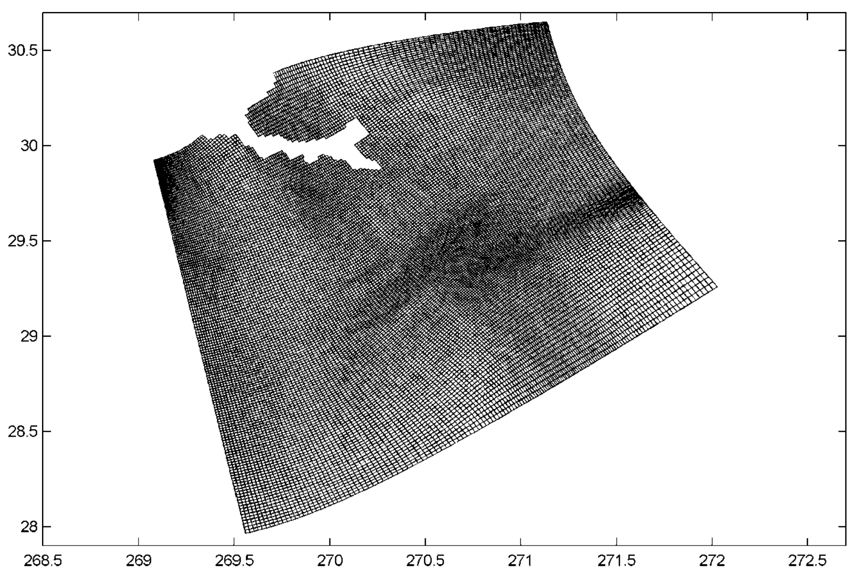

Figure 91 Model grid

Boundary conditions

Boundary conditions for the detailed model have been generated with an overall model of the Gulf of Mexico. The bathymetric data for this model has been obtained from the ETOPO5 data set. The overall model has a horizontal grid spacing of approximately 20 km (Figure 92). The same figure also shows the computational grid of the detailed model in red. The GOM model has been successfully calibrated to predict water levels in the vicinity of the Mississippi Delta. Figure 93 shows a time series of water levels at South Pass (at the Southern tip of the *Birdfoot*). The blue line shows the computed water levels whereas the red line represents the water level prediction based on astronomical components.

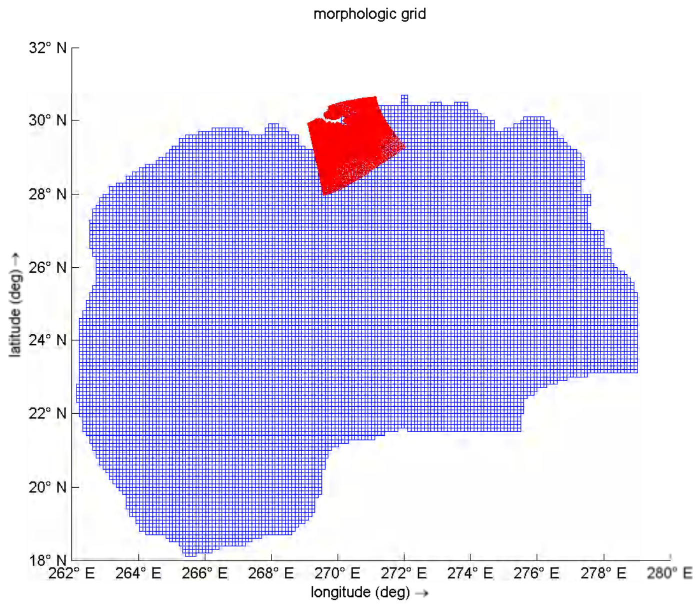

Figure 92 Computational grid of Gulf of Mexico model

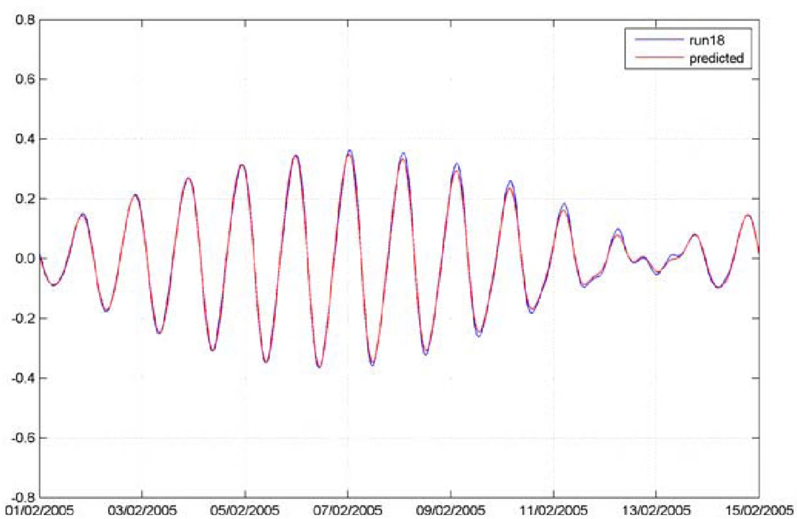

Figure 93 Computed (blue) and predicted (red) water levels at South Pass

An automatic nesting procedure has been used to derive boundary conditions for the detailed model from the GOM model.

Hurricane (incl Spiderweb)
A spatially and time varying wind field has been applied in order to include Hurricane Katrina in the model. The track of the hurricane, the maximum pressure drop and the maximum wind speed are well described by this wind field.

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E Values to be protected and optimal flood protection levels

This appendix focuses on risk based design of flood defense systems and application of economic optimization to the New Orleans metropolitan area.

The analysis on optimal flood protection levels, reported in this appendix, obviously makes use of estimates for the costs of increasing flood protection levels. The cost estimates used in this analysis are not the final cost estimates derived in the current study. Instead, preliminary cost estimates were used. Towards the end of the project the cost estimates have been adjusted, leading to higher values. Obviously, this called for repeating the analysis on optimal flood protection levels. However, since the analysis based on the 'old' cost estimates led to the conclusion that the optimal flood protection level is not very sensitive to the cost estimates (Section E.4.4 concludes that the optimal flood protection level does not change assuming a 50% increase in costs), there was no need to repeat the derivation of optimal flood protection levels using the latest, higher cost estimates.

E.1 Introduction

"How safe is safe enough?" This question has to be answered in the design of engineering systems. The question is how much protection society desires at which costs, and thus how much risk is tolerated. This is of course ultimately a political decision. However, information about the consequences of this decision is often desirable, and risk management techniques may be helpful to provide this information ("risk based informative decision making"). The concept of risk encompasses both the probability of a failure and the consequences of the failure. Risk is generally defined as the product of probability and consequences.

The risk concept can also be used for the design of flood defense system. In this context, the risk based principles have been extensively used and explored by USACE in the water management sector (Moser, 2005). Also in LACPR risk will be an important element. A so-called risk-informed decision framework has been developed (LACPR, 2007).

Since the major flood of 1953 the Dutch authorities use risk-based principles in the design, management and maintenance of the flood defenses. In this appendix the principles used in the Netherlands for risk based design of flood protection systems are applied to the New Orleans area. The results will give insight in the order of magnitude of the protection level that could be chosen based on such an analysis. The analyses focus on the metropolitan area of New Orleans and will be based on simple yet realistic information.

Section E.2 gives background information regarding the risk based design of flood defenses in the Netherlands. Section E.3 provides an overview of information and assumptions used for the New Orleans area. Section E.4 presents the results and sensitivity analyses. Section E.5 contains a closing discussion and conclusions.

E.2 Risk based design of flood defenses in the Netherlands

Large parts of the Netherlands are below the sea level or the high water levels in rivers and lakes. Without the protection of levees, dunes and hydraulic structures (e.g. storm surge barriers) large parts of the country would be flooded regularly. Due to this situation the Netherlands has a long history of flood disasters. The last disastrous flood occurred in 1953. A storm surge from the North Sea flooded large parts of the Southwest of the country. Apart from immense economic damage, more than 1,800 people drowned during this disaster.

Until 1953 levees were constructed to withstand the highest known water level. After the 1953 flood the Delta Committee was installed to investigate the possibilities for a new approach towards flood defense. The committee proposed to reduce vulnerability by shortening the coastline and closing off the estuaries. In addition, flood protection standards for flood defenses were proposed.

An econometric analysis led to the optimal protection level for the largest flood prone area, South Holland (Dantzig, 1956). In this economic optimization the incremental investments in more flood protection are balanced with the reduction of the risk. The investments consist of the costs to strengthen and raise the levees. In the simple approach it was assumed that flooding could only occur due to overtopping of the flood defenses. Thereby each levee height corresponds to a certain probability of flooding (the higher the levees the smaller the probability of flooding). Levee heightening leads to reductions of the probability of flooding and the expected damage (= probability x damage). By summing the costs and the expected damage or risk, the total costs are obtained as a function of the protection level. A point can be determined where the total costs are minimal, this is the so-called optimum. The approach has been applied after the 1953 storm surge to determine an optimal protection level for the largest flood prone area, South Holland.

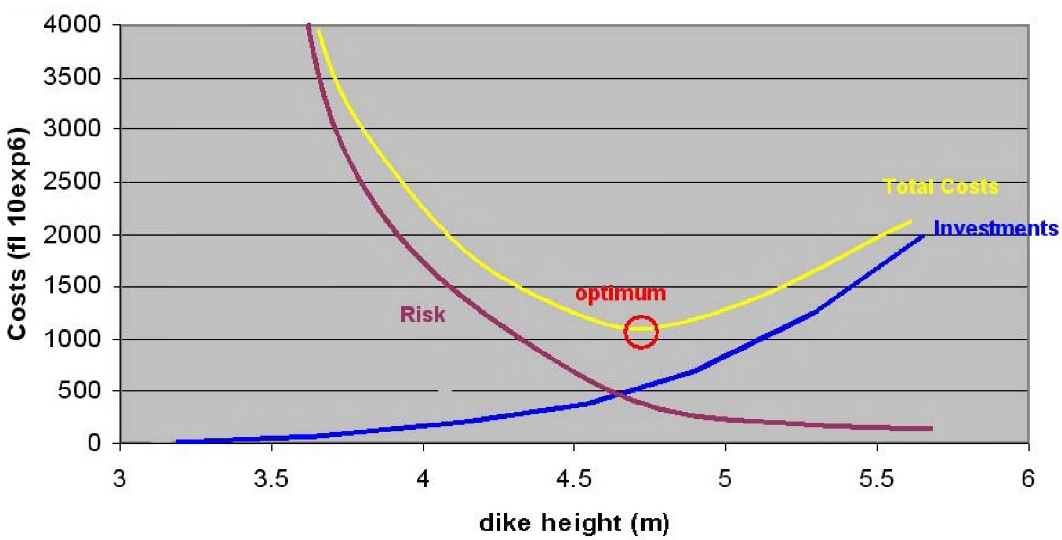


Figure 94 Principle of the Economic optimization approach by the Delta Committee.

The analysis of the Delta Committee laid the foundations for the new safety approach, in which levees are dimensioned based on hydraulic design parameters (design water level, waves) with a certain probability of exceedance. The current design criteria and the process for safety evaluation of the flood defenses are based on these design water levels. This approach to flood protection is laid down in the flood protection act of 1996.

The flood prone areas in the Netherlands are divided in so-called levee ring areas, i.e. areas protected against floods by a system of water defenses (levees, dunes, hydraulic structures) and high grounds. The height of these standards depends on the (economic) value of the area and the source of flooding (coast or river). For coastal areas design water levels have been chosen with exceedance frequencies of 1/4,000 per year and 1/10,000 per year. For the Dutch river area the protection standards were set at 1/1,250 per year and 1/2,000 per year. Some smaller levee ring areas bordering the river Meuse in the South of the country have a protection standard of 1/250 per year.

Recent developments in flood risk management

The protection standards have mostly been derived in the 1960's. Since then, the population and economic value in these levee ring areas have grown drastically. Recent investigation (RIVM, 2004) therefore concluded that these standards are no longer in proportion to economic and societal values which are protected. In the last decade the Dutch Ministry of Transport, Public Works and Water Management has initiated projects to investigate and evaluate the flood risk, see for example (Rijkswaterstaat, 2005; MinVenW, 2006). In these projects it is investigated how the estimate of the actual probability of flooding can be improved. While the traditional protection standards are mainly based on the analysis of overtopping of the flood defenses, other mechanisms, such as seepage and sliding can lead to failure as well. Also the consequences of flooding (esp. economic damage and loss of life) and mitigating measures are investigated. Outcomes of these projects will be used to assess and evaluate the level of flood risk in the Netherlands and the need for alteration of the current policies and standards.

E.3 Case study area and approach

This section describes how the economic optimization is applied to a case study area in South East Louisiana. The case study area is described in Section E.3.1, the approach, assumptions and input information in Section E.3.2.

E.3.1 Study area: New Orleans

The focus area is the central part of New Orleans, partly North of the Mississippi River and partly South of the Mississippi river (Figure 95). It is bounded by the wetlands in St. Charles Parish in the West, Lake Pontchartrain in the North, Lake Borgne in the East. Due to a connected series of flood defenses (levees and flood gates) this system makes three levee ring, i.e. an area protected by an enclosed system of flood defenses. The area is threatened by flooding from different sources. Hurricanes, high river discharges and heavy rainfall can all lead to flooding. The focus in this investigation is on the protection against hurricane flooding. For an integrated and complete analysis the different threats and their mutual relationships have to be considered, but that is beyond the scope of the current project.

Proposed flood defense scheme in the current project

The current project proposes a new or upgraded flood protection system for the New Orleans metropolitan area and includes three levee rings: two Northern levee rings (East bank) and one Southern levee ring (on the West bank) (see Figure 95). In brief, the works in the two Northern levee rings include an upgrade of the existing levees along Lake Pontchartrain (22 miles in the Levee ring 1, and 13 miles in Levee ring 2) and the Eastern side of the city (14 miles). In the Easter alignment 19 miles of new levees will be constructed. Floodgates will be constructed in the Inner Harbor Navigation Channel (IHNC) and in the Intracoastal Waterway.

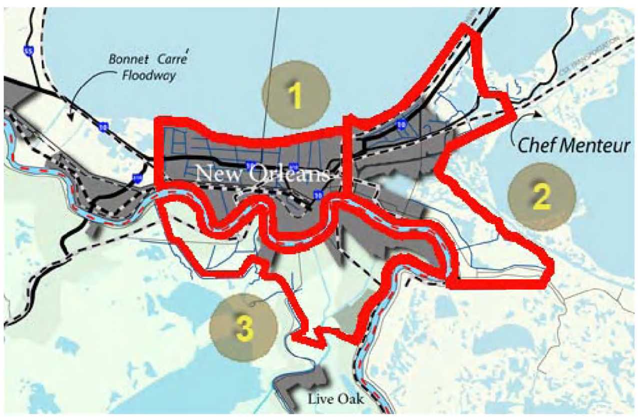


Figure 95 Overview of the three levee rings analyzed in the risk analysis: (1) Northern levee ring 1: central part; (2) Northern levee ring 2: East Orleans and St Bernard; (3) Southern levee ring.

Potential damage

The IPET-study estimates that Hurricane Katrina caused $21 billion property damages and $7 billion damages to public structures and utility infrastructures in New Orleans (IPET, 2007). The IPET-report notes that there would have been $10 billion damage if the levees would not have breached (so this part of the damage would be only related to overtopping and rainfall).

A Dutch study (Kok *et al.*, 2006) estimates the total economic damage in the flooded areas of New Orleans at approximately $30 billion. This estimate is found by combining various sources that provide insight in different parts of the damage. The estimate is in the same order of magnitude as the estimate by IPET (total $28 billion). These amounts do not include the costs of all damages. For example, the costs of the reduced activities of the local companies and the costs of social disruption are not included. In the Netherlands, the costs of the reduced activities are included in the assessment of the total damage, and these costs are often in the range of 25-50% of the material damage (Kok et al., 2007).

Table 10 gives an overview of pre- and post Hurricane Katrina damage values for the levee rings distinguished in Figure 95. Before Hurricane Katrina, the total maximum damage in the Northern levee rings is estimated at $57 billion. The maximum damage is determined for a situation where the whole area is flooded up to 35 feet deep. This is not realistic but gives an estimate of the absolute maximum damage. In the post Hurricane Katrina situation, taking into account reductions in the population and the economic value, the maximum damage in the same area was estimated at $33 billion, implying a reduction of more than 40 percent.

Table 10 Overview of maximum damage values (expressed in billion $) for the various levee rings (Source: data used by IPET consequence analysis, mean values)

	Pre-Katrina	1 June 2006
Total North 1	44.2	32.1
Total North 2	12.8	1.3
Total North	57.1	33.5
Southern levee ring 3	19.3	19.3

Population

Before Hurricane Katrina, the New Orleans region had a population of about 1.3 million people. After Hurricane Katrina (on July 1, 2006) the population was estimated at approximately 1 million people (Table 11).

Table 11 Population of the New Orleans region (Source: U.S. Census Bureau, Population Division. *County total population and estimated components of population change: April 1, 2000 to July 1, 2006*. From a compilation by the GNO Community Data Center. <http://www.gnocdc.org>)

	July 1, 2005	July 1, 2006
Jefferson	451,049	431,361
Orleans	452,170	223,388
Plaquemines	28,903	22,512
St. Bernard	65,147	15,514
St. Charles	50,554	52,761
St. John	46,150	48,537
St. Tammany	219,814	230,605
Northern levee rings	765,393	476,150
Total	1,313,787	1,024,678

The considered levee ring includes Orleans and St. Bernard parish and parts of Jefferson parish. Based on the spatial distribution of the population it is estimated that 55% of the pre-Katrina population of Jefferson Parish lived within the considered Northern levee rings. In total this results in population estimates for the levee ring of 765,000 people (pre-Katrina) and 476,000 people (post Hurricane Katrina).

E.3.2 Approach, assumptions and input information

Approach

In the current project, the economic optimization approach is applied as proposed by the Delta Committee after the disastrous 1953 flooding in the Netherlands (Dantzig, 1956) [4)]. To carry out the economic optimization the information is needed for the following elements:

1. The damage due to flooding;
2. The protection level for different system configurations expressed by means of a probability of flooding; and
3. The investment costs required for improvement of the system as a function of the protection level.

Further below, the assumptions and input information for these points are summarized.

General assumptions

- The protection level of New Orleans is assessed for three levee rings (two levee rings North of the Mississippi River, and one South of the Mississippi River, see Figure 95).
- The main focus of the study is on the protection against hurricane flooding (the Hurricane Flood Protection System). However, breaching of the Mississippi River levees can also lead to flooding of the city with disastrous consequences. Because the protection system is considered as a levee ring, both hurricane and river flooding protection have to be included from a theoretical point of view. However, since flooding from the sea due to hurricanes and flooding from the Mississippi River are often considered as independent, the optimization can be done independently. The flooding probability of the levee ring is the sum of the probability from flooding from the sea and the flooding probability from the river (and floods due to excessive rainfall have also to be added).
- Due to limitations in the availability of time and information, indicative, but realistic estimates are used for input data for investment costs, flood damage etc. The presented data are best (but realistic) estimates based on available sources. The sensitivity of the outcomes (i.e. the optimal level of protection) will be investigated for different values of the above-mentioned parameters.

Flood damage

For the analysis of damage, the focus is on the potential damage due to hurricane flooding. The considered levee ring is very large and it can flood in different ways and at different locations. As a result different hurricane scenarios could lead to flooding of different parts of the levee ring and different magnitudes of flooding. The internal topography and the presence of internal boundaries, such as the ridges, could affect or stop the flood flow. For a full analysis different flood scenarios for various hurricane intensities and breaching points would have to be defined.

4 It is noted that recently an improvement of this approach has been proposed by (Eijgenraam, 2006). In the discussion in Section E.5 it is investigated whether application of these new formulation leads to a different outcome.

For each scenario a probability of occurrence would have to be determined. Such an approach would require an in-depth and detailed assessment that would not be possible within the constraints of the current project. Here a simplified approach is chosen and one "average" damage value is used. It represents the average damage for different possible flood scenarios of the levee ring. Because it is an average damage value it is assumed to be independent of the return period of the hurricane. In further analysis different flood scenarios could be developed to assess the damage for different hurricane sizes, and breaching and overtopping locations.

In assigning a damage value, the part of the damage is used that can be related to the performance of the hurricane protection system. This implies that damage due to failure (breaching) and overtopping of levees will be included. Hence, if a hurricane protection system is designed in such a way that less overtopping will occur the damage will be less. The damage due to rainfall has to be excluded from the analysis as this is related to the drainage and pumping systems (note that there could be interactions between the performance of the drainage system and the hurricane damage). The pumping system might reduce damage due to levee overtopping. However, it is not expected that this effect will lead to a totally different damage value.

Pre-Katrina population and damage numbers were used. This assumption is driven by the expectancy that population after Hurricane Katrina will continue to grow to the pre-Katrina situation. This growth could be triggered by the development of a better flood defense system for New Orleans.

For determination of an average damage value the available data for Hurricane Katrina (see above) were used as a reference. It is assumed that the average damage caused by flooding of the two Northern levee rings is $25 billion. This is 35% of the maximum damage for the whole area (pre-Katrina levels). Note that it is assumed that economic losses of local companies are included in the loss figures. The sensitivity of the possible outcomes for the average damage value will be investigated later.

The following damage information was used:
1. Northern levee ring: central New Orleans: $15 billion
2. Northern levee ring: East New Orleans: $10 billion
3. Southern levee ring: $5 billion

In the economic optimization the Present Value of the yearly expected damage is calculated. An infinite horizon is used, and a real discount rate of 4% is assumed (that is: long term interest rate minus inflation). This percentage is often used in the Netherlands for long term public investments, but recently this figure was lowered by the Dutch government to 2,5 %. Next, it is assumed that the damage will increase, because of economic growth. It is assumed that the yearly increase in damage is 1%. The flooding probability will increase because of sea level rise. A figure of 1% per year is assumed for this reason. This means that in the calculation of the Present Value the discount rate is adjusted to the economic growth and the annual probability. Simple mathematics shows that a net discount factor of 2% per year has to be used.

The sensitivity of the outcomes for other values of the discount rate is examined in the sensitivity analysis.

Protection levels

For the analysis of the protection level of different system configurations the concept of the design water level is applied. It is assumed that the system is designed to safely (i.e. without failure) withstand water levels below the design water level. Water levels exceeding the design water level will lead to severe overtopping and consequent failure of the flood defense system. For the hydraulic conditions a probability of exceedance (per year) can be derived. This implies that the probability of failure of the flood defense system equals the probability of exceedance of its design water level.

The design water levels are used as input for the design of the flood protection system. A system has been designed in such a way that it could safely withstand the hydraulic conditions below the design water level. The effects of wave run-up will also be taken into account in the design. The analysis focuses only on the probability of exceedance of a certain water level. For a full probabilistic approach the joint probability of both water levels and waves has to be considered.

The above approach also implies that the possibility of breaching of the flood defense system for water levels below the design water level is not considered. It is assumed that the system is designed in such a way that the contribution of other failure mechanisms than overtopping to the system failure probability is negligible. Thereby the contribution of other failure mechanisms than overtopping (e.g. piping, instability) is not included in the analysis.

- In analyzing the protection level the pre-Katrina situation is taken as a starting point. It is estimated that the pre-Katrina protection level was 1/50 per year.
- The construction works after Hurricane Katrina can be seen as a first improvement of the system reliability to approximately a level of 1/100 per year. It is thus investigated in this analysis whether further improvement is justified (see below).
- The order of magnitude of the optimal protection level is analyzed by considering various predefined protection levels: 1/100, 1/500, 1/1,000, 1/5,000, 1/10,000, 1/100,000 per year.
- The relationship between return period and storm surge level is based on results of IPET, see Figure 96 for an example for Lake Pontchartrain. From such figures the increase in the surge level can be estimated that corresponds to a reduction of the return period by a factor 10. For example, Figure 96 shows that a reduction of the return period from 100 to 1,000 year corresponds to an increase of the surge level by 3 to 4 feet. Based on the available data it is assumed a linear relationship between the natural logarithm of the return period and the surge level for return periods larger than 100 years. These values have thus been extrapolated. The validity of this extrapolation for high return periods is questionable (see discussion in Section E.5). Similar figures have been used to calculate the increase in water levels for other areas, such as Lake Borgne.

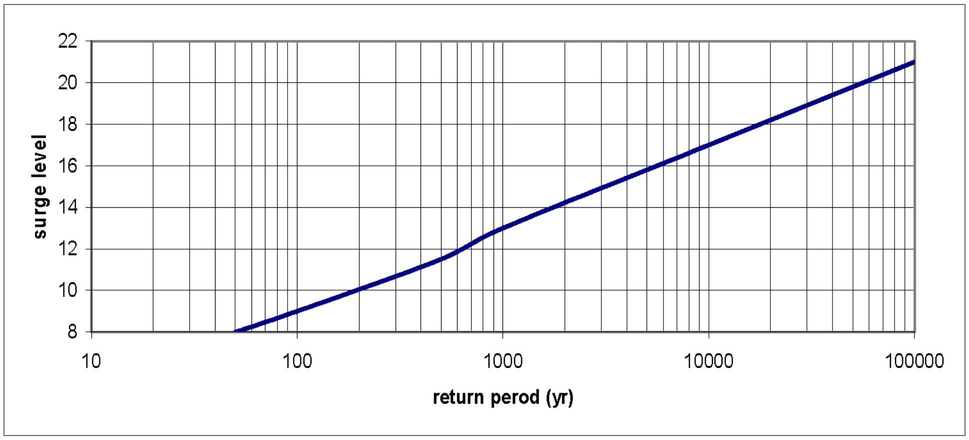


Figure 96 Lake Pontchartrain: relationship between return period and surge level (source: IPET, extrapolated to a return period of 10,000 years)

- In the determination of design water level, conservative assumptions have been made with respect to the effects of wetlands. Because it is assumed that the project investment is done for a long time span (at least 100 years) possible deterioration of wetlands in this period is accounted for. This implies that the design water levels are based on a situation in the future with a reduced area of wetlands around New Orleans. The assumed surge levels concern a future situation and are thus higher than the current surge levels (they are assumed to be approximately 4 feet higher than the current surge levels). The calculated failure probabilities are thus valid for a situation where the above deterioration has taken place. This implies that the design water levels and calculated failure probabilities are somewhat conservative for the current situation. This also implies that the stabilization or creation of wetlands could increase flood protection (see discussion in Section E.5).

Investment costs in the flood defense system

- The required investments in the flood defense system are estimated. It is investigated how much investments are required to make a safe system for water levels below the design (water) level.
- The physical measures in the base case consider levee strengthening and the creation of storm surge barriers. The effects of other measures (e.g. damage reduction and wetlands) can be considered in the same conceptual manner. In the base case optimization these effects are not treated here in detail. A discussion of the effects of wetlands on the outcomes is included in Section E.5.
- The investment costs include the costs of additional costs of management and maintenance.
- The investment costs made in the context of Taskforce Hope have been included in the cost estimates. These are the costs to bring the hurricane protection level to a 1/50 year protection level.
- The cost estimates have been made based on the length of the levees that have to be upgraded or constructed. For each protection level a unit price has been assumed per km levee strengthening or construction, see Appendix J on Costs of Measures and Strategies.

- The costs of floodgates in the Inner Harbor Navigation Channel and MRGO have been assumed as fixed costs. It is thereby assumed that they are constructed in such a robust way that they are functioning well for different protection levels.
- As stated above, the estimates of investments are based on conservative design water levels that are valid for a projected situation with deteriorated marshes.
- Overall, the cost estimates are first order and indicative. For a realistic calculation of investment costs more detailed designs have to be used. To account for variations and deviations in the cost estimates the investment costs have been included in the sensitivity analysis.

E.4 Results of economic optimization

E.4.1 Base case Northern levee ring, central New Orleans

The current annual risk of this levee ring is equal to $300 million (= $15 billion x 1/50). This value can be converted to a present value by dividing by the "net" discount rate (0.02), leading to a present value of $15 billion. If the protection level is improved to 1/100, the present value of the annual risk will decrease with $7.5 billion, and if the protection level is lowered to 1/1,000, the present value of the risk will decrease with $14 billion. This decrease in present value can be considered as the benefits of the project. However, in a cost benefit analysis also the cost of the improvements in flood protection is important.

The results for the base case are presented in Table 12 and Figure 97 (both show the same information in different forms). The optimal level of flood protection that follows from the analysis is 1/5,000 years (indicated in bold in Table 12).

Figure 97 shows the following. In terms of total costs there is not much difference with a 1/1,000 or 1/100,000 per year protection level. The additional investment costs to reach a 1/10,000 per year level of protection ($200 million) or a 100,000 per year level ($700 million) are relatively limited. For protection levels of 1/100,000 per year and higher the contribution of the risk costs to the total costs becomes negligible. Further sensitivity analyses are presented in Section E.4.4.

Table 12 Economic optimization for Northern levee ring, central part of Orleans: Input information and results

Return period (yr)	100	500	1,000	**5,000**	10,000	100,000	1,000,000
Flooding prob. (per year)	1/100	1/500	1/1,000	**1/5,000**	1/10,000	1/100,000	1/1,000,000
Design surge level Lake Pontchartrain (ft)	9	11	13	**13**	17	21	25
Investments ($)	2,2E+09	2,4E+09	2,6E+09	**2,9E+09**	3,1E+09	3,6E+09	4,1E+09
Risk ($)	7,50E+09	1,50E+09	7,50E+08	**1,50E+08**	7,50E+07	7,50E+06	7,50E+05
Total costs ($)	9,71E+09	3,95E+09	3,39E+09	**3,02E+09**	3,17E+09	3,60E+09	4,12E+09

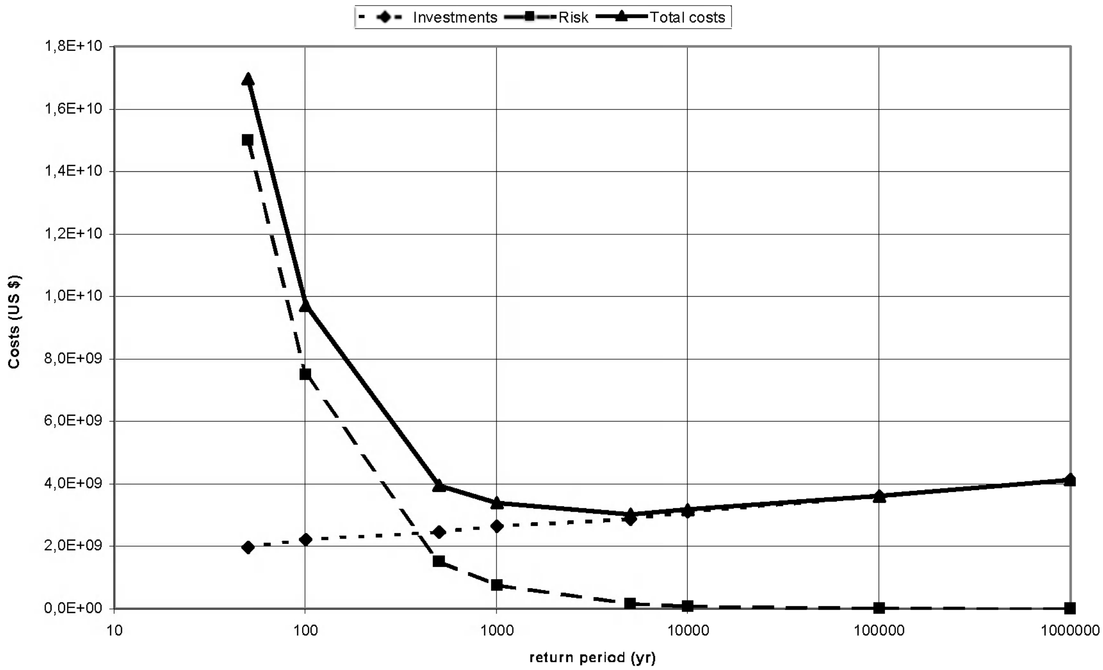


Figure 97 Results of economic optimization for the Northern levee ring, central part of New Orleans

E.4.2 Base case Northern levee ring, New Orleans East

The **annual risk** of this levee ring is equal to $200 million (= $10 billion x 1/50). This value can be converted to a present value by dividing by the "net" discount rate (0,02), leading to a present value of $10 billion. If the protection level is improved to 1/100, the **present value** of the annual risk will decrease with $5 billion, and if the protection level is lowered to 1/1,000, the present value of the risk will decrease with $9.5 billion. This decrease in present value can be considered as the benefits of the project. However, in a cost benefit analysis also the cost of the improvements flood protection is important.

The results for the base case are presented in Table 13 and Figure 98 (both show the same information in different forms). The optimal level of flood protection that follows from the analysis is 1/1,000 years (indicated in bold in Table 13).

Table 13 Economic optimization for Northern levee ring, New Orleans East: Input information and results

Return period (yr)	100	500	**1,000**	5,000	10,000	100,000	1,000,000
Flooding prob. (per year)	1/100	1/500	**1/1,000**	1/5,000	1/10,000	1/100,000	1/1,000,000
Design surge level Lake Borgne (ft)	14	17	**18**	20	22	26	30
Investments ($)	3,9E+09	4,4E+09	**4,7E+09**	5,1E+09	5,5E+09	6,4E+09	7,4E+09
Risk ($)	5,00E+09	1,00E+09	**5,00E+08**	1,00E+08	5,00E+07	5,00E+06	5,00E+05
Total costs ($)	8,86E+09	5,40E+09	**5,15E+09**	5,17E+09	5,55E+09	6,40E+09	7,36E+09

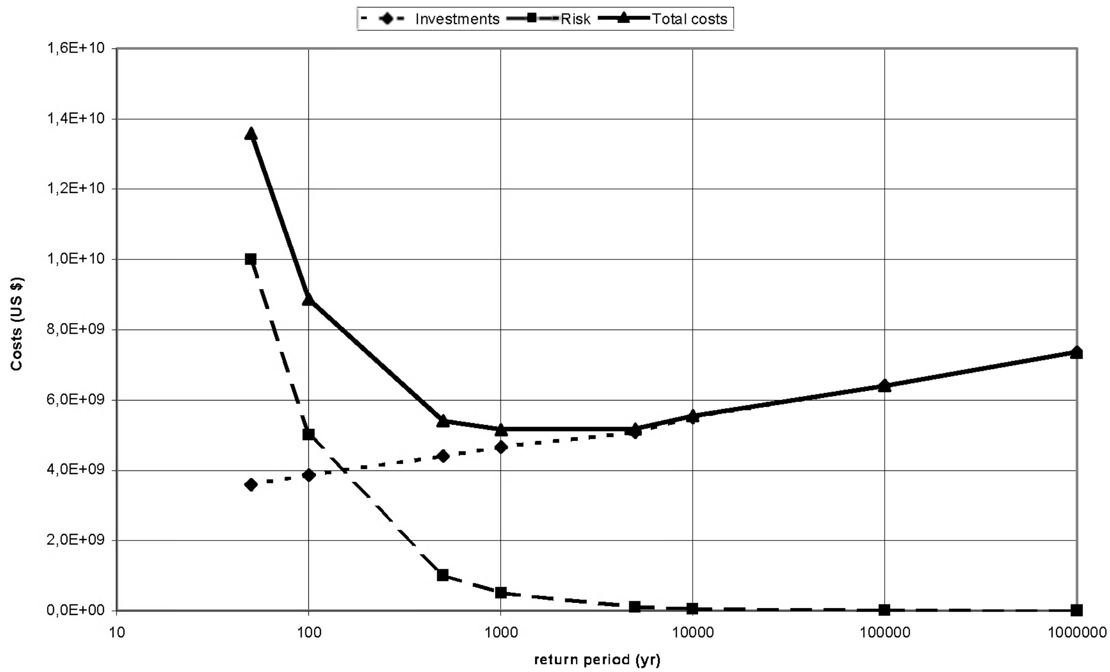


Figure 98 Results of economic optimization for the Northern levee ring, New Orleans East

E.4.3 Base case Southern levee ring

The **annual risk** of this levee ring is equal to $100 million (= $5 billion x 1/50). This value can be converted to a present value by dividing by the "net" discount rate (0,02), leading to a present value of $5 billion. If the protection level is improved to 1/100, the **present value** of the annual risk will decrease with $2.5 billion, and if the protection level is lowered to 1/1,000, the present value of the risk will decrease with $4.7 billion. This decrease in present value can be considered as the benefits of the project. However, in a cost benefit analysis also the cost of the improvements in flood protection is important.

The results for the base case are presented in Table 14 and Figure 99 (both show the same information in different forms). The optimal level of flood protection that follows from the analysis is 1/1,000 years (indicated in bold in Table 14).

Table 14 Economic optimization for Northern levee ring, central part of Orleans: Input information and results

Return period (yr)	100	500	**1,000**	5,000	10,000	100,000	1,000,000
Flooding prob. (per year)	1/100	1/500	**1/1,000**	1/5,000	1/10,000	1/100,000	1/1,000,000
Design surge level Barataria Basin North (ft)	9	11	**13**	13	17	21	25
Investments ($)	3,4E+09	4,0E+09	**4,2E+09**	5,2E+09	6,2E+09	7,3E+09	8,3E+09
Risk ($)	2,50E+09	5,00E+08	**2,50E+08**	5,00E+07	2,50E+07	2,50E+06	2,50E+05
Total costs ($)	5,87E+09	4,49E+09	**4,46E+09**	5,24E+09	6,20E+09	7,26E+09	8,31E+09

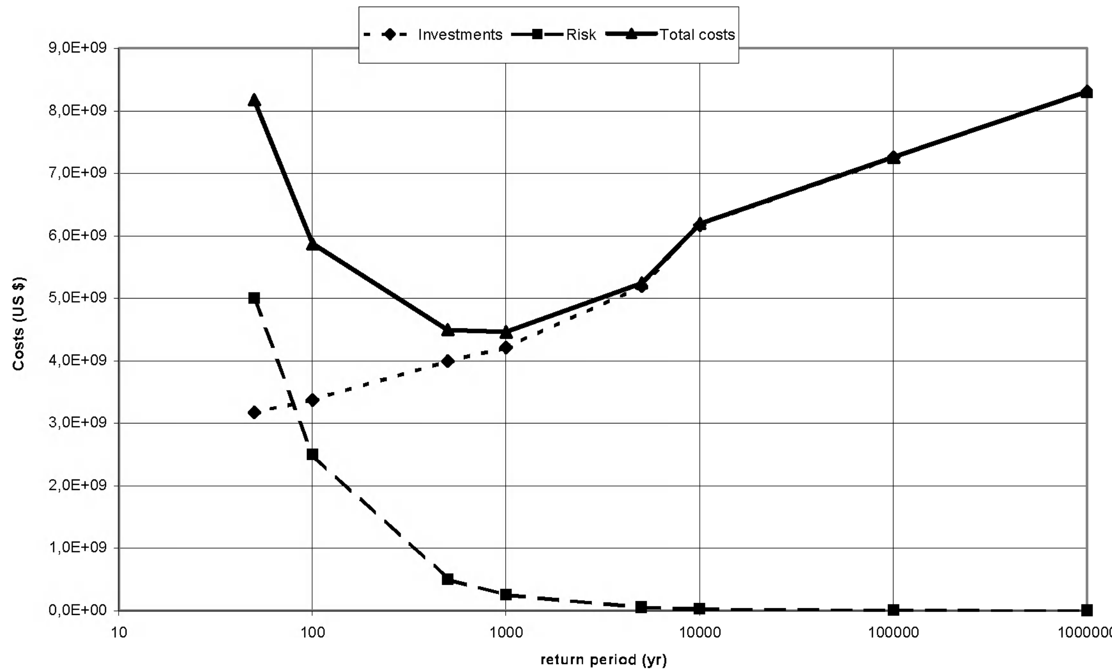


Figure 99 Results of economic optimization for the Southern levee ring

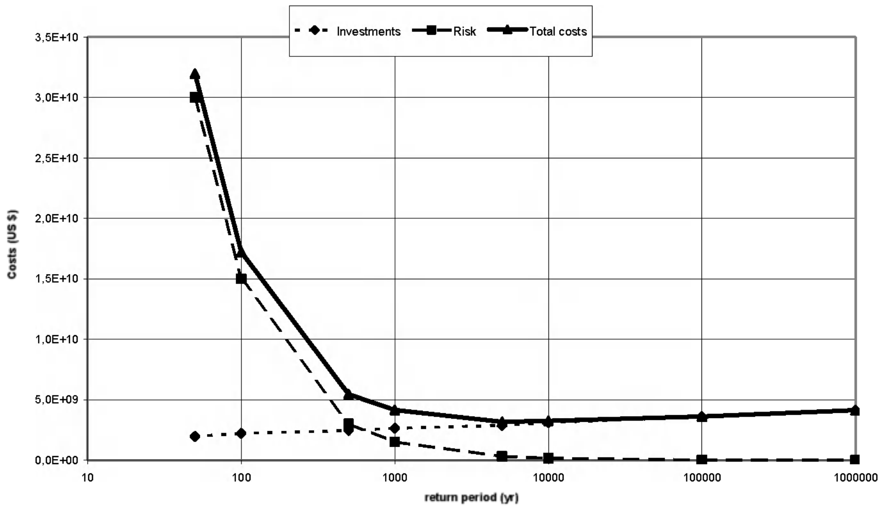
E.4.4 Sensitivity analyses

In this paragraph the sensitivity of the outcomes of the calculated optimal protection level is investigated for some parameters: The flood damage value, the value of the real discount rate and the investment costs. Only the results of Northern levee ring are shown, i.e. the central part of New Orleans.

Damage value

In the base case a flood damage value of $15 billion has been assumed. The economic optimum for two other values, namely $5 billion and $30 billion. The results are shown in Figure 100. For the damage value of $5 billion the optimal level of protection is lowered to 1/1,000 per year. A larger damage value of $30 billion the level of protection remains at 1/5,000 per year.

Damage = $5 billion: Optimum: 1/1,000 per year



Damage = $30 billion: Optimum: 1/5,000 per year

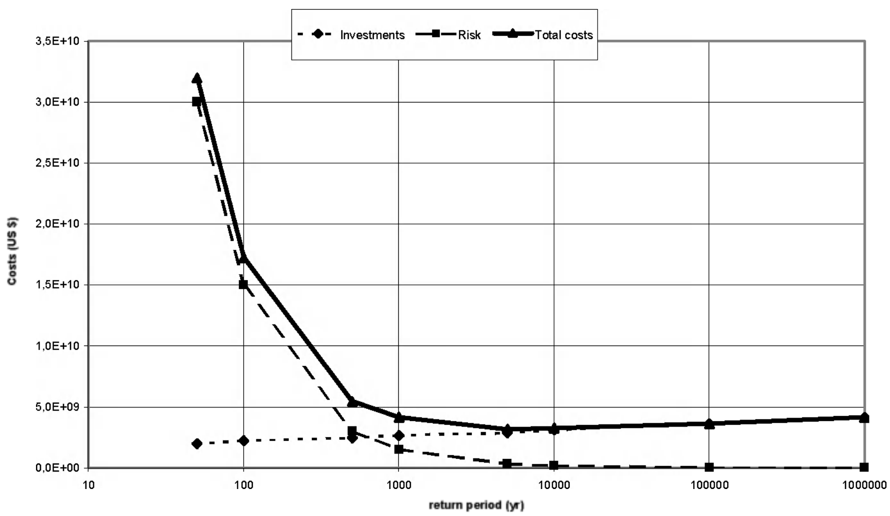
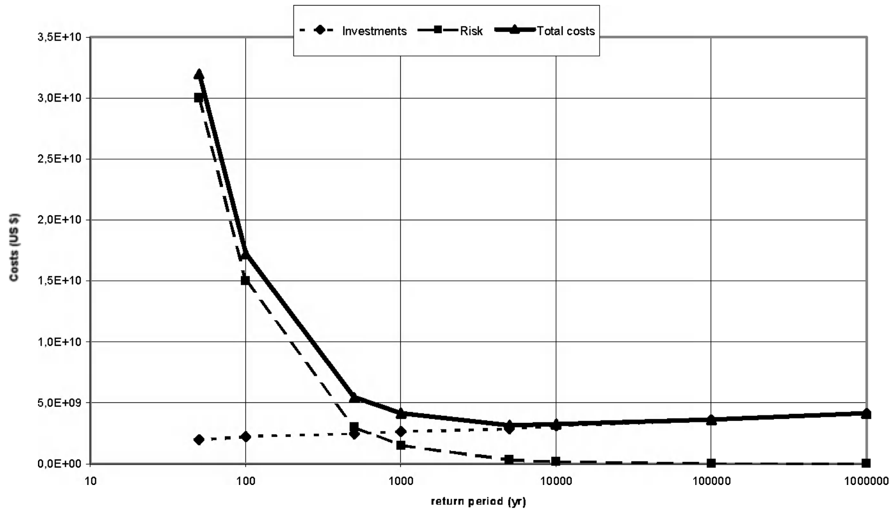


Figure 100 Sensitivity of economic optimum for the damage value

Discount rate

In the base case a net discount rate of 2% has been assumed. In this sensitivity analysis the effects of choosing a lower (1%) or higher (4%) net discount rate are investigated. The lower discount rate results in an optimum of 1/5,000 per year. For the higher discount rate the optimum also remains at 1/5,000 per year.

Real discount rate = 1%: Optimum: 1/5,000 per year



Real discount rate = 4%: Optimum: 1/5,000 per year

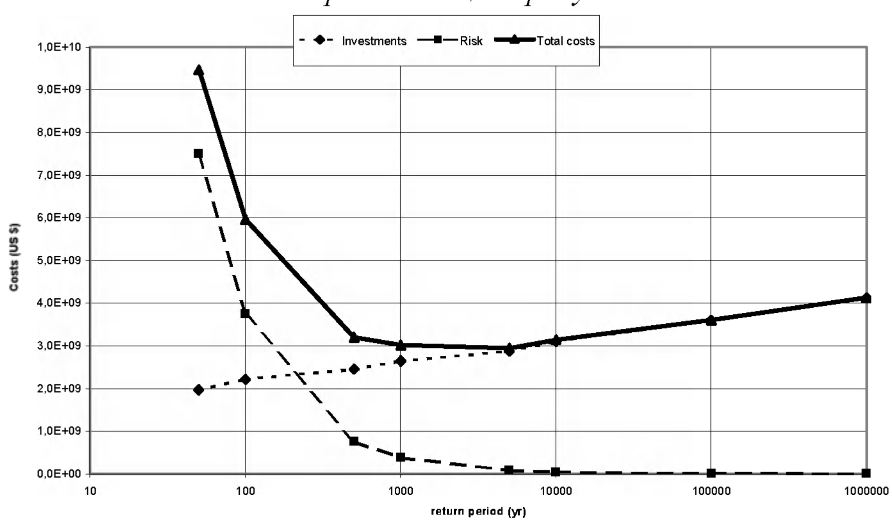


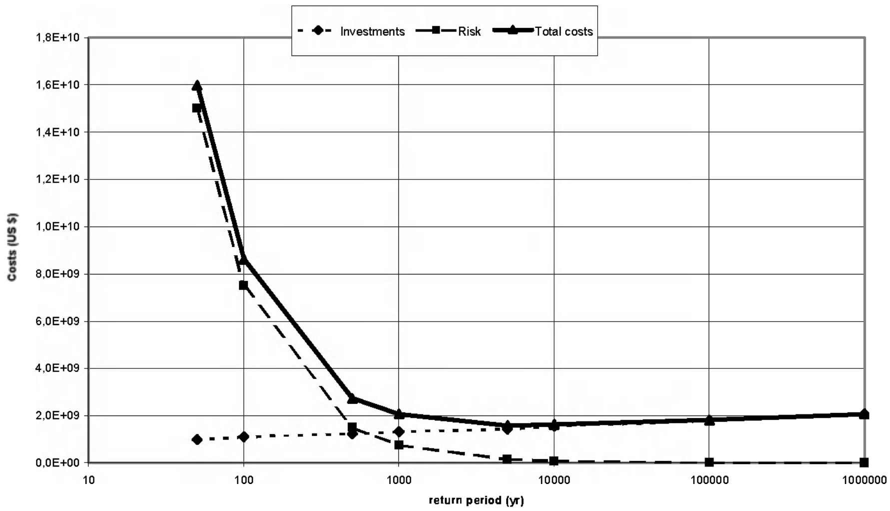
Figure 101 Sensitivity of economic optimum for the net discount rate

Investment costs

The investment costs have been estimated based on rough indicators. There is thus considerable uncertainty associated with these estimates. The influence of investment costs on the optimum has been investigated.

Firstly, the influence of 50% reduction of investment costs has been investigated. This leads to an increase of the total cost, but it does not change the optimum. Secondly, a 50% higher investment costs has been assumed. In that case the optimum does not change and remains at a level of 1/5,000 per year.

50% lower investment cost: Optimum: 1/5,000 per year



50% higher investment cost: Optimum: 1/5,000

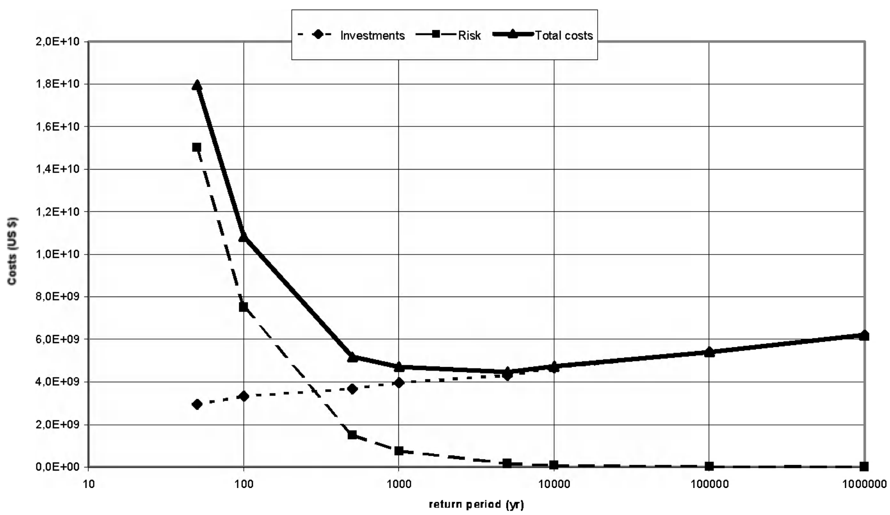


Figure 102 Sensitivity of economic optimum for different investment costs

Table 15 Results of sensitivity analysis for Northern levee ring 1

	flooding probability
Base case	1/5,000
Flood Damage	
50 % lower	1/1,000
100% higher	1/5,000
Net Discount rate	
50% lower	1/5,000
100% higher	1/5,000
Investment costs	
50% lower	1/5,000
50% higher	1/5,000

A summary of the results of the sensitivity analysis can be found in Table 15.

E.5 Discussion

This section discuses a number of issues of relevance to the assessment of the risk. These issues could form the basis for more detailed assessments in future studies.

Measures and the effects of wetlands

In the analyses of measures in the previous sections mainly the effects of levees and storm surge barriers have been included. However, other measures in the multiple lines of defense strategy could reduce the risk as well. Examples of such measures include: wetlands, ridge-levees, compartment levees within one levee ring and evacuation.

One specific measure that receives much attention is the stabilization and creation of wetlands. Their presence could reduce the surge levels near populated areas. The impact of wetlands on the surge levels used for design can be taken into account. As has been stated above, conservative assumptions have been made in the determination of design water levels with respect to the effects of wetlands on surge heights and waves. Because it is assumed that the project investment is done for a long time span (at least 100 years), possible deterioration of wetlands in this period is already accounted for. As an indicative example the effect of the stabilization or creation of wetlands is conceptually shown in Figure 103 for the Lake Pontchartrain area (surge levels for wetlands are just shown as an example).

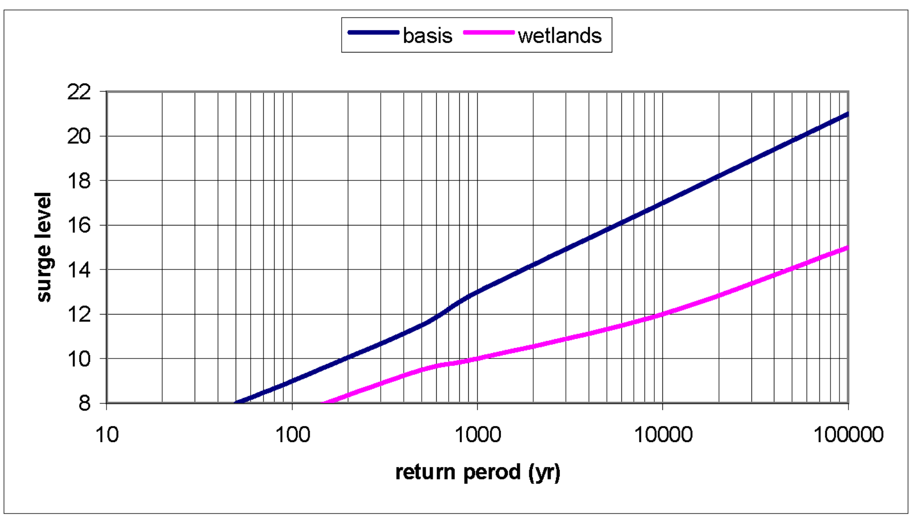


Figure 103 Example of reduction of surge levels due to wetlands. Note: values are assumed and should be verified based on actual calculations.

In the context of cost benefit analysis an indicative analysis of the effects of wetlands can be given as follows. The stabilization and creation of wetlands around the city could lead to a reduction of surge levels near the city. For example, the creation of wetlands East of New

Orleans would reduce the 1/10,000 year storm surge level East of New Orleans from 22 tot 15 feet. Due to the reduction of surge levels the height and strength of the levees around the city can be reduced and the investment costs in levees would be lower. In the analyses in this report conservative surge levels have been used valid for a future situation with deteriorated wetlands. This situation could be reached on a longer term (50 to 100 years). Currently, the protection level of the levee rings will be higher than calculated in the examples. It has been assumed that the surge levels with further loss of wetlands are approximately 4 feet higher than the current levels. Based on the surge level return periods it is estimated that the stabilization of the wetlands could result in a flooding probability that is a factor 10 lower than the flooding probabilities that have been reported. For example, assume a situation where a design is made for a 1/1,000 per year protection level for a situation without wetlands. If it is possible to stabilize or restore the wetlands the actual protection level of this design could be 1/10,000 per year.

The effects of wetlands could also be taken into account in a cost benefit approach. In the previous section an optimal level of protection for the Northern levee ring has been determined of 1/5,000 per year. If the investments would only concern levees the costs are estimated at $5.2 billion for the two Northern levee rings (both with protection level of 1/5,000). If a combined approach of levees and wetlands would be chosen the costs for the levees only would be $3.6 billion (because improvement of the marshes may lead to lower water levels). From a cost benefit point of the combined strategy (levees and wetlands) would be a better investment than levees only if the costs would be smaller than $1.6 billion. However, this reasoning does not yet take into account the time needed for the improvement of the marshes.

However, additional benefits could be assigned to the creation of wetlands, e.g. increases in ecological values and beneficial effects for fisheries. In that case more investments in wetlands are justified.

The restoration of wetlands is a relatively slow process. It might take 10 – 50 years to stop the process of deterioration of the wetlands, and even more time to increase the quality of these wetlands. This timing problem needs from a risk management point of view more attention, and more research. Possibly, the best thing from a risk management perspective is to put more emphasis on the protection with levees, at least in the short-term, in order to gain time for the restoration of the other line of defense: the marshlands.

Overall, a further analysis of the effects of wetlands on surge levels and the associated costs would be needed to make definite statements regarding their effectiveness. Relevant issues are the effects of wetlands under extreme hurricane conditions and the fact that the reduction of surge levels is dependent on the hurricane track and the duration of the hurricane.

Failure mechanisms and design water levels

In the presented analysis it has been assumed that the levee system catastrophically fails if the design water level is exceeded. It is thereby assumed that the system is designed in such a way that the contribution of other failure mechanisms than overtopping to the system failure probability is negligible. However, failure mechanisms other than overtopping could be relevant for the failure analysis. During Hurricane Katrina, for example, flood defenses have failed because of other reasons than overtopping. Therefore, the analysis of the contribution of these mechanisms to failure is strongly recommended with the approaches developed in the IPET "risk analysis" project.

For the analysis of measures and investment costs so-called design water levels have been used. Results have been from the IPET study and these are available for return periods below 1,000 years. For higher return periods (10,000 years and further) design water levels are to be considered as rather uncertain. In addition, physical limits to hurricane characteristics (pressure, wind speeds) and hydraulic effects (surge and waves) could affect the design conditions for higher return periods. Therefore, the hydraulic boundary conditions for higher return periods have to be examined further.

Average flood damage and flood scenarios

In the presented analysis an average damage has been assumed (see Section E.3.2). For a full analysis, different flood scenarios for various hurricane intensities and breaching points would have to be defined. In a risk analysis different flood scenarios can be elaborated and their probabilities and consequences can be estimated. For assessment of the consequences two dimensional hydraulic simulation models can be used to analyze the flood characteristics of a scenario as input for damage modeling. An example of the results of a flood simulation for New Orleans is shown in Figure 104.

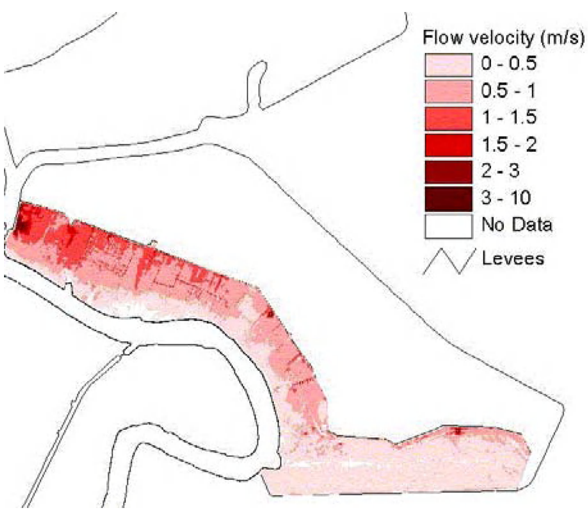


Figure 104 Flow velocities for Lower Ninth Ward from flood simulation (Maaskant, 2007)

Method for the economic optimization

In the elaborations in this report the method for economic optimization proposed by van Dantzig (1956) has been used. Recently, an improvement of this approach has been proposed by (Eijgenraam, 2006). In essence, the difference is that van Dantzig assumes one major improvement at the current moment, while Eijgenraam considers the periodic character of the improvement of the flood defense system under changing conditions such as economic growth, sea level rise etc., as illustrated by Figure 105. Application of Eijgenraam's approach to the Northern levee ring leads to an optimal level of protection of 1/3400 per year (Kuijper, 2007). This is in the same order of magnitude as the optimum of 1/5,000 per year that has been found in Section E.4.1. The optimum found by Eijgenraam's method is somewhat higher and this can be explained by (1) the fact that Eijgenraam's approach assumes that additional measures will be implemented in the future, so that the protection level can be maintained, and (2) the fact that in the application of the economic optimization in Section E.4 only discrete steps for the protection level have been used (1/100; 1/500; 1/1,000 per year, etc.).

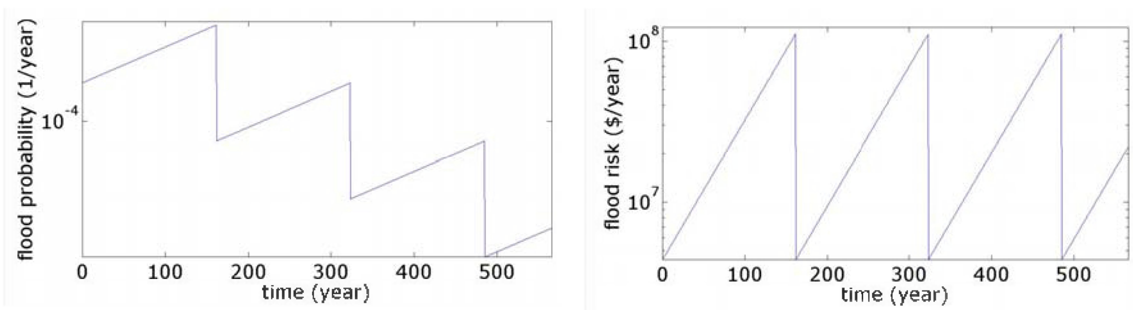


Figure 105 The optimal periodic improvement of flood defenses. On the vertical axes the flood probability (left figure) or the flood risk (right figure) and on the horizontal years the number of years. Flood probability increases because of sea level rise, but probability decreases if new investments are made. The flood risk is at a constant level after a new investment is made.

Application to other areas

The economic optimization has been applied to levee rings around densely populated areas with high (economic) values. This resulted in high levels of protection in the order of magnitude of 1/1,000 to 1/5,000 per year. The levee ring concept can also be used for other populated areas in coastal Louisiana. For example for Plaquemines Parish, it could be investigated if local communities could be protected by a levee ring. For these cases it is expected that the economic optimization will lead to lower levels of protection, because the required investment costs will be relatively high, while the protected value is relatively limited. For some cases it could even turn out that investment in a levee ring system is not justified from a cost-benefit point of view. In these cases other strategies could be investigated to offer a certain minimum level of protection for these areas, e.g. raising of homes, mounds, evacuation plans, etc.

Loss of life and risk criteria

The current analysis is mainly based on the analysis of economic damage. One other important aspect for decision making is the number of fatalities caused by a flood. Hurricane Katrina caused more than 1100 fatalities in the state of Louisiana. Future flood scenarios of New Orleans might lead to loss of life. An estimate of the loss of life can be given based on: (1) information regarding the flood characteristics; (2) an analysis of the exposed population and evacuation and (3) an estimate of the mortality amongst the exposed population. This shows that several measures could reduce the loss of life, such as evacuation or the limitation of the flooded area. Methods have been developed for the estimation of loss of life (IPET, 2007; Jonkman, 2007). In the context of risk assessment criteria could be developed that indicate the acceptable probability of a certain number of fatalities. These are indicated in a so-called FN-curve. An example of such a criterion that is used for the risk assessment of large dams by the U.S. Bureau of reclamation is shown in Figure 106.

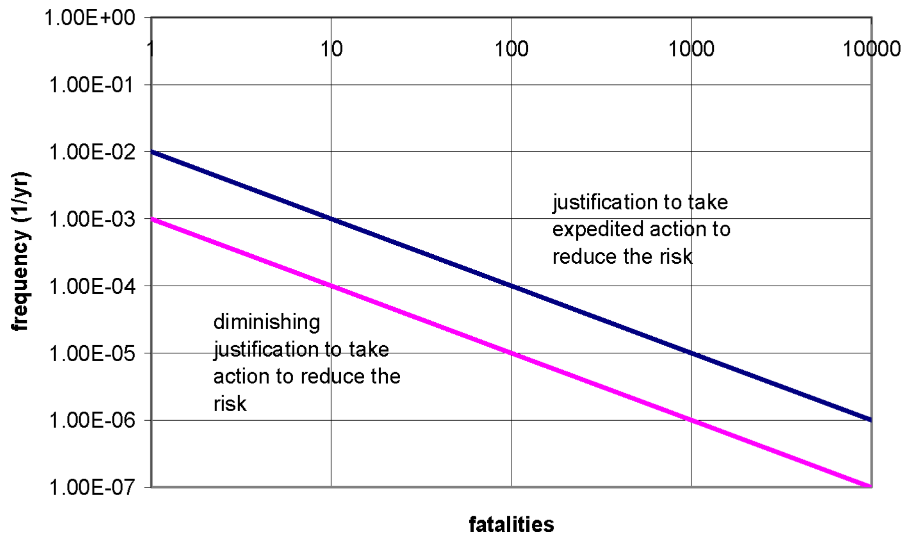


Figure 106 USBR's criteria for large dams (USBR, 2003)

Proposed flood defense scheme and developments in time

In the current project, the flood defense scheme is developed at a conceptual level. The investment costs have been estimated based on rough indicators. Hence, there is considerable uncertainty associated with these estimates. Although anticipated developments have been taken into account in the proposed design, several developments could affect the outcomes of the economic optimization:

- Loss of marshes, sea level rise, increased hurricane activity could lead to increase of loads.
- Subsidence of the soil or new insights in behavior of designed flood defense works could affect the resistance of the system.
- Changes in construction techniques, market prices, etc. could lead to differences investment costs.
- Changes in population, economic activity and spatial development could lead to changes in flood damage.

Assumptions have to be made with respect to these developments in the current proposed designs. However, given the uncertainty in such future developments it is recommended to develop a management and maintenance system, see also Appendix K on Management and Maintenance. By means of a management system it could be investigated whether the system that is in place still complies to the initially intended design criteria. If the performance of the system has weakened over time, e.g. due to subsidence, corrective action could be taken to improve the performance, see Figure 107. In the context of the risk assessment it could even be desired that the strength/ resistance of a system increases over time when the consequences of failure increase (e.g. due to economic or population growth). Figure 107 also explains why additional strength (on top of the minimal requirements) could be given to a new system that is constructed. It can be shown that this is attractive from an economical point of view (Eijgenraaam, 1996). In that case some degradation can be accepted before corrective action is needed. This is also reflected in the concept of "robust design".

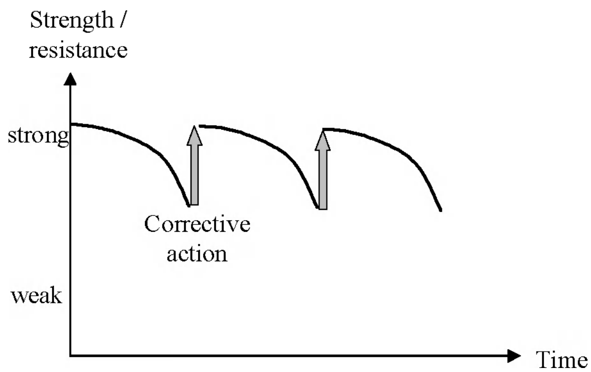


Figure 107 Development of the resistance of a system over time and the effects of periodic corrective action

E.6 Conclusions

This appendix describes a preliminary economic optimization for the protection level of New Orleans. Indicative, but realistic estimates were used as input data. The following has been found:

1. Although preliminary and not yet fully realistic the presented outcomes indicate that it is possible to determine the optimal level of flood protection for the different levee rings in coastal Louisiana.
2. The optimal protection level for the proposed Northern levee ring of New Orleans is estimated to be in the order of magnitude of 1/5,000 per year. This outcome is not very sensitive for changes in damage level and the investment costs. Only when lower damages are assumed, the optimum level of protection reduces to 1/1,000 per year.
3. The optimal level of protection for New Orleans East levee ring and the Southern levee ring are 1/1,000 per year.
4. The protection levels are calculated taking into account the deterioration of the marshes, which may take place after 50-100 years. These level correspond with protection in the **current** situation in the order of magnitude of 1/50,000 for the Northern levee ring (central) and 1/10,000 for the other two levee rings in New Orleans.
5. The results indicate that for densely populated areas, such as the Northern levee rings of New Orleans it is justified to choose a considerably higher protection level than the current level of 1/100 per year. Although the investment costs will be high (billions of dollars), a very large amount of flood damage can be prevented. The investments are expected to be cost-effective.

6. The outcomes also show that a differentiation in protection levels between areas could be justified based on the economic optimization. Such a differentiation in protection levels between areas also exists for levee rings in the Netherlands. The most valuable levee ring areas in the Netherlands have a protection level of 1/10,000 pear year, while other levee rings have protection levels of 1/4,000, 1/2,000 and 1/1,250 per year.
7. The results of the economic optimization can be considered as a technical advice to the decision makers. The decision is a political choice, including more factors than economic factors.
8. The presented analyses are limited to the (direct) economic flood damages. In decisions concerning an adequate protection level also other consequences, such as loss of life could be taken into account. Although this has not been done in the presented analysis, it is possible to include these other damage categories in terms of economic damage. This would lead to a higher damage level and thus to a better level of protection. Also, alternative risk criteria could be developed. For example, risk limits could be set that indicate for which probability a certain number of fatalities is considered to be acceptable.

Recommendations:

1. In this document a rough and first order economic optimization has been performed for New Orleans. To obtain better results further investigation of the following factors is recommended:
   - The defense schemes in this risk management approach mainly focus on levees and barriers. Other types of measures (e.g. wetlands) and combinations of measures have to be investigated.
   - In the analyses conservative assumptions have been made with respect to the design water levels as large-scale deterioration of wetlands has been assumed. On a longer term, the stabilization or (re)creation of wetlands could improve the flood protection of the areas behind the levees. However, the restoration of wetlands is a relatively slow process that takes decades. A further investigation of the effects of wetlands on surge levels is recommended. Also, the timing of these measures needs more attention within a risk management context. The wetland restoration may take a long time, but improvements in flood protection are desired on a shorter time-scale.
   - Better and more detailed cost estimates are needed. The cost estimates used in this risk analysis are considered high. Lower estimates will result in higher protection levels.
2. The outcomes of the IPET risk analysis are very useful as improved input data for the presented optimization problem. It is recommended to investigate how the analyses from the IPET risk analysis can be used for the economic optimization. One specific issue is the determination of design water levels to higher return periods and the validity of the extrapolation to higher return periods.
3. The presented approach could be applied to other "levee-ring" regions in coastal Louisiana.
4. The choice for a level of flood protection concerns a societal / political choice. It is recommended to start a discussion on protection levels and the corresponding decision criteria and to involve the relevant decision makers and stakeholders.

References Appendix E

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F Soft soil engineering and levee design approach

Introduction

There are two distinctly different types of levees that can be considered in the framework of flood risk reduction:

1. (Very) high levees that can safely resist the hydraulic loads. This means limited or no wave overtopping over the crest of the levee (this approach is traditionally applied in the Netherlands), or levees that are made resistant to overtopping, at least with the crest above surge level, probably well protected by an asphalt cover.
2. A lower levee at some distance in front of a second levee. Looking from the direction of the sea, the first levee will primarily function as a "surge-breaker": it will reduce the surge level for the second levee. This means the levee can be lower than the surge level, but must resist extensive water flow over the crest of the levee and must withstand wave attack on the sea side. There is no experience in the Netherlands with this kind of levee.

For the improvement of the protection of New Orleans against hurricane surges, new levees on soft soils have to be built. The existing U.S.-plans are based upon stability calculations for undrained soil. In case of insufficient bearing capacity of the soil these plans include soil improvement by mixed-in-place techniques or by using concrete or steel structures instead of just soil. The approach followed in the Netherlands differs substantially from the U.S. approach. Effective stress and pore pressures are always considered separately. Even in areas with very soft soils just under the water surface embankments have been made with soil only.

Developing new levees includes making decisions on the following points:

1. Levee slopes: if very gentle slopes are chosen, they can be made so that waves will not break on the levee. Some loss of cover material can be accepted as long as the core of the levee remains. If steeper slopes are chosen, the surface has to be protected against breaking waves.
2. Levee height: a high levee without overtopping can be chosen or a lower levee with overtopping: the latter is also possible, but it means that the crest has to be protected.
3. Levee type: a choice has to be made between strengthening existing levees or building completely new levees.
4. Existing surface: levees can be built upon existing land or in water.

In the Netherlands, surge levels with a probability of occurrence of 1/10,000 per year hardly exceed +5 m. Wave overtopping (limited to 1 l/s per m of levee, equivalent to about 0.1 gallon per second per foot of levee) is virtually not accepted in the designs. Surge levels in coastal Louisiana can be considerably higher, which makes it difficult to design a levee as crest levels may become very high and exceed experience, at least experience in the Netherlands. Designing for no overtopping implies that no real experience is available with the overtopping of levees, except from the floods in the Netherlands in 1953. In addition, there is limited experience with overtopping levees covered with asphalt. Hence, any levee solution for coastal Louisiana implies more than just applying "proven technologies" and should be accompanied by additional tests and research, combining international expertise.

The only experience with heavily overtopped earthen levees is a hurricane protection around a refinery along the Gulf Coast in the U.S., designed in the year 2000. This is, however, a very positive experience, because the levees withstood Hurricane Katrina and prevented loss of the refinery.

Another recent experience is testing inner slopes of levees with a wave overtopping simulator in the Netherlands. First tests showed that erosion resistance of clay covered with grass is in general high. As long as the inner slope does not geotechnically slide (which means that gentle inner slopes should be used), a grass covered slope may resist large overtopping.

Levee development

For reaches shown in Figure 108 areas, the LACPR-project has made calculations, as shown in enclosure F of LACPR report Engineering Investigations page 187. An alternative calculation, based upon the Dutch view, is described in this section.

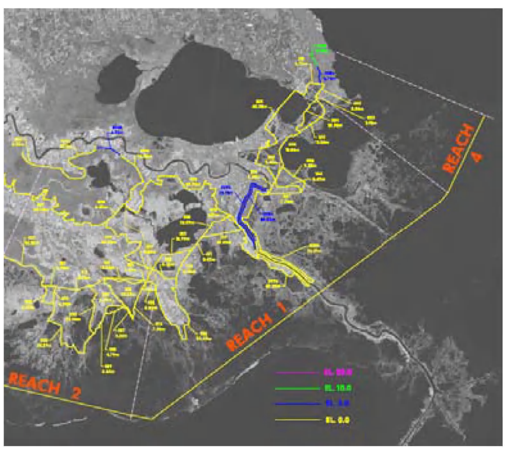

Figure 108 Locations of Reach 1 and Reach 4 for differentiation in soil parameters

Failure of a levee obviously differs from failure of a concrete or steel structure. In soil mechanics failure usually means shearing. The shear stress depends on the stress between the soil particles. In the situation with soil saturated with water according to Archimedes this stress, the effective stress, is total stress minus the pore pressure.

$$\sigma' = \sigma - u$$

with:

σ' = effective stress
σ = total stress
u = pore pressure

The Mohr Coulomb model is used to calculate shear resistances. The resistance against sliding highly depends on the effective stress.

$$\tau = c' + \sigma' tg\varphi'$$

with

τ = shear stress
c'= drained cohesion
ϕ' = friction angle

This means that reducing the value of u is another possibility to make the soil stronger. In the Netherlands, with it's wet, saturated soft soils, this way of strengthening is the usual practice. In many other places, calculations are based upon

$$\tau = c_u$$

with

c_u = undrained cohesion

Considering the shear stress in this way, lowering the value of u does not change the value of τ.

Improving soil properties by mixing in place with grout or cement is one way; improving the shear stresses by reducing the pore pressures is another way to increase the shear stresses.

Upper layers in the Netherlands consist of Holocene peat and clay, impermeable and compressible. Loading on such layers leads to an immediate rise in pore pressures. Effective stresses, and shear resistance as well, increase only slowly. However, this process can be accelerated.

In the following, Dutch design principles will be applied for New Orleans soils.

Soils

Regarding the available materials in the New Orleans area, the following is noted:

- Available materials are generally silty. Silt is deposited in areas with little water movement. A typical property of silt is little cohesion. If applied without drying, this material allows only very gentle slopes.
- There are local sand ridges at the surface. Sandy areas are often in use (built-up areas), so not available for use. Typical properties of sand are the lack of cohesion but a good angle of friction as well as good permeability. Deep sand is generally fine (in contrast: not the coarse sand as usually found in the Netherlands), and covered with silty material. Locally there are more coarse sand layers, generally thin and hence relatively expensive to use. Coarse sand can be used for drainage layers, but the small available quantity means that there is not enough sand for large-scale applications.
- Clay has good cohesion and little permeability. Good clay is available, but has to be scraped from large areas. Due to the high water content and the low liquid limit it will be necessary to dry it before use.

All in all, in coastal Louisiana:

- there are limited quantities of sand, with coarse sand available in even smaller quantities when compared to fine sand;
- good quality clay is available, but not easy to collect; and
- most material is inferior because it does not have sufficiently good properties for use in levees.

More information about the soils in coastal Louisiana can be found at:

- http://ees.uno.edu/kulp/GCAGST_2002_topstratum_manuscript.pdf;
- Technical Report V Appendix 2 page 42 gives geotechnical profiles.

More information about drained soil properties can be found at:

- Technical Report V Appendix 2 page 35 (properties, including drained cohesion and drained shear strength);
- Mc Clelland (1966) (compression indexes and measured excess pore pressures).

Ridge-levees

In some of the possible options for hurricane protection an additional line of defense has been proposed: a first system of low levees to reduce the surge to some extent and a second system to protect against flooding. Of course the first system can be designed as a conventional levee with heavy armoring to protect for wave overtopping and also overflow. Here, however, an alternative is introduced under the heading "ridge-levee"

At several locations (sand) ridges do exist along the Mississippi and they have been there for ages. The crest level of these ridges is between 5 and 10 feet, which allows fresh water vegetation and a bird habitat. The ridge-levee idea originates from these existing ridges and has two components:

1. the ridge-levee should be constructed exclusively with soils and it should withstand the hydraulic loads from surge and waves (technical design);
2. the ridge-levee should increase ecological values, not in the least because the footprint of the levee takes up existing, valuable marshes.

Technical design

Numerical simulations have shown that low levees, with a crest level between +2 m to +8 m, do decrease the surge level at the coast to some extent. Such levees will experience wave attack on the seaward side and extensive overflow if the surge increases above the crest level. The idea is to create a levee which can withstand these hydraulic forces with only a grass cover. The leading principle is that soil covered with grass is quite erosion resistant as long as the hydraulic forces are not too large. The cross-section of the "surge breaking" levee has been drafted based on the following considerations, see also Figure 109.

Remarks on the technical design of ridge-levees:

1. Geotechnical failure mechanisms, like slip failures, should be avoided. This can be done by using very gentle slopes and soil improvements of the very soft top layers.

2. Really gentle seaward slopes will hardly experience wave attack. Designs have been made and levees have been built with a slope of 1:8 and with a clay and grass cover only. For such a gentle slope the waves break into the backflow of water and not on the slope itself. It is the same effect as breaking waves in a beach surf zone: the waves break, but forces are dissipated in the water. For this reason it is proposed to build the seaward slope as a gentle 1:10 slope.
3. When overflow occurs, high velocities on the crest will be present with an increase in velocity at the transition to the inner slope. It is this edge that probably will experience some damage. In order to have a large erosion capacity it is proposed to design a wide crest, much wider than for a conventional levee. As first guess it should be between 20-60 m (70 to 200 feet) wide. Even though erosion occurs, it will take a long time before real breaching is a fact.
4. In order to prevent slip failures also the inner slope should be gentle. It is proposed to apply a slope of 1:6.
5. The crest height should be determined on basis of hydrodynamic calculations and the optimum effect on surge level reduction. The crest level can easily vary between +4 m and +8 m, without changing the principles described above.

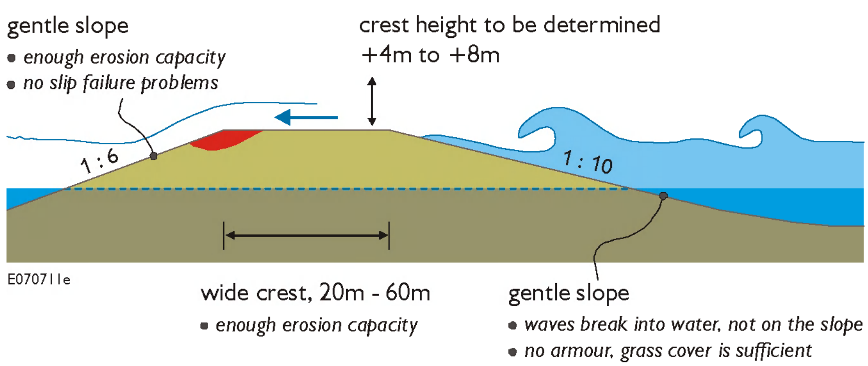

Figure 109 Basic technical principles of a ridge-levee

Ecological design – the "rich" levee-ridge

Based on technical issues a ridge-levee has a width above water of about 100 m (330 feet). This is probably too narrow the become a suitable habitat for anything else than a few bushes. Birds and mammals need a wider area to be able to hide from predators. This implies that the ridge-levee should become wider.

A second idea is that if a wider area will be created, this should also be clearly above water. In such a case fresh water vegetation can exist and may be even fresh water pools can be created to some extent.

Based on above ideas it is proposed to accompany the technically designed levee with gentle banks on each side, see Figure 110. A 1:100 slope on the seaward side, starting at +2 m gives an area of about 200 m wide. A similar, but maybe shorter and steeper slope could be made on the inner side. The whole area becomes about 300 to 500 m wide, probably enough to develop a bird habitat. Another alternative could be to create the banks as a horizontal level, say between

+1 m and +2 m. The optimum height should be determined on survey or knowledge from the existing ridges.

The banks can be built from existing soft soils. It should be explored what could be the optimum way to build these banks.

The project team notes that in this design flood protection has been improved (the surge breaker) and that negative effects of taking part of the salt marshes have been mitigated by creating a bird habitat.

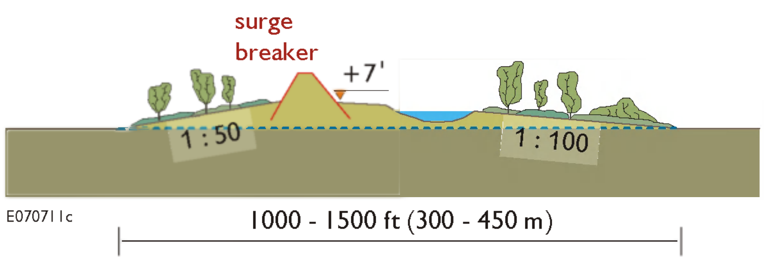

Figure 110 The "rich" levee-ridge; wide banks to create a fresh water and bird habitat (drawing at distorted scale).

Some additional remarks

Levee design
As described above, it is recommended to use gentle slopes and a wide crest, to reduce hydraulic forces during design conditions on the levee (surge breaker) as much as possible. Given such a design with mild slopes etc., the implementation phase will probably be the dominating phase for geotechnical failure mechanisms like slope stability and squeezing. Given the large dimensions of the levee, significant settlements will occur during and after the implementation phase. These can be reduced somewhat when the soft top layer is removed (cunet), and accelerated using drainage during execution (which will also help execution stability).

Settlement calculations
To have some idea about the amount of settlement two calculations were made for conditions as found by Mc Clelland, borehole 1 (marshland or shallow water, Birdfoot), because for this borehole the necessary soil parameters were available.

1. The first calculation has been made without any external load, only dissipation of measured excess spore pressure have been taken into account. Only the compression index C_c was known, that means only consolidation has been considered, no creep. Time for consolidation was unknown (no consolidation coefficients were given). Expected consolidation times are long (measured pore pressures give an indication of slow consolidation). The calculated long term settlement is 1,5 m (5 feet).
2. The second calculation has been made with load (gross) 10 m (32 feet) sand, gentle slopes 1:30 (outside) and 1:10 (inside). Settlement 4 to 5 m (13 to 16 feet). Because of settling under the water table the weight of the load will decrease. A compensating load in the

calculation has been added. Result: a settled levee 8 m (26 feet) above ground level with 5 m settled under water.

Table 16 Soil schematization for settlement calculation

depth - ground level		depth-zero level	unit weight		void ratio	compression index		OCR*σ'	
Ft	m	m	lb/ft³	kN/m³	e_0	Cc	C'	t/ft²	kN/m²
2	0,61	1,52	110	17,29	1,36	0,42	12,94	0,475	45,49
31	9,45	10,36	101	15,87	1,89	0,78	8,53	0,425	40,7
47	14,33	15,24	100	15,71	2	0,81	8,53	0,65	62,24
67	20,42	21,34	99	15,56	1,94	0,98	6,91	0,85	81,4
87	26,52	27,43	106	16,66	1,58	0,67	8,87	0,85	81,4
122	37,19	38,10	102	16,03	1,5	0,77	7,48	1,35	129,28
147	44,81	45,72	125	19,64	0,75	0,24	16,79	1,5	143,64
162	49,38	50,29	107	16,81	1,34	0,67	8,04	1,75	167,58

$$S = \Sigma \frac{h}{C'} \ln\left(\frac{\sigma'_n}{OCR * \sigma'_o}\right)$$

with :

S = *settlement*

h = *thickness of compressible layer*

C' = *compression index*

σ'_n = *new effective stress*

σ'_o = *existing effective stress*

OCR = *over consolidation ratio*

Figure 111 and Figure 112 show the results of settlement calculations made with MSettle. Horizontal and vertical scale are not equal. Load, soil layers, settlement of the different layers and the piezometric levels of the different layers have been indicated.

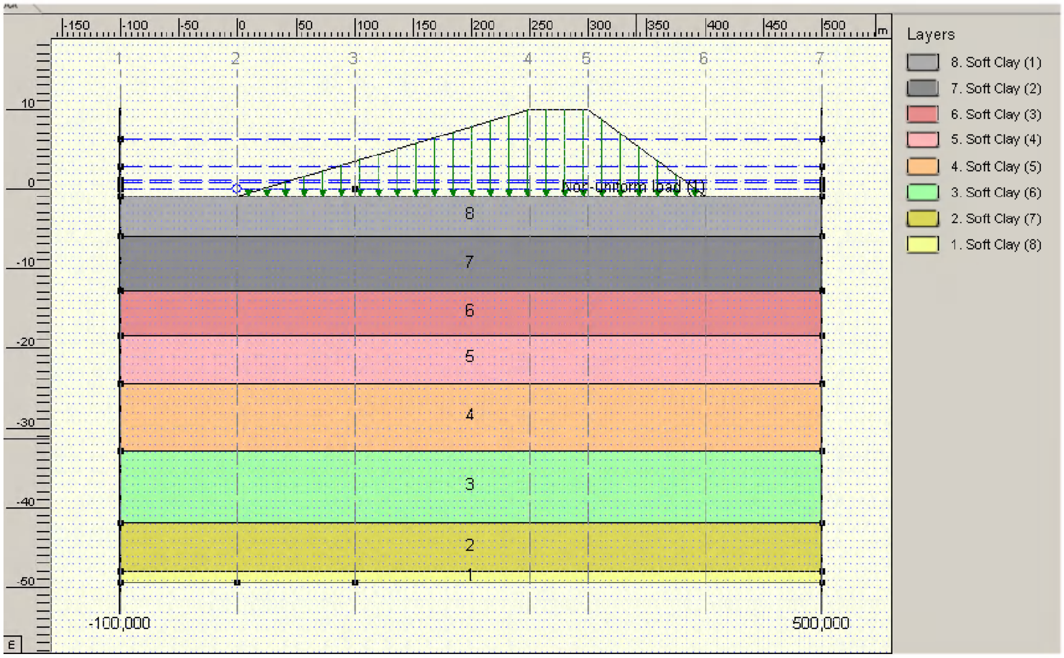

Figure 111 Settlement calculation (horizontal and vertical scale not the same): original geometry plus embankment. Valid for marshland or very shallow water.

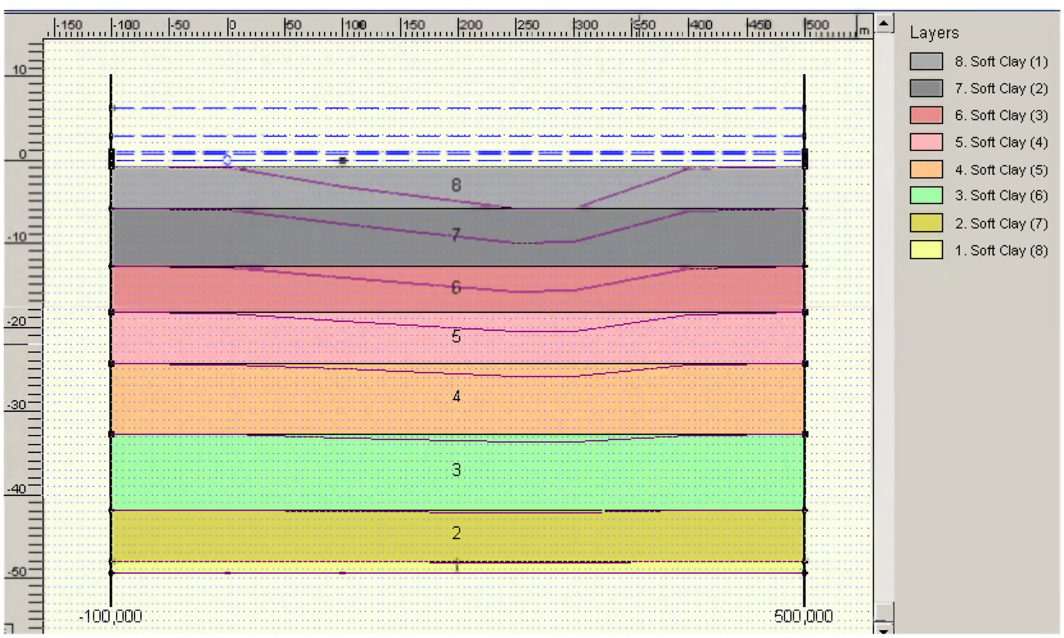

Figure 112 Settlement calculation (horizontal and vertical scale not the same): settled geometry. Valid for marshland or very shallow water.

Stability calculations

U.S. calculations for unconsolidated soil are shown in enclosure F of the LACPR report on Engineering Investigations. In order to compare these with an approach based upon consolidated soil the following stability calculations have been made.

Dutch approach (based upon Mohr Coulomb and Archimedes):

$$\tau = c' + \sigma' \operatorname{tg} \varphi'$$
$$\tau = c' + (\sigma_{total} - u) \operatorname{tg} \varphi'$$

with:

τ = shear stress
c' = drained cohesion
σ' = effective stress
σ_{total} = total stress
u = pore pressure
φ' = friction angle

Calculations have been made for reach 1 (Enclosure F)
Levee height 40 feet, inside slope 1:4 and 1:10.
Also calculated has been the influence of 70% excess pore pressure (30% consolidation).

Correlations between undrained and drained strength have been made based upon Technical Report V Appendix 2 page 35. From the undrained strength mentioned in enclosure F pag 189 the drained strength has been estimated.

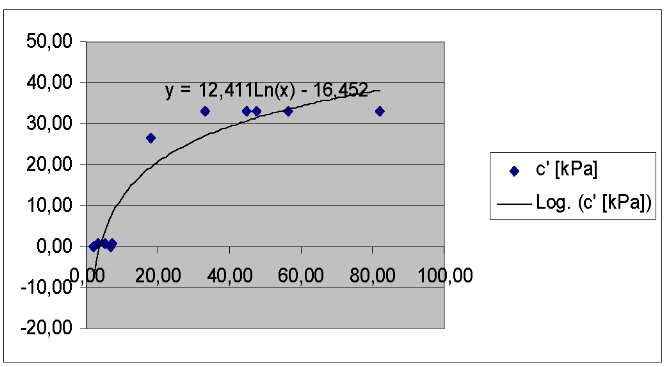

Figure 113 Correlation undrained cohesion c_u with drained cohesion c'.

For an undrained cohesion around 10 kPa a drained cohesion 10 kPa is calculated, which is not a realistic value (this value should be lower)

tangent of friction angle	**friction angle (°)**
0,25	14
0,5	27
0,75	37

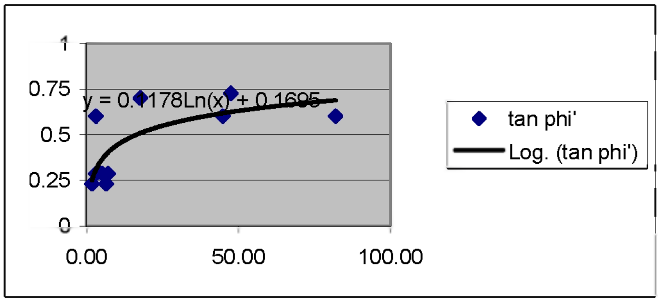

Figure 114 Correlation undrained cohesion c_u with tangent of drained friction angle φ'

Table 17 Soil schematization for stability calculation

layer number	depth - ground level ft	m	unit weight pcf	SI	undrained cohesion c_u psf	kPa	drained cohesion c' kPa	friction angle phi'
5	-15	-4,57	95	15,22	200	9,58	11,6	23,5
6	-30	-9,14	100	16,02	200	9,58	11,6	23,5
7	-45	-13,72	100	16,02	312,5	14,96	17,1	26,0
8	-60	-18,29	100	16,02	462,5	22,14	22,0	28,1
10	-75	-22,86	100	16,02	612,5	29,33	25,5	29,6
11	-90	-27,43	100	16,02	762,5	36,51	28,2	30,7
12	-105	-32,00	100	16,02	912,5	43,69	30,4	31,6
13	-130	-39,62	100	16,02	562,5	26,93	24,4	29,1

Table 17 presents the soil schematization used in a stability calculation based upon above mentioned correlation. As an alternative to these calculations, additional calculations have been made with 10 kPa reduced to 2 kPa.

For orientation some stability calculations have been made with Bishops method of circular slip planes.

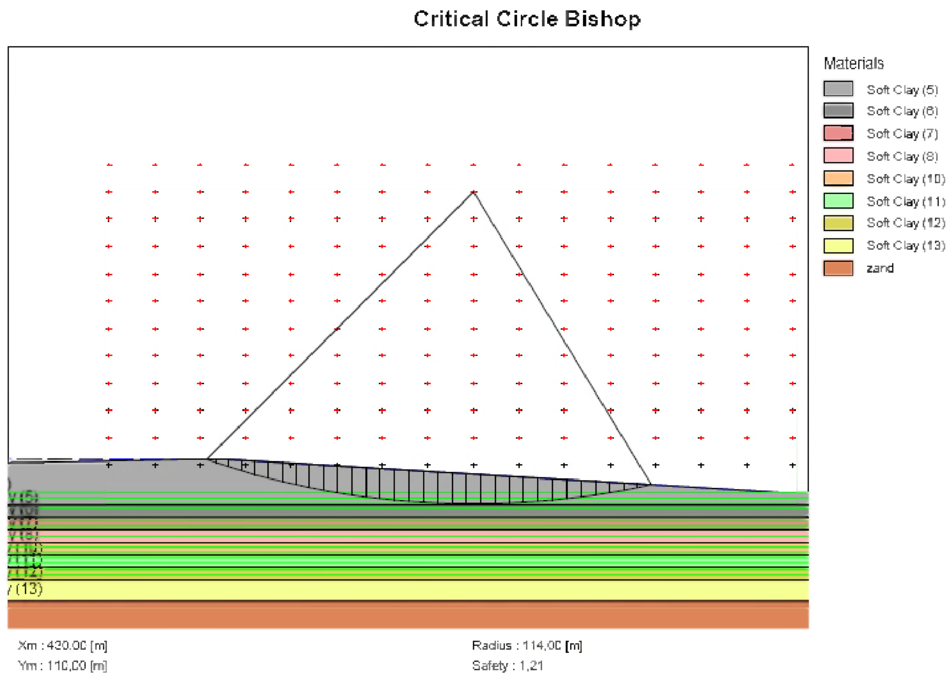

Figure 115 Levee of silty material, stability slope 1:10, layers above SL – 13,72 m limited drained cohesion, excess pore pressure 70% of load (consolidation 30%)

Without excess pore pressures the calculated safety factor is 1,82. With excess pore pressures the safety reduces to 1,21. Generally, these values for levees in the Netherlands are accepted.

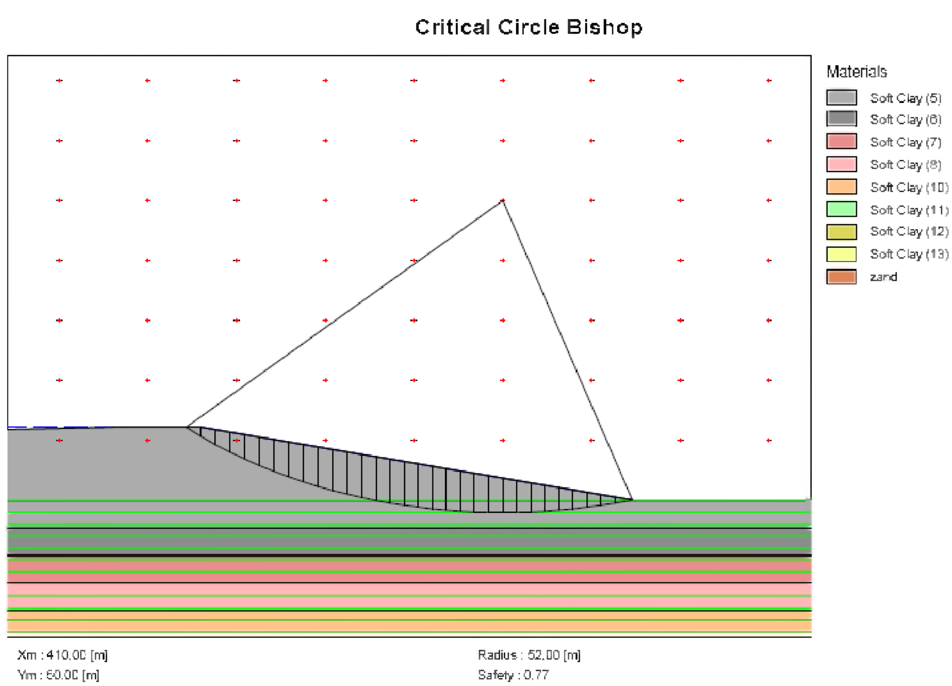

Figure 116 Levee of silty material, stability slope 1:4, layers above SL – 13,72 m limited drained cohesion, no excess pore pressure

Without excess pore pressures the calculated safety factor is 0,77. This value is below the generally in the Netherlands accepted value.

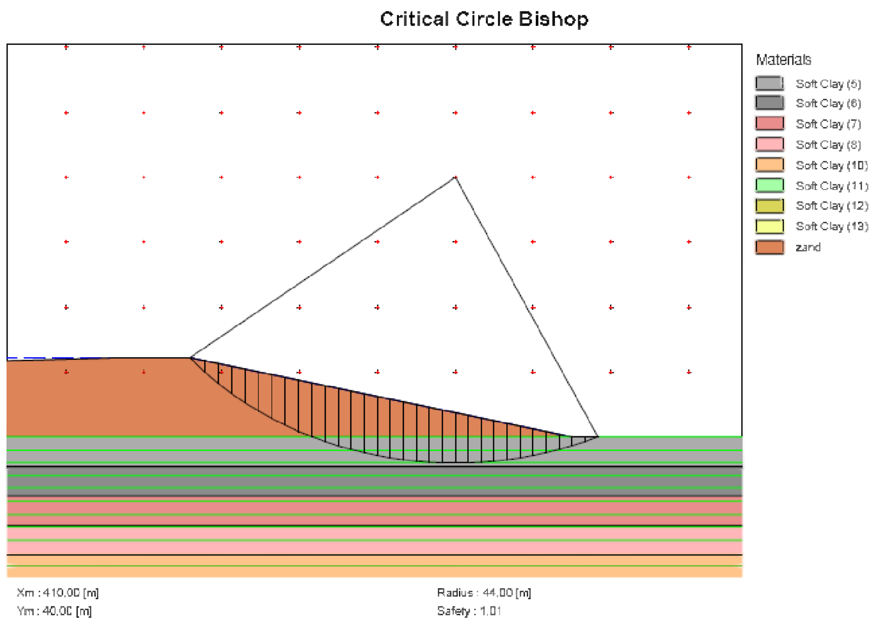

Figure 117 Levee of sand, stability slope 1:4, layers above SL – 13,72 m limited drained cohesion, no excess pore pressure

Using sand the stability factor raises to 1,01, a little too low for a permanent situation. A slope with an added horizontal part will do.

However, this calculations are only made for macro stability. Other phenomena's such as erosion or micro-stability can, and probably will, mean that extra measures have to be taken along the surface of the levee, at the waterside as well as the crest and the landside.

Figure 118 Levee near Hook of Holland, Netherlands, with steep slope landside, silty material, after heavy rainfall. Newspaper photo.

Construction

During construction consolidation is poor. The U.S. practice is based on improving the subsoil by mix in place techniques (Figure 119).

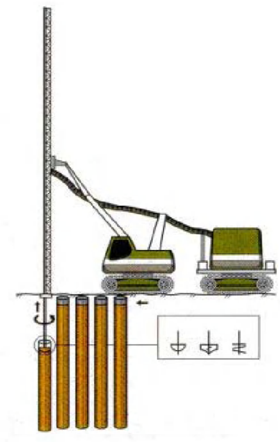

Figure 119 Schematic representation of improving the subsoil by mix in place techniques

In the Netherlands improving strength properties of weak soil by staged construction is usual. Dutch practice is based upon the decreasing of the pore pressures. This can be accelerated, for example by vertical strip drains (see Figure 120).

Figure 120 Inserting vertical strip drains to decrease pore pressure

Hydraulic fill is not excluded, but pore pressures should decrease as soon as possible. Piezometer devices are used for monitoring.

Dry fill is not at all considered as a better way of filling then hydraulic fill, as long as good drainage is made possible. Soil is heightened in layers of one ore two feet thickness and compacted by rollers or bulldozers. In very weak areas making the beginning of the construction of an embankment can be a problem. Small excavations and soil improvement with coarse sand, or in the worst case, use of geotextiles may be necessary.

Erosion

To have some idea about the erosion, calculations have been made for the following conditions:

- Surge level 10 m;
- Wave height 5 m;
- Wave period 14 sec;
- Spilling waves: if surf similarity number < 0.5, which in this case would mean a slope more gentle than 1:16.

Design details: overtopping and erosion
Surge 10 m. wave 4-5 m, period 14 sec
Heavily armored 270 < q < 800 l/m/s = massive overtopping: crest height 11 m (10*1.1)
Lightly armored 30<q<90 l/m/s = light to moderate overtopping: crest height 12 m (10*1.2)
Grass q<10 l/s/m = non overtopping: crest height 15 to 18 m (10+ run-up 2%)
Notice: correlation with heavy rainfall

Design details: seaward structure (steep) slope
Surge 10 m. wave 4-5 m, period 14 sec
Slope 1:4
Armor weight 3 to 6 tons
Thickness 2 D50= 1 to 2,5 m
Under layer 10%= 0.3 – 0.6 tons

Erosion strength
Some study is recommended to assess the relation between execution method (hydraulic fill, compaction) and the erosion strength of the base materials, e.g. the silty materials. It is known from experience that the erosion strength of good but traditionally applied unprotected clay layer is limited. It is, however, also known that better compaction has a significant effect on the material strength. Recently, a study was carried out on the erosion strength of "boulder clay", a frequently used base material for Dutch levees, with some promising results. Moreover, the tests with the wave overtopping simulator showed that grass cover increases the erosion strength enormously when compared to bare clay.

However, rather than relying completely upon studies, a full scale test in situ should be done.

Conclusions and recommendations

1. The improvement of soil properties by mixed-in-place techniques is unusual in the Netherlands. Instead, accelerating the decrease of pore water pressures in the subsoil and

the increase of effective stresses is common use. Settlements of approximately 60% of the elevation are expected.

2. Toplayer: to be able to construct a levee in shallow water or marshland it may be necessary to excavate the toplayer (2 or 3 feet), to replace it by sand, as coarse as possible, and to fill with the same material until above the water level. Use of fascine mattresses or geotextiles is restricted to special cases.
3. The construction of levees by means of hydraulic fill is not considered as an inferior method. Dry filling by trucks "over the head of the fill" is not recommended. Staged construction in combination with monitoring of pore pressures is usual practice.
4. Most of the material that is relatively easily available for levee construction is silty. This material is fine and compressible, has little permeability and has little cohesion, and it is described as poor building material. However, it is not completely unapt for building. Because of the little cohesion the maximum of friction should be mobilized, and this means dewatering. The more sandy the material is, the better it can be used in a levee core, but it has to dry as soon and as much as possible. In case of hydraulic filling it should be spread in thin layers, employing the advantages of the warm climate, and compacted by bulldozers. Dewatering can also be improved by adding horizontal sand layers, as a sandwich construction. However, in this silty material only gentle slopes can be made, which means that a lot of this inferior material and much space will be needed. In case of hydraulic filling much dredging capacity will be necessary. The construction phase will be critical due to the need to reduce the pore pressures. When in use, in case of high water outside, stability will not be the main problem, due to the impermeability of the material, the gentle slopes and the short stage load. Erosion is the more important mechanism then.
5. Regarding the construction of levees, the use of structures in or upon the soil construction is not recommended. Irregular settlements under the levee and horizontal movements of structures may create space for penetrating water that may undermine the structure. Furthermore, overtopping water will fall down over the top of the structure and may cause extra erosion.
6. Protection and covering: in case of very gentle slopes spilling waves instead of breaking waves are to be expected. In the Netherlands, a covering layer of good clay in combination with a good grass cover appears to be sufficient. Depending of the duration of loading by surge and/or waves, loss of material can be accepted as long as the levee does not fail completely.
7. If selected material can be used, steeper slopes may be possible. To derive good designs, collecting additional geotechnical data (drained cohesion and drained friction angle) and data about soil availability and costs is recommended.
8. Most important of all: after construction, a system for regular inspection and repair of failures should be developed.

G Structures

This appendix focuses on the design and construction of structures that were considered in the framework of the project. In that context, the design and construction philosophy are addressed, as well as the physical conditions, boundary conditions, the purpose of works, the solution principles, the design, and construction.

It is noted that this study is at reconnaissance level only. Against that background, preliminary designs were made to ensure that the proposed structure that can be constructed and allow for costs estimates for levees and constructions, suitable as elements for estimations for the overall costs for the different strategies.

It is also noted that the design team visited the New Orleans area during the course of the project, which offered the opportunity to familiarize itself with the characteristics of the sites where possibly measures will be implemented.

Design and construction philosophy

Based on lessons learned in the Dutch Delta, the project team is convinced that the integration of technical and ecological aspects is a prerequisite to reach a sustainable solution. Technically sound levees and structures like storm surge barriers have been constructed in the Dutch Delta in the period from 1953 to 1987. The restrictions of water flow and interruption of the natural flows of sediment and nutrients resulted in severe negative impact on the ecosystems and substantial environmental damages that cannot be reversed. Substantial investments are needed now for the most essential counter measures, aiming at a new ecological sustainable balance.

The project team applied the following guidelines in designing – at reconnaissance level – the various structures that are needed for providing flood protection and stabilizing the landscape:

- For economic reasons, levees and other works can only be made to a to be determined affordable protection level. Appendix E of this report describes the results of a tentative analysis op the optimal protection level, leading to the conclusion that for the metropolitan area of New Orleans a protection level of 1/1,000 or better is justified from an overall economic point of view.
- Proven technology should be applied as much as possible in order to assure reliability of both the designs and initial cost estimates.
- Innovative solutions should be developed step-by-step, and where needed pilot projects should be developed to learn by doing.
- When designing measures related to functioning of the ecosystem, the long-term ecological balance should be kept in mind, and delta and wetland formation processes should be recognized in the planning stage.

Physical conditions

The physical conditions of the Mississippi Delta do not differ essentially from the conditions in the Dutch Delta. The soft soils encountered in The Netherlands are more or less comparable to the Mississippi Delta. Of course differences exist, including the following:

- The Mississippi Delta top layer of the subsoil (Holocene) generally has a higher bearing capacity and smaller grain than generally found in The Netherlands.
- The climate is quite different in the Mississippi Delta: warmer and more rainfall.
- The vertical tide is smaller in coastal Louisiana when compared to the Netherlands.
- Storm surges caused by hurricanes are somewhat higher than the Dutch hydraulic design parameters, but have a shorter duration.

It is concluded that for levees and structures like sluice gates and storm surge barriers the normal Dutch practices in design and construction are sufficient for application in coastal Louisiana; development of new and hence unfamiliar methods and techniques are not required.

The ecosystem in the Mississippi Delta differs substantially from that in the Netherlands. Obviously, differences in climate play an important role in explaining these differences. However, the natural values of both deltas in ecological values and the importance of these values for human activities (fisheries, recreation, etc.) are comparably rich in actual and potential value. The coastal Louisiana landscape is worth restoring and protecting, not only from a flood management point of view.

Hydraulic design parameters

The most important hydraulic design parameters for structures, namely surge levels and waves, were estimated from measured data and inter- and extrapolation using results from IPET, LACPR and modeling carried out in the framework of the current project. See Appendix I for more details. To allow for input for the economic optimization of flood protection levels, the range of water levels and subsequently levee elevations and cost estimates covered probabilities of occurrence between 1/100 and 1/1,000,000 per year.

Types of measures for which preliminary designs were made

Based on Dutch and coastal Louisiana practice, the solution principle for the design and construction of *flood risk reduction structures* is geared towards creating levee rings that encircle areas that require flood protection. If openings are needed in such ring, a storm surge barrier will be incorporated in the levee ring. Because the analysis is geared towards providing a certain level of flood protection for a flood-prone area, not only the threat of hurricane surges is taken into account, but also the threat of Mississippi River flooding. Hence, also the levees along the Mississippi River are included in the analysis. The types of measures analyzed in this context are:

- The construction of new levees
- Upgrading of existing levees

- Constructing storm surge barriers in navigation canals
- Construction in storm surge barriers in waterways that are currently in open connection with the Gulf

The main technical design principle for *landscape stabilization* is to restore and (re-)create the physical situation (the abiotic conditions) to kick-start the desired natural ecosystem development. The construction principles include changing soil elevation, providing the supply of fresh water and nutrients, changing water management. Two types of ecosystems require special consideration: (1) salt water marshes and (2) fresh water (cypress) swamps. In the salt water marshes along the coastline the predominant vegetation is Spartina grass, for which a soil elevation MSL + 0.2 to + 0.4 m is ideal. Obviously, the diversion of excessive amounts of fresh water will be detrimental for salt water swamps. More inland, in fresh water swamps, cypress trees flourish at land elevations above MSL + 1.0 to + 2.0 m. The supply of sufficient fresh water, also to prevent salt water intrusion, is conditional. The types of measures analyzed in this context are:

- The development of ridge-levees
- Salt water marsh restoration
- Fresh water cypress swamp creation by hydraulic fill
- Fresh water cypress swamp creation by artificial polders
- The development of structures to divert fresh water, nutrients and sediments from rivers to wetlands.

Additional design considerations

Design aspects like reliability, constructability and redundancy have been placed at the highest possible level, and the cost estimates reflect the attention for these aspects.

Redundancy in the design aims to reduce the possibility of a catastrophic breach in a levee in case of wave overtopping or surge overflow. This design consideration will result in very strong and redundant structures.

New levees

The main design principle selected is an earth fill levee body with a flexible asphalt protection cover on top. This design allows for flexibility in settlement and can safely deal with considerable wave overtopping without the risk of a levee breach. For planning purposes, all levees considered in this project are designed on the basis of the following features and are able to cope with significant overtopping and some overflowing.

The hydraulic fill is extracted from the source area, preferably nearby, and pumped directly to the construction site for the levee. In order to rapidly come up with a cost estimate, it is assumed that the material is dredged from the bed of the Mississippi River. At a later design stage, possibly more local sources can be identified, which will lead to a cost reduction. The construction material expected to be found in the Mississippi riverbed is expected to be sufficiently sandy to be used in the traditional Dutch hydraulic levee construction method.

Depending on the site conditions, the existing top layer of the subsoil could be very soft. In that case, the of 1 to 3 m of the top layer may be required. Because the deeper subsoil may be soft and containing much water, vertical strip drain systems have been used at all new levee locations. Also this element may be optimized in a later design stage. The thickness of the individual layers of hydraulic fill in a levee is estimated to be between 2 and 3 m.

The main dimensions of the levee have been derived from the surge level and the wave conditions. Slopes of 1:6 have been chosen at the surge side. Such slope is cost-effective for wave energy dissipation. The inner slope is chosen at 1:4, which is a safe value considering overflow and soil mechanical stability.

The flexible asphalt protection cover on the levee allows for lower levee heights when compared to levees with a grass cover, because flexible asphalt can safely deal with more overtopping than a grass cover can. Hence, in cases where there is sufficient space available to temporarily store the water brought over the levee by wave overtopping, the crest of the levee is selected at 1.5 m (6 feet) higher than the hurricane surge level. Where such space behind the levee is not available (for example at the Lakefront area of Lake Pontchartrain, where houses are built directly behind the levee), 2.5 m (8 feet) is added to the surge level to determine the crest level; this with the objective to reduce wave overtopping. Where wave overtopping would be no problem at all (for example in case of a levee on the land-bridge between Lake Pontchartrain and Lake Borgne), only 0.5 m (2 feet) is added to the surge level to determine the crest level of a levee on that location. It is noted that in these examples the surge level is determined by the flood protection level, which in this analysis is considered in the range of 1/50 to 1/100,000 per year.

The protective asphalt layer consists of a foundation layer of 0.2 m flexible sand-asphalt and a top layer of 0.2 m flexible asphalt concrete. It covers the entire soil body of the levee. At the surge side, from one third of the elevation of the levee downwards, a different asphalt structure, namely stones penetrated with asphalt, gradually increases in thickness from 0.4 to 1.2 m. At the landside, the protective layer ends in a filter construction forming an energy dissipation area with the objective to still overtopping water, preventing erosion at the inner toe of the levee. At the top of the levee, air vents have been included, this with the objective to release trapped air during a storm surge.

In the calculation for the quantities of material required for hydraulic fill, the potentially considerable settlement of the subsoil is accounted for.

The above described design for a sea defense proves to be cost-effective in the Netherlands. Figure 121 shows a schematic cross-section of this design.

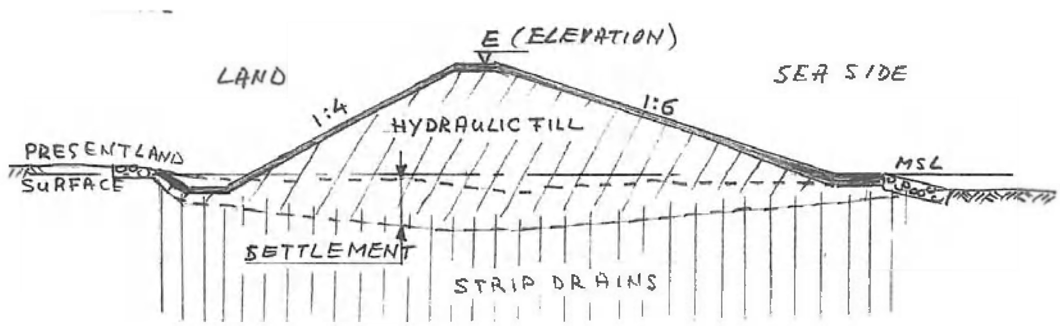

Figure 121 Schematic cross-section for a new levee (not to scale).

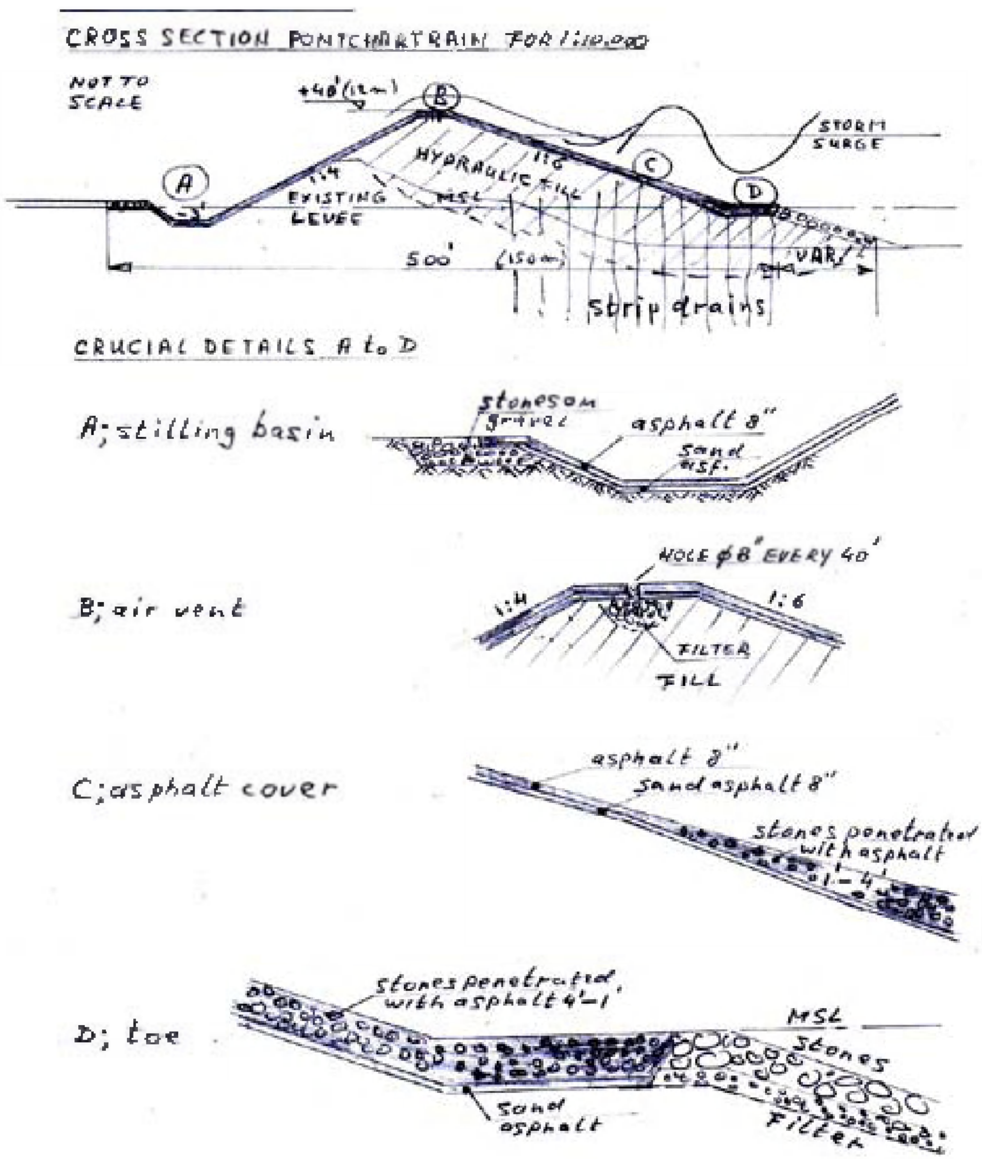

Figure 122 Schematic design for upgrading an existing levee, with several construction details

Upgrading existing levees

The proposed levee construction principles for upgrading existing are identical to the principles applied for the design of new levees.

When upgrading an existing levee, the subsoil will generally be better when compared to a new levee, because the existing levee has already settled over its lifetime. In addition, access to the construction site for upgrading a levee will generally be easier when compared to a new levee. Because existing levees are part of an existing infrastructure, including road networks, water management structures like pumps and sluices, and generally close to housing areas and industrial sites, upgrading existing levees can also be more complicated when compared to building a new levee. Figure 122 provides an overview of upgrading a levee, including construction details.

Storm surge barriers in navigation canals

When a levee ring crosses a waterway that is of importance for navigation, a storm surge barrier design was applied that imposes no limit on the height of ships limitless height ships. Depending on the type of navigation to accommodate, two types of barriers have been chosen: one for barge transport with an opening of 40 m (130 feet) wide and one for fishing boats and recreational vessels of 15 m (50 feet) wide. The sill depth for both types has been chosen at MSL –7 m (–20 feet).

Construction of this barrier is traditionally in a construction pit, assumed to be a cofferdam, which is pumped dry after the foundation piles, the sheet piles and the underwater construction floor have been made in water inside the cofferdam. During construction a diversion channel must be available for the safe passing of ships. The dredging of this diversion channel has been included in the design.

Special attention must be given to the double sheet pile walls under the construction to prevent seepage and piping and the double sheet pile walls connecting the structure to the soil body of the levee with its cover of asphalt layers.

The cost calculation includes all costs: construction costs, temporary diversions, up to and including installation for emergency power and remote control.

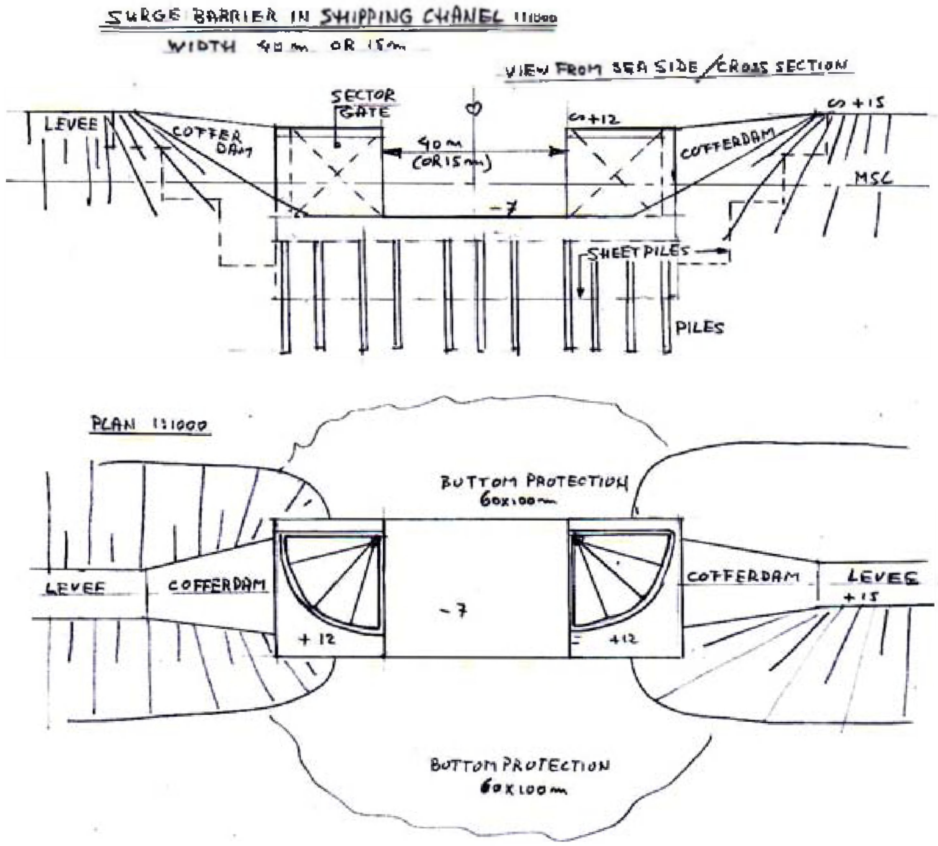

Figure 123 Preliminary design of a storm surge barrier in a navigation canal

Storm surge barriers in waterways in open connection with the sea

When a levee ring crosses a waterway that acts as an opening for the natural (daily) exchange of water (salt or fresh), a storm surge barrier to accommodate these flows has been incorporated in the flood protection system. The design and construction principles are the same as for the surge barrier in navigation canals. To disturb the natural flow as little as possible during construction, diversions have been included as well as a staggered construction of the various sluices of the barrier over time. See Figure 124.

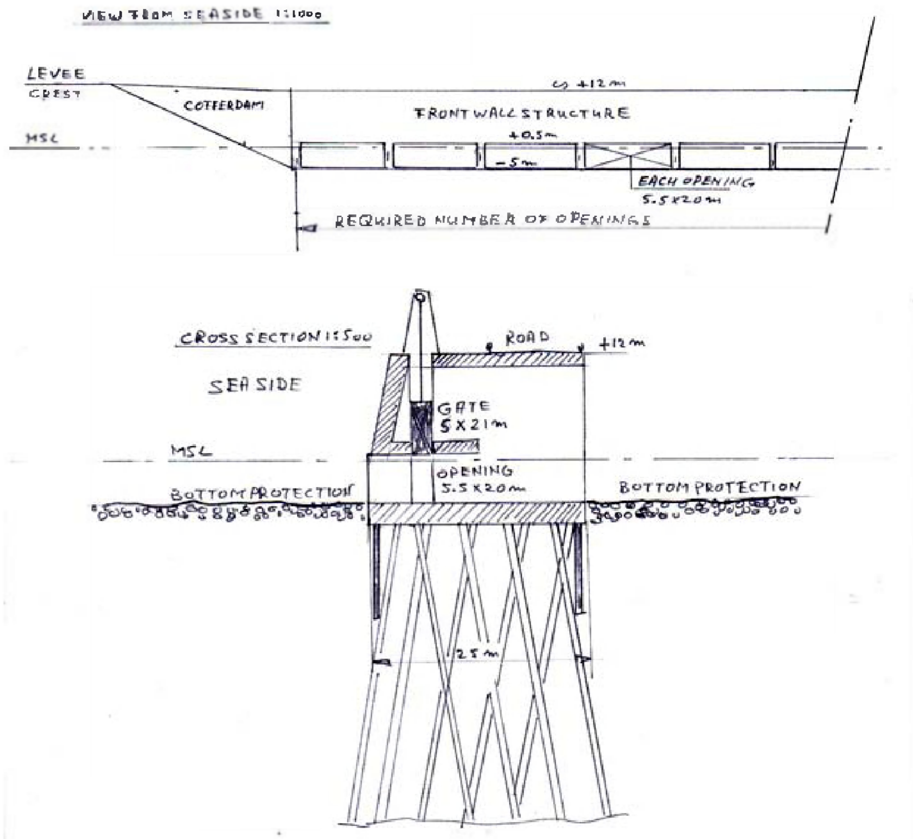

Figure 124 Schematic cross-section of an in- and outlet structure

Ridge-levees

The design principle for a ridge-levee is quite different from a traditional levee. A ridge-levee aims to reduce a hurricane surge, as opposed to stop it as is the objective of a traditional levee. Furthermore, a ridge-levee serves an ecological objective in landscape restoration, unlike a traditional levee. The construction principles for ridge-levees, however, are the same as for traditional levees, i.e. also based on providing a hydraulic fill.

Because of the gentle slopes applied, the footprint of a ridge-levee is considerable. Also, the crest level is relatively low: only between 2 to 4 m above MSL. Natural growth of trees and shrubs on the slopes and crest of the ridge-levee is stimulated.

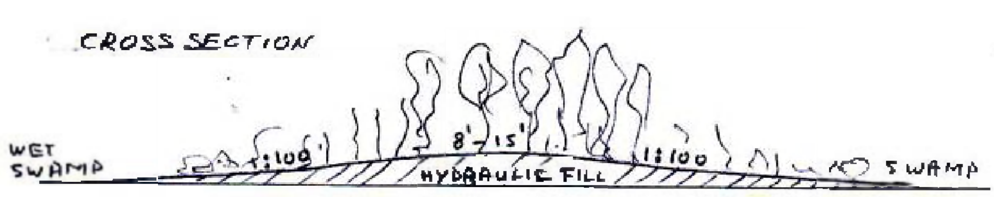

Figure 125 Schematic cross-section ridge-levee (distorted scale)

Salt water marsh restoration

Stabilization of salt water marshes in coastal Louisiana refers to a huge surface area, and is important not only to from an ecological point of view, but also from a flood management perspective. Focus on measures should be on counteracting the continuing erosion process. This erosion process is the result of a number of processes, including sea level rise, subsidence, lack of sediment inputs, and – also as a result of the many man-made canals – increased exposure to wave attack because and changes in water levels.

Wetlands already turned into open water and the many man-made canals lead to an increase in wind waves to develop, causing erosion of the vegetated areas, which in turn creates more open water and hence even more surface area for wind waves to gain energy.

To stop this erosion process, the plan is to plug and locally fill the small canals, thereby reducing the fetch (open length of water). This plan has not been worked out at reconnaissance level, with sufficient detail to allow for a cost estimate. The implementation will ask for (a series of) small cranes and barges to bring sediment in the area. Depending on the location this can be plugging canals, separating open water in compartments, filling other areas with sediment, etc., as illustrated by Figure 126. As a source of sediment, a large hopper or cutter dredge takes sediment form the river bottom of the Mississippi River or another location, for example the Birdfoot area, and provides soil deposits for the small-scale equipment working in the salt-water marshes.

In general terms approximately 3/8 of an inch (1 cm) of new sediment is brought artificially into the salt water marshes every year. The accumulation of plant detritus is expected to add between 3/8 and 3/4 of an inch per year (1 to 1.5 cm/yr) in a natural way. This effort will be maintained over 50 years to come in order to come to a new natural equilibrium that will sustain itself.

The costs estimated for this work is estimated at about $ 250,000 (to be exact $241,920; but this number suggests an accuracy that is not justified) per square mile per year (€70,000 per km^2/yr). This cost estimate has been derived as follows:

- bringing on average 1 cm of sediment per year to 1 km^2 involves 10,000 m^3/km^2/yr;
- the associated cost is roughly estimated at €70,000 per km^2 per year; and
- the Net Present Value over a period of 50 years roughly amounts to €1.4 million per km^2, or $4.84 million per square mile of wetland.

In the current project this measure is considered for a surface area of 1,800 km^2 (694 square miles) in the Pontchartrain Basin, and 1,500 km^2 (579 square miles) in the Barataria Basin. The annual sediment supply (based on the rule of 1 cm/yr) for these areas amounts to 18 million m^3/yr (23.5 million cubic yards per year) for the Pontchartrain Basin and 15 million m^3/yr (19.6 million cubic yards per year) for the Barataria basin. The source for this material can be dredging from the Mississippi River, the Birdfoot area or other locations. Further analysis is suggested to find suitable sources of material.

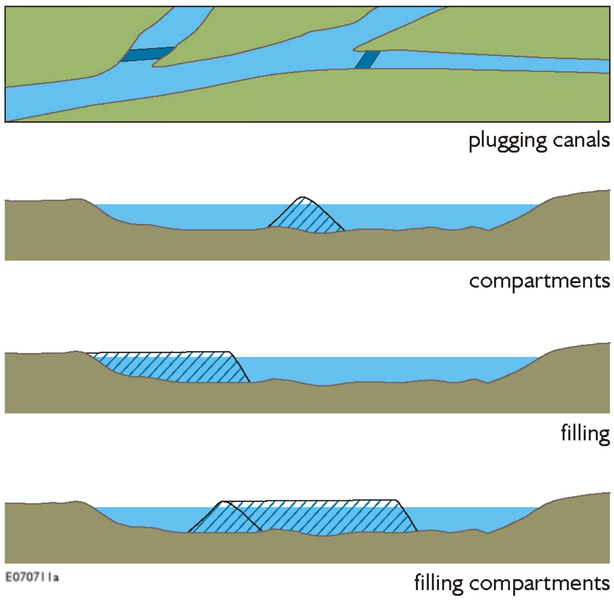

Figure 126 Various measures that can be undertaken in the context of marsh stabilization

Fresh water cypress swamp creation

Fresh water cypress swamp development can be kick-started by increasing the elevation of existing areas by hydraulic fill and by ensuring a fresh water system by the supply of sufficient fresh water (see Figure 127). Because increasing the elevation of land is relatively expensive, the choice was made to realize this in strip of land of limited width, immediately outside the levee rings of New Orleans. The width of this strip varies between 1/3 and 1.25 mile (0.5 to 2 km), and hydraulic fill will bring up the elevation to about MSL + 3 to +6 feet (MSL +1 to + 2 m). Sufficiently mature cypress forest located close to the levee system is expected to play an important role in reducing the wave loading on these levees.

Fresh water supply to the newly swamps is directly from the Mississippi River. Stimulating the sediment inflow to help in maintaining or increasing the width and/or elevation on the long term should be considered.

Artificial polders for cypress swamp development

Instead of increasing the land elevation artificially, the water table can be lowered by creating polder and pumping out the water (see Figure 127). By means of an active fresh water supply, cypress swamp development can be stimulated. The natural accumulation of detritus and sediment inflow leads to a land elevation increase, of importance to re-create sustainable cypress swamp areas.

This polder development is in a strip that is between 1 and 6 miles wide, and is located immediately outside the levee system of New Orleans. The levee around this polder can remain low; a height of about 7 feet (2 m). Fresh water supply to this strip will ensure the development of fresh water vegetation. Given the climate conditions, shrubs, bushes and trees will develop rapidly. Where this strip fresh water vegetation is sufficiently wide, this strip can play an important role in reducing the hurricane surge level next to the levees.

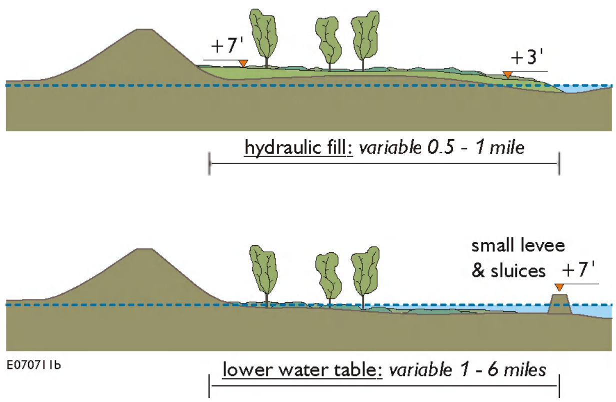

Figure 127 Two methods for fresh water cypress swamp creation: applying hydraulic fill (top figure) or with polder principle (bottom figure).

For the development of possible strategies, it is assumed that further research will point out which of the above described measures on fresh water cypress swamp creation and artificial polders for cypress swamp development is best suitable for implementation. In the various possible strategies, the Net Present Value of the cost of fresh water cypress swamp creation is roughly estimated at $10 million ($10.368.000) per square mile (€3 million per square kilometer)

Sediment diversion form the river and river water inlet structure

Various options can be identified for diverting water and sediment from the Mississippi River to the wetland area, ranging from pipe structures, diversion sluices to crevasses in the river embankment. Several diversion sluices are in place already, including the Carnarvon sluice just downstream of New Orleans. This structure serves as a reference for the types of structures that will be required for future increases in the amount of water diverted to the wetlands.

The analysis on hydraulics and morphology carried out in the framework of this project (see Appendix D) led to the conclusion that given the relatively low sediment concentration in the Mississippi River, very large diversion flows would be required to convey substantial amounts of sediment to the wetlands. This is also the lesson after about ten years of experience with the Carnarvon diversion sluice: this diversion works well in controlling the salinity distribution in the wetland area served by this sluice, but has not brought in large amounts of sediments. If large or many diversion structures were to be considered with the objective to bring in large amounts of sediments, this idea would have to be rejected because of the dramatic effect on the salt water marshes. Hence, additional *large* diversion structures should not be developed.

To maximize the amount of sediment diverted from the river, an option would be to locate the intake of the diversion sluice as low as possible, as illustrated by Figure 128. Sediment concentrations are generally higher near the bottom when compared to water from the river surface, so a low intake diverts water with a higher sediment concentration. To realize that, the sill level of the diversion structure is located 3 feet or more below the natural riverbed. As part of the intake, sheet pile walls extend into the river and guide the water and bottom sediment into the structure. In the structure, the water enters a narrowing channel, thus increasing the water velocities to lift the sediment load to the bordering discharge canal into the wetlands. A network of dedicated canals will be needed, keeping up the necessary water velocities to transport the sediment into the designated areas. Because of the large distances the sediment has to be conveyed, additional mechanical transport, like hydraulic fill may be necessary.

However, because the sediment concentrations in the Mississippi River are fairly evenly distributed in the vertical cross-section of the river, the additional costs of such structure when compared to a diversion structure of which the intake is not located very deep do not outweigh the benefit of the extra amounts of sediments that can be diverted from the river.

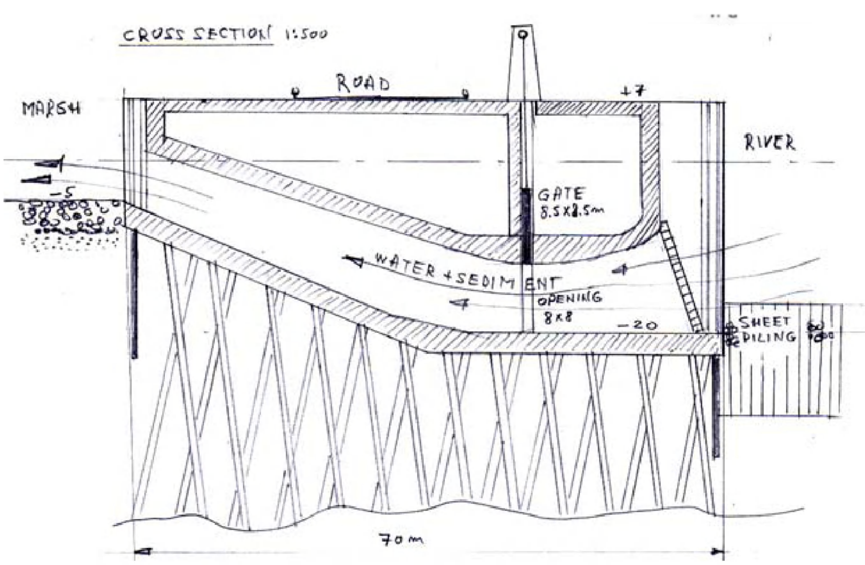

Figure 128 Preliminary design of a structure to divert water and sediment from the river.

H Identification and screening of measures

H.1 Introduction

This appendix describes two steps in the policy analysis approach of this project, namely the identification of possible measures, and the screening of measures.

The identification of measures results in a long-list of measures that potentially can be of help in reaching the objectives of the project: i.e. flood risk reduction, landscape stabilization and if possible enhancing the local and regional economy. The ideas for these measures originate either from other studies on this topic, or from the project team.

The screening of measures is aimed at making a distinction between so called promising measures and measures that should be considered as not-promising with regards to the project objectives and goals. In essence, a "negative" approach is followed in this step, and the question is addressed whether or not there is a reason why a particular measure should be excluded from further consideration in the next steps of the analysis. If there is a compelling reason why a measures should be considered as not-promising, more detailed work on the evaluation of that measures is not considered useful.

The result of the screening process is a list of promising measures, that is used as the starting point for the composition of strategies: alternative sets of measures that in combination reach or attempt to reach the project objectives and goals. It is noted that not all promising measures are necessarily included in one or more of the strategies: that depends on the orientation of the strategies, and ideas about the relative impact of individual measures. For example, if two possible new levee alignments protect the same built-up area, while the only difference in impact of these measures is that one is considerably more expensive than the other, than the more expensive option most likely will not be included in a strategy.

This appendix first focuses on non-structural measures to reduce flood risks. The following sections provide an overview of the structural measures for the metropolitan area of New Orleans and in the Pontchartrain and Barataria basins. These measures, summarized in Chapter 4 of this report, are divided in five categories of measures, which differ in time scale, effect and intention. Flood risk reduction is the main point of entry for this grouping:

1. Direct protection of incorporated values;
2. Closed basin hurricane surge protection;
3. Measures to consolidate and increase present natural surge reduction;
4. Basin surge reduction measures; and
5. Interventions for long-term natural surge reduction.

Measures in groups 1) and 2) are engineered structures that, by definition, provide risk reduction to a pre-determined level, while the other (landscape stabilization type) measures are designed to reduce hurricane surges and are evaluated in terms of their contribution to risk reduction, both in a short-term and long-term perspective. Landscape stabilization in this grouping is considered to be a part of a multiple lines of defense strategy.

H.2 Non-structural measures

In flood risk management, generally two types of risk reduction measures are considered: structural measures; and non-structural measures. Non-structural measures generally comprise the following measures:

a) flood proofing of buildings in order to reduce damages in case of flooding;
b) the provision of flood early warning systems;
c) development of evacuation plans;
d) zoning and land-use measures, aimed at reducing potential flood damage; and
e) the provision of flood insurance schemes.

Sometimes also organizational aspects of flood risk management are ranked under the heading of non-structural measures. This generally refers to the institutions involved in flood risk management and their responsibilities, funding, etc., as well as laws and regulations dealing with (aspects of) flood risk management. This report does not focus on possible organizational measures for flood risk management in Louisiana or the United States in general. Appendix K of this report provides a series of examples that could be used for inspiration when further considering this important type of measures. Important, because these measures can provide the legal basis for more concrete measures, and important because the institutional aspects are of course of crucial importance to guarantee ‘measures on the ground’.

Where in this report non-structural measures are brought forward, it is the above type of organizational measures that is aimed at. The types of non-structural measures listed in the above points a) thru e) will only receive limited attention in this study for the following reasons:

a) Flood proofing of buildings is generally only economically feasible in rural areas and in case the potential flooding depth does not exceed one floor level. In coastal Louisiana, this measure is already widely implemented, for example on Grand Isle.
b) Weather forecasting and flood early warning systems are already in place and function well, as proven during Hurricane Katrina.
c) Also evacuation plans are already largely in place, as proven during Hurricane Katrina. Elements of evacuation planning will most likely be improved in the near future, including for example the organization of mandatory evacuations, during which transportation has to be arranged for in particular the sick, the elderly and people lacking means of transportation.
d) Zoning and land-use measures can be quite effective in minimizing flood damages. In the Netherlands and other European countries, land-use is strictly regulated, and the development of new houses or industries in floodprone areas outside a levee system is prohibited or strictly regulated. In the U.S.-setting, where governmental interference with land ownership is much less accepted when compared to Europe, strict zoning regulations will most likely not be adopted. The project team considers such measures as not practical for coastal Louisiana.
e) Flood damage insurance schemes are in place in the US.

H.3 Measures for direct protection of incorporated values

This group of measures aims to protect concentrated values in the delta with a surrounding flood protection system. This section directly links to Chapter 4.1 of the main report, and Figure 129 illustrates the location of the measures in this group.

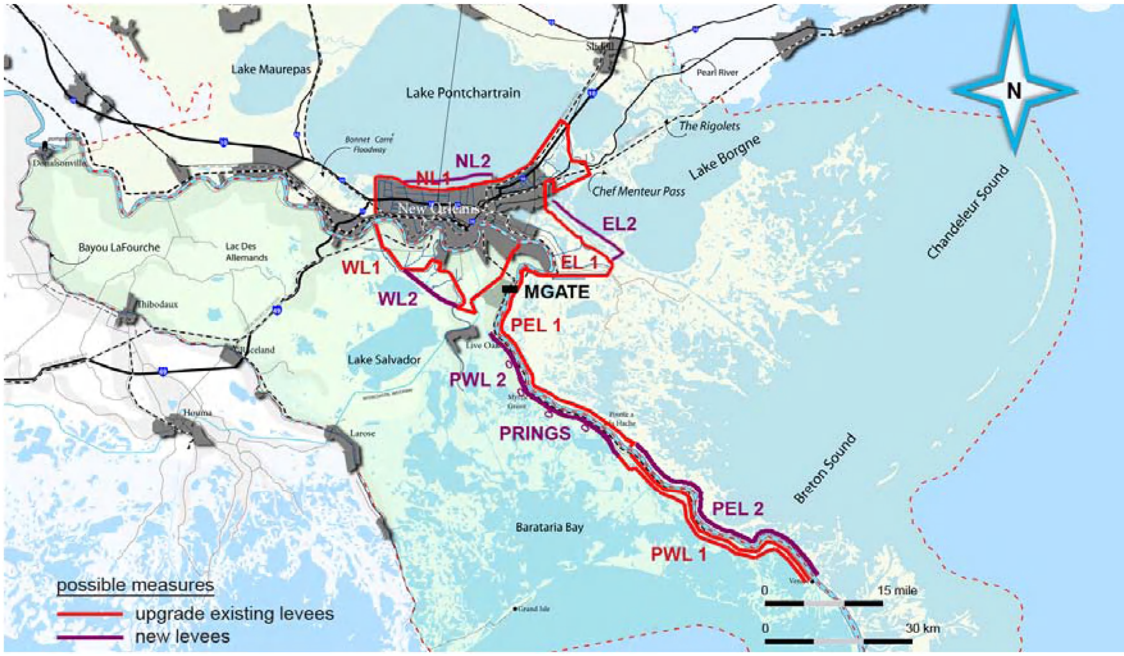

Figure 129 Alternative alignments for levee systems protecting New Orleans and Plaquemines Parish (codes are explained in the text of this appendix).

Levees on the North side of New Orleans, along Lake Pontchartrain

For this location two promising alternatives were identified:

- measure **NL-1**, which aims at upgrading the existing levees; and
- measure **NL-2**, a new levee in front of the full length of the existing levee, a few hundred meters in the Lake.

For both alternatives NL-1 and NL-2, the existing or to be renewed pumping stations and a new storm surge barrier with two sector doors and an opening of 40 m to the Industrial Canal must be considered and integrated in the design. Flood protection for the city, drainage water management and navigation are important aspects to consider. It is noted that levee improvement or the development of a new levee (NL-2) could trigger the development of a boulevard for the City of New Orleans.

Levee NL1: Improvement of the existing levees. Levee NL-1 follows the alignment of the existing levee. The existing levee profile is not high enough for extreme hurricane events. Levee improvement along the entire length on the landside of the existing levee is technically speaking most attractive. Given intensive land use on the land side, however, this study assumes that improvements will made on the lakeside. At the location of the Industrial Canal, a storm surge gate will be incorporated in the levee. The existing and to be renewed pumping stations are incorporated in the levee as well.

Levee NL-2: New levee in front of full length of existing levee. This new levee, with gates to allow the outflow of pumped drainage water during normal conditions, would offer several advantages when compared to upgrading the existing levee:

1. upgrading the space-confined existing waterfront can be avoided,
2. in case during high water levels at Lake Pontchartrain the gates would have to be closed, the temporary storage of pumped drainage water would be possible in the buffering space between the existing levee and the new levee;
3. severe wave attack on more vulnerable structures outside the existing levee would be avoided;
4. a new boulevard can easily be incorporated in the new levee.

Levees on the East side of the City of New Orleans

For this location two promising alternatives were identified:

- Levee **EL-1**, which aims at upgrading the existing levees; and
- Levee **EL-2**, a new levee in front of the existing levee, that would allow for flood protected space between the existing and new levee, that could be used for a variety of functions, assuming there is a need for such space.

Levees on the West side of the City of New Orleans

For this location two promising alternatives were identified:

- Levee **WL-1**: Improvement of existing levees Southwest of New Orleans.
- Levee **WL-2**: a new levee West of New Orleans, in front of the existing levee, partly with the objective to shorten the overall length of the levee system. This would provide some additional space for future urban expansion.

Levees in Plaquemines Parish

Levees **PEL1**, **PEL2**, **PWL1** and **PWL2**: On the East side of the Mississippi River the existing levee PEL-1 will be upgraded and a new levee PEL-2 will be constructed adjacent to PEL-1 up to Venice. On the west side of the Mississippi River the existing levee PWL-1 will be upgraded and a new levee PWL-2 will be constructed adjacent to PWL-1 up to Venice.

These levee alternatives are considered not feasible and hence excluded from inclusion in possible strategies. Given the increase in hurricane surge levels that can be expected before these levees, the crest level of these levees should be substantial, and the reduction of flood risks in the parish is not expected to outweigh the high construction costs.

Measure **P-rings** aims at replacing the existing, long and narrow levees with smaller rings of sufficient height around villages and industrial complexes in the parish, and to remove long stretches of levees in rural and empty spaces along the Mississippi River in order to allow hurricane surges to dissipate. As a result, storm surge levels would meet less obstruction from levees, and be lower when compared to the existing situation. During Hurricane Katrina, temporarily a significant increase of surge levels occurred on the North side of the existing levee. Had the Plaquemines levees be replaced by smaller rings, the maximum surge levels during Hurricane Katrina would have been lower. Measure P-rings will allow water to flow into the river and eventually cross the river to the wetlands on the other river bank. This measure is labeled as a promising measure.

Storm surge barrier in Mississippi River (downstream of New Orleans)

Measure **MGATE:** a storm surge barrier in the Mississippi River near Pointe à la Hache. In the event that a hurricane storm surge moves up the Mississippi River, New Orleans could potentially be flooded by a surge moving upstream the river. A surge barrier downstream of the city, that would be closed during a hurricane threat, could prevent this. This barrier would be comparable to the existing barrier in the Rhine River that protects the Rotterdam area against storm surges. That barrier has a width of 1200 feet and water depth of 50 feet, which is sufficiently large for the safe passage of ocean going navigation when the barrier is open.

During the closure of such gate in the river, the river discharge has to be stored temporarily. The river area between the levees provides a certain amount of storage space, but given the discharge of the Mississippi River additional storage space will be necessary. A logical storage space for river water are the wetlands East and / or West of the river. To enable storage in those areas, the existing levees between the barrier and New Orleans would have to be removed. There is an additional reason why the removal of those levee stretches is promising, namely to allow the dissipation of hurricane surges that in the existing situation build up on the wetland side of the levee, like happened during Hurricane Katrina behind the Plaquemines levee. In such cases, removal of the levee would allow water to flow into the river and eventually cross the river to the wetlands on the other river bank.

If stretches of levees were to be removed downstream of New Orleans, a storm surge that moves up river could dissipate via these stretches, and a storm surge barrier would not required. It is for this reason that a barrier in the Mississippi River is considered not-promising. This measure is therefore not considered any further in the planning process.

H.4 Measures for closed hurricane surge protection

The measures in this group are features to close off either or both Pontchartrain and Barataria basins during a hurricane threat. This section directly links to Chapter 4.2 of the main report, and Figure 135 illustrates the location of the measures in this group. Each of these measures is considered promising.

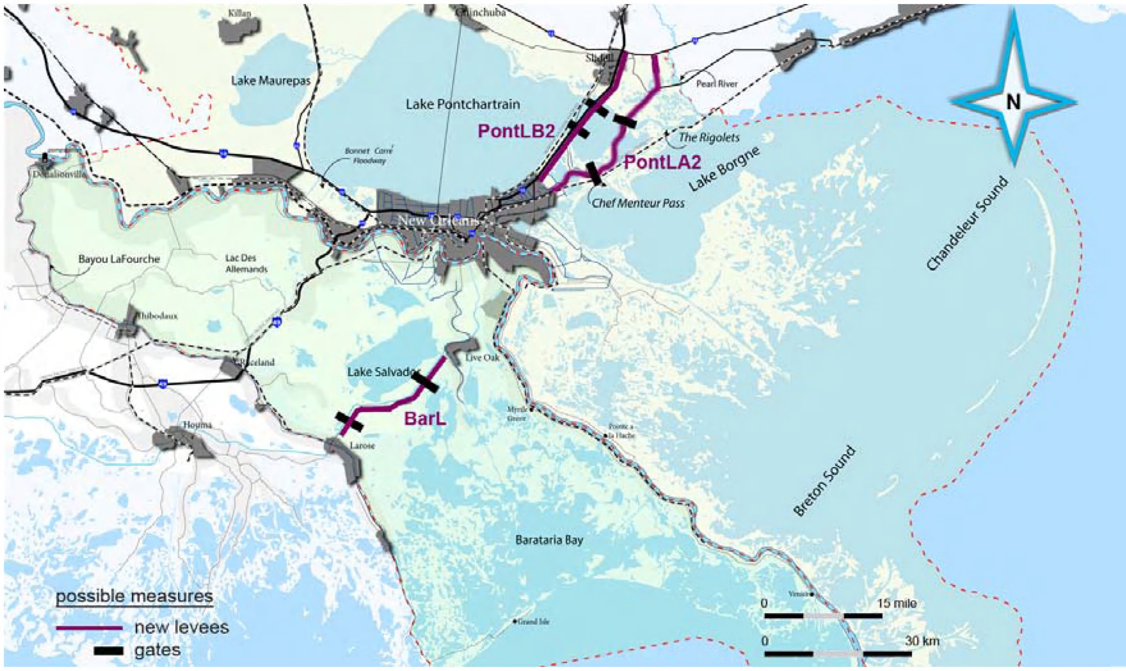

Figure 130 Possible measures for closed hurricane surge protection (codes are explained in the text of this appendix).

Gated levees to close off the Pontchartrain basin

Measure **PontLA2**: a new levee barrier, essentially following the alignment of highway C90, with openings to allow exchange of water between Lake Borgne and Lake Pontchartrain, potentially realized by heightening the level of C90. Storm surge gates are built in the openings in the levee (Chef Menteur and Rigolets). These gates will only be closed when a storm surge is anticipated. The height of the levee can be limited to about 10 to 15 feet, provided the levee can safely deal with overtopping waves and overflow.

Measure **PontLB2**: a new levee barrier, essentially following the alignment of Interstate I10, with openings to allow exchange of water between Lake Borgne and Lake Pontchartrain. Storm surge gates in these openings will only be closed when a storm surge is anticipated.

Gated levees to close off the Barataria basin

BarL: gated levee system between Lafourche and Plaquemines, following the alignment of the Intracoastal Waterway. Also in this levee system the gates will only be closed when a storm surge is anticipated.

H.5 Measures to consolidate and increase present surge reduction

The measures in this group are aimed at consolidating and increasing the present natural hurricane surge reduction capacity of the delta system. This section directly links to Chapter 4.3 of the main report, and Figure 131 illustrates the location of the measures in this group.

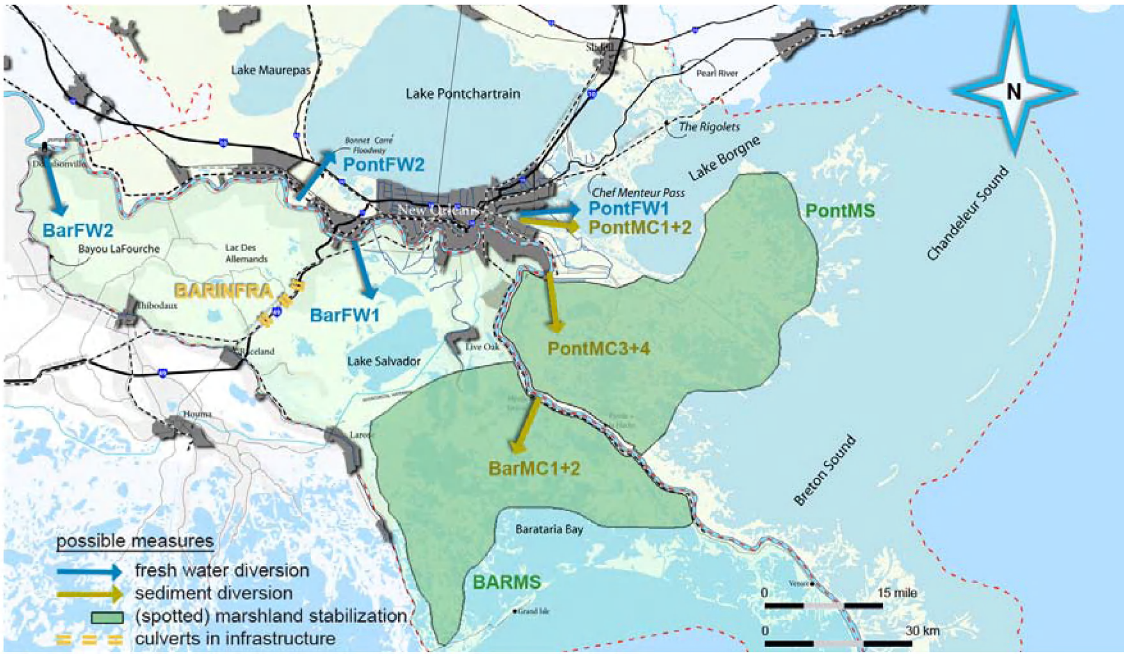

Figure 131 Measures to Consolidate and Increase Present Natural Surge (codes are explained in the text of this appendix).

Strategic dumping of dredged material

Measure MDUMP: strategic dumping of material dredged from the Mississippi navigation channel. In the current situation, 7 to 10 million cubic yards is dredged annually. Dumping this material at strategically selected locations will contribute to marshland stabilization. Such dumping is already carried out to a certain extent. The measure is considered promising.

Fresh water diversions

The diversion of fresh water from the river to the marshes and wetlands is promising in view of restoring salinity gradients in the marshes, as well as the supply of nutrients and sediment to the wetlands.

The following measures are considered:

- measure **PontFW1**: fresh water diversions towards the Lake Borgne area, possibly via the Industrial Canal and Inner Harbor Navigation Canal.

- measure **PontFW2**: fresh water diversions Lake Pontchartrain, possibly via the existing Bonnet Carré spillway. This measure will bring fresh water to Lake Pontchartrain, and is expected to help improve the salinity gradient.
- measure **BarFW1**: fresh water diversion just upstream of New Orleans towards the Barataria Basin.
- measure **BarFW2**: upgrade the existing fresh water diversions (Bayou Lafourche) in order to increase the fresh water supply to the Barataria basin.

Marshland stabilization

For both the Pontchartrain Basin and the Barataria Basin, there is an urgent need to stabilize the landscape and prevent further loss of wetlands. Two promising measures are identified, that could potentially be applied for large wetland areas:

- measure **PontMS**: spotted marshland stabilization in the Pontchartrain Basin, mainly achieved by plugging or completely closing existing canals. The idea is to start in priority areas where most effect can be expected (marshland priority maps).
- measure **BarMS**: is a comparable measure but for the Barataria basin.

Marshland creation

For new marshes to develop, the abiotic conditions need to be created first. This refers to water and nutrients, but also to the land level. To convert open water into marshes, sediment needs to be supplied. There are two alternatives for such sediment supply:

1. bring the sediment in the marshland area by means of the diversion of river water, or
2. bring the sediment in the area by means of piped sediment supply.

The first option, i.e. bring sediment into the area by means of the diversion of river water, four locations were selected. These locations are to a large extent identical to the locations discussed before for fresh water diversion. The following measures were identified:

- measure **PontMC1**: sediment diversions in the direction of Lake Borgne. There is a link with the fresh water diversion at the same location (measure PontFW1);
- measure **PontMC3**: enlarged sediment diversions at the existing Carnarvon diversion sluice;
- measure **BarMC1**: sediment diversions in the direction of the Barataria basin.

Modeling of the flow of water and sediment through these diversions was carried out in the framework of the current project. The results are described in Appendix D, and led to the conclusion that given the sediment concentrations in the river the amount of fresh water that is needed to deposit significant amounts of sediments would be so large that a considerable part of the wetlands would be permanently changed into freshwater (instead of a gradient from fresh, brackish to saltwater). Hence, it is concluded that a significant marshland creation is virtually impossible without seriously disturbing the salinity gradient. These measures are therefore considered as not-promising.

An alternative for the supply of sediments through river diversions is the piped supply of sediments to areas where wetland creation is desired. For this option the following three measures for piped sediment supply were identified:

- measure **PontMC2**: to bring sediment to the wetland area in the Pontchartrain basin close to New Orleans;
- measure **PontMC4**: to bring sediment to the wetland area in the Pontchartrain basin further away from the city; and
- measure **BarMC2**: to bring sediment to the Barataria basin.

Adapting existing infrastructure in the Barataria basin

Measure **BarINFRA** is aimed at building culverts at regular intervals under the existing interstate and railway in the Barataria basin to allow the movement of fresh water, nutrients, sediments and animals into the marshlands. The highway and railway currently to a large extent block such movement. This promising measure will contribute to the restoration of the natural dynamics of the system.

H.6 Basin surge reduction measures

The purpose of the measures in this group is to limit the effect of hurricane surges entering the basins by adsorbing its energy either through reshaping the existing outer barrier islands or through creating a new string of man-made ridge-levees inside the Pontchartrain and Barataria basin. This section directly links to Chapter 4.4 of the main report, and Figure 132 illustrates the location of the measures in this group.

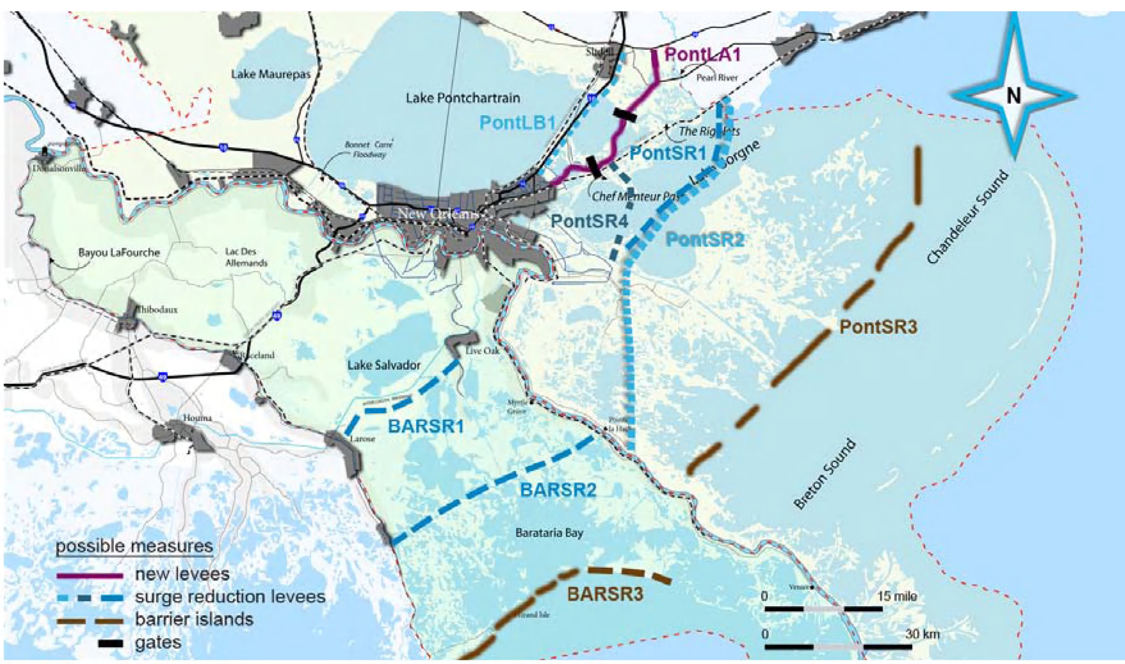

Figure 132 Basin surge reduction measures (codes are explained in the text of this appendix).

Open levees (no gates) in the Pontchartrain basin

Measure **PontLA1**: new open levee barrier, essentially following the alignment of highway C90, potentially realized by heightening the level of C90, with openings to allow exchange of water between Lake Borgne and Lake Pontchartrain via the Chef Menteur and Rigolets passes. Pending the outcome of hydrodynamic simulations, the idea is that because some flood water can be safely stored in lake Pontchartrain during a hurricane, the openings in the levees do not have to be closed completely during a storm surge. Therefore, the levee has erosion resistant openings. This measure assume a traditional levees at these locations.

Measure **PontLB1** : new open levee barrier, essentially following the alignment of Interstate I10, with openings to allow exchange of water between Lake Borgne and Lake Pontchartrain. This measure is based on the same idea as measure PontLA1, but follows a different alignment.

An advantage of measure PontLA1 over measure PontLB1 is that more dwellings are protected by measure PontLA1. At this stage in the analysis, both measures are considered promising.

Ridge-levees in the Pontchartrain and Barataria basins

Measure **PontSR1**: open levee system (ridge-levees) aimed at surge reduction, crossing Lake Borgne. This alignment offers the advantage that current land use on the land bridge remains unaffected and that the land bridge itself is also protected. For design considerations for ridge-levees, reference is made to Appendix F.

Measure **PontSR2**: open ridge-levee like PontSR1 but following another, longer alignment, further in the direction of the Gulf, over the marshes East of Lake Borgne, all the way to Pointe à la Hache.

Measure **PontSR4**: open ridge-levee like PontSR1 but following another, shorter alignment, around the Western section of Lake Borgne.

Measure **BarSR1**: open ridge-levee in the Barataria basin, located at the Gulf side of GIWW, connecting Jesuit bend at the Mississippi levee and the landward side of the Lafourge levee.

Measure **BarSR2**: open ridge- levee further seaward than BARSR1, connecting the most seaward tip of the Lafourge levee and Pointe à la Hache. This ridge-levee could be an effective measure in reducing surge levels near New Orleans, but the distance to New Orleans proves an important factor, as illustrated by Appendix D. This alignment is too far away from New Orleans to have a significant impactsee any effect of this levee on the waterlevel at New Orleans

All the these ridge-levees are considered promising, except for – as mentioned – BarSR2.

New barrier islands Pontchartrain basin

Measure **PontSR3**: outer storm surge reduction, aims at developing a string of new barrier islands in the Pontchartrain basin, with the objective to reduce the surge levels around New Orleans. Hydrodynamic calculations, reported in Appendix D, clearly illustrate that such barrier islands do not have a significant effect on surge levels close to New Orleans. The volume of water behind the string of barrier islands and the distance between these islands and New Orleans are so large that the surge near New Orleans is not significantly reduced by these islands. Therefore, this measure is classified as not-promising.

Upgrade barrier islands Barataria basin

Measure **BarSR3**: outer surge reduction: sand barrier islands. The idea behind this measure is that upgraded barrier islands in the Barataria basin (higher, wider, longer) might help reduce surge levels near New Orleans. The hydrodynamic screening analysis reported in D proved that this measure is not effective. The volume of water behind the barrier islands and the distance to New Orleans are too large to cause a significant effect on surge levels near the city. Therefore, this measure is labeled as not-promising.

H.7 Interventions for long-term natural surge reduction

The final group of flood risk reduction measures consists of options for large-scale interventions in the Mississippi Birdfoot area. The idea is to reduce (stop) the current wastage of sediment resources, which are now to a large extent dumped in the depths of the Gulf of Mexico. This section directly links to Chapter 4.5 of the main report, and Figure 12 illustrates the location of the measures in this group.

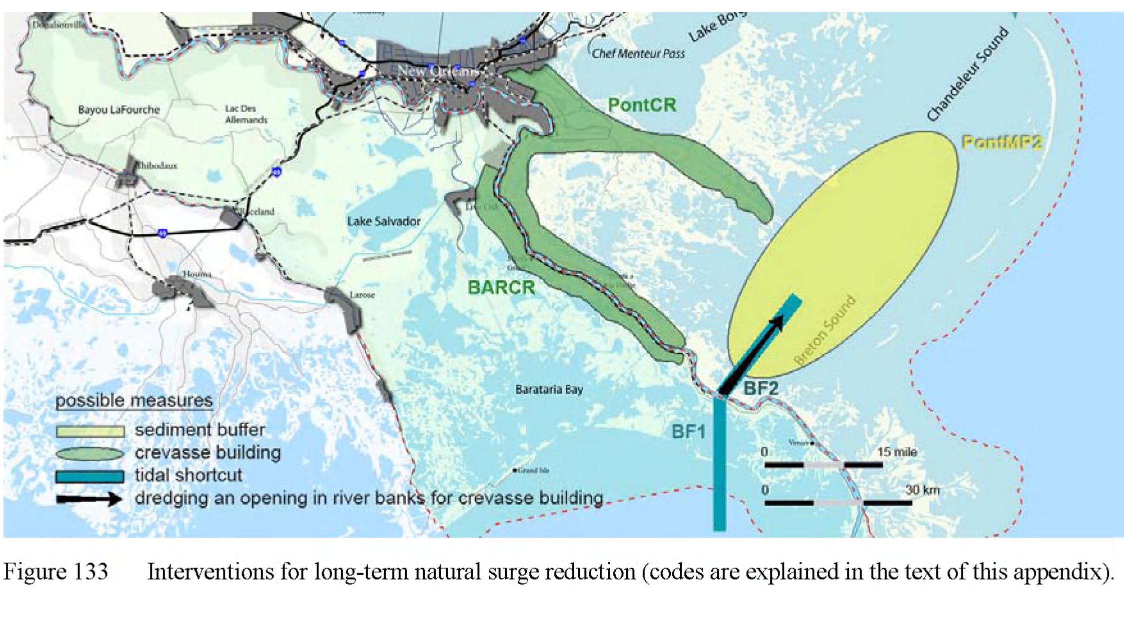

Figure 133 Interventions for long-term natural surge reduction (codes are explained in the text of this appendix).

Shortcut Birdfoot /Minimize of sediment loss

Measure **BF1**: tidal shortcut Birdfoot on both sides of the river, with the objective to keep the sediments close to the existing coastline. Several options for this measure were considered:

The project team identified several options for this measure:

- Dredging a 3 mile (5 km) wide opening in the West bank of the river. The depth of this opening is 17 feet (5 m). Navigation would continue to use the existing navigation channel.
- Dredging two relatively narrow (0.6 mile / 1 km) but relatively deep (50 feet / 15 m) channels on the East and West bank of the river respectively. These new channels would be the access channel for ocean-going navigation to reach the Mississippi River. In this alternative, the existing Birdfoot would no longer be maintained and would eventually – after a long process of decay – disappear, while its sediments would benefit the coastal zone. It is assumed and considered feasible to shape these channels in such a way that ocean going navigation can pass these channels and enter or exit the river without difficulties.

For both options a simulation model was developed for hydrodynamics, morphology and salinity. The results of this analysis are reported in Appendix D.

The dredging of the two narrow and deep diversion channels will cause a large drop in salinity levels over a large area of the coastal zone. This will have a profound impact on local habitats. In the narrow and deep option approximately 80 percent of the river discharge will enter the Gulf of Mexico through the diversion channels. The impact on salinity levels in the coastal zone is so severe that the project team reached the conclusion that because of this effect this measure should be considered as not-promising, even though the measure does result in bringing substantial amounts of sediment to the coastal strip.

Also the wide and shallow diversions proves to be a not-promising measure, as illustrated by Appendix D. Disconnecting the Birdfoot will lead to a tidal currents through the newly dredged channel. There will be no or hardly any redistribution of the sediment in the longshore direction to nourish the delta. Furthermore the total volume of sediment that would need to be dredged from the wide channel is so large that this measure is considered to be not feasible.

Measure **BF2**: dredging an opening on one side of the river bank of the Mississippi river in order to create/stimulate crevasse building. The opening will be on the Pontchartrain side of the Mississippi River. Natural processes would be used in this way to build marshland, which helps to reduce hurricane surges. This measure can be qualified as quite flexible. After for example a period of 10 years the opening could be moved to another location. The process that is expected to occur compares to the ongoing (natural) crevasse building in the Atchafalaya Delta.

Measure **PontMP2**: creating an underwater sediment buffer combined with a shortcut of the Mississippi River (measure BF1). This subtidal plateau of dredged material is expected to eventually lead to natural barrier buildup by wave action. Potentially, the dimensions of this plateau could be optimized to provide large-scale habitat for oyster beds. Because measure BF1 is labeled as not-promising, and this measure PontMP2 will require large amounts of sediment that would be difficult and expensive to find without measure BF1, measure PontMP2 is labeled as not-promising and excluded from the next steps in the planning process.

Pontchartrain and Barataria crevasse building

Measure **PontCR**: crevasse building for long-term marshland creation. This measure will use MRGO to supply large quantities of fresh water and sediment to the marshes around the Lake Borgne area and the Lake itself. It would lead to new sub-deltas, enhancing natural process by large-scale diversions of the Mississippi (about 15% of the river flow).

Measure **BarCR**: Crevasse building for long-term marshland creation. Creating new sub-deltas, enhancing natural process by large-scale diversions of the Mississippi River (about 15% of the river water) to create crevasses West of New Orleans.

Appendix D reports on hydrodynamic and morphological simulations for these two possible measures. It can be concluded that crevassing has a much larger effect on the salinity distribution than on deposition of sediments in Barataria basin and in Pontchartrain basin. The amount of fresh water that is needed to deposit significant amounts of sediments would be so large that a large area in both basins would be permanently changed into fresh water. Measure BarCR and PontCR are both considered to be not-promising.

H.8 Overview of promising measures

Based on the information provided by the earlier sections of this Appendix H, Figure 134 provides an overview of the measures that passed the screening process successfully.

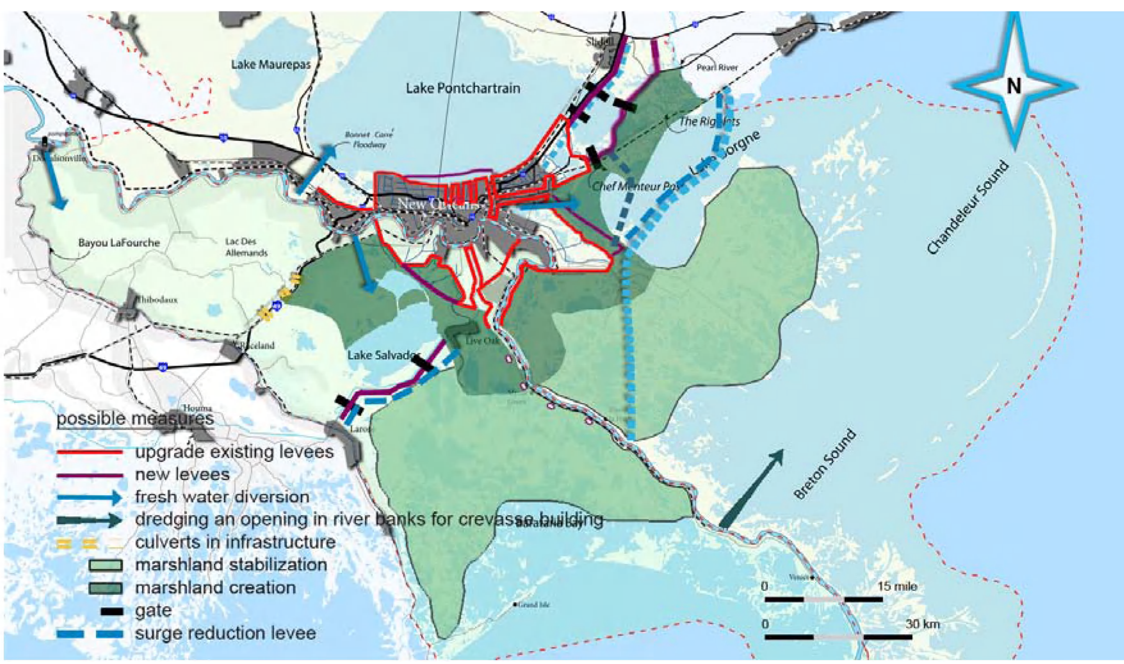

Figure 134 Overview of promising measures that passed the screening process for individual measures.

H.9 Overview of which measures are included in strategies

After the selection of promising measures, five strategies were designed as described in Chapter 5 of this report. Table 18 provides an overview of the strategies and the measures included in the autonomous development and each of the five strategies. Reference is made to Chapter 5 for more information on the idea behind each possible strategy.

Table 18 Overview of which measures are included in the autonomous development and in each of the five strategies.

	measure	autonomous development	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
measures for direct protection of incorporated values							
North	NL1 or NL2	X	X	X	X	X	X
East	EL1	X	X	X	X	X	X
West	WL1 of WL2	X	X	X	X	X	X
Pla	Prings: ring levees Plaquemines	X	X	X	X	X	X
gated levees							
PontLA2	gated levee barrier along road C90						X
BARL	gated levee barrier (GIWW alignment)						X
measures to consolidate and increase present natural surge reduction							
MDUMP	strategic dumping of Mississippi dredged material		X	X	X	X	X
Infrastructure							
BARINFRA	culverts in existing interstate + railway		X	X	X	X	X
freshwater diversions							
PontFW1	fresh water diversions Lake Borgne		X	X	X	X	X
BARFW1	fresh water diversion New Orleans (Barataria)		X	X	X	X	X
BARFW2	extend fresh water diversion (Bayou Lafourche)		X	X	X	X	X
marshland stabilization measures							
PONTMS	marshland stabilization		X	X	X	X	X
BARMS	marshland stabilization		X	X	X	X	X
marshland creation measures							
BARMC2	increased sediment supply by piped solutions			X			
PontMC2	increased sediment supply by piped solutions			X			
PontMC4	increased sediment supply by piped solutions			X			
basin surge reduction measures							
PontLA1	new closed ridge-levee along C90 plus gates					X	
PontSR4	open levee surge reduction west of Lake Borgne					X	
BARSR1	open levee (GIWW alignment), overtopping					X	
interventions for long-term natural surge reduction							
BF 2	large-scale opening for crevasse building				X		

1 Tentative hydraulic design parameters

1.1 Hurricane surge design levels

The probabilistic method and results for surge and wave modeling, developed in the framework of the IPET and LACPR projects, will eventually provide final information on extreme surge levels and wave heights in the project area based on comprehensive and detailed calculations. However, this method, the associated models, and the results are not published to date (IPET Volume VIII is not published yet) and hence are not available for use in this research project. Therefore, for the current planning purposes surge levels and wave heights at various locations within the planning area were preliminary estimated for a range of probabilities. These estimations are based on preliminary IPET-results and expert judgment.

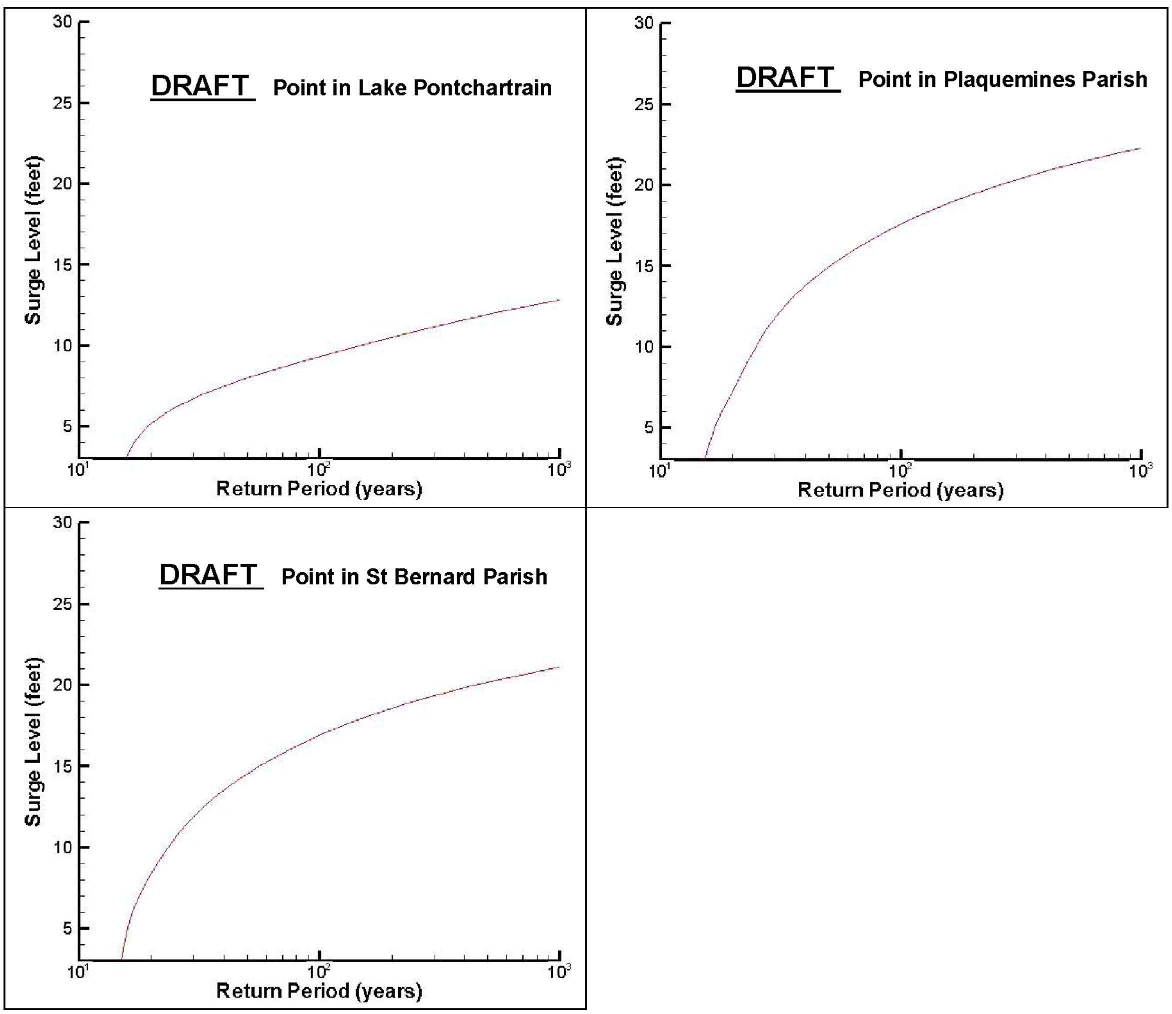

Figure 135 Tentative relations between surge height and probability of occurrence, for points in Lake Pontchartrain, Plaquemines Parish and St. Bernard Parish (draft results IPET project)

Key locations for this information are Lake Pontchartrain, Lake Borgne, Plaquemines East, Barataria Basin (middle) and Barataria Basin (North). These locations are considered to be representative for the planning design of Hurricane Protection structures around New Orleans proper. Use was made of draft results from the IPET-study, as presented in Figure 135. These curves show the relation between the return period in years and the maximum surge level during the hurricane event at that particular location.

Table 19 Design Hurricane Surge Level at Lake Pontchartrain (Surge Levels to NAVD88, according IPET study, extrapolated in the current project to higher return periods)

return period	**surge level**		**significant wave height**	
(years)	**(feet)**	***(meter)***	**(feet)**	***(meter)***
100	9	*2,7*	5.3	*1.6*
500	11	*3.3*	6.5	*2.0*
1,000	13	*3.9*	7.7	*2.3*
10,000	**17**	***5.1***	**10.0**	***3.1***
100,000	21	*6.3*	12.4	*3.8*
1,000,000	25	*7.5*	14.8	*4.5*

Table 19 shows that the design surge level in Lake Pontchartrain is estimated at 17 feet with a probability of one in 10,000 years. The values are estimated from limited available information whereas the Hurricane Katrina surge level in Lake Pontchartrain was considered to be a 1 in 100 to 1 in 500 years extreme event. The relationship between surge level and return period above 100 years is assumed to be linear and estimated to be 4 feet increase per factor 10 increase of return period. In the Netherlands, a similar linear increase of around 3 feet is used for design purposes. This crude assumption is used for all key locations. The significant wave height is estimated at 0.6 times the surge level (not the water depth). This could be an underestimate but probably sufficiently accurate for planning purposes, which is aimed at comparing alternative strategies and not designing them for construction.

Calculations reported in Appendix E showed that the economic optimum for the flood protection level of the metropolitan area of New Orleans is in the order of 1/1,000 per year or better. For the sake of mindset and comparison, the estimated 1/10,000 surge level will be used as a basic reference to compare alternatives and to estimate the effects of measures.

The 1 in 10,000 years surge levels at various locations around New Orleans are listed in Table 20. The highest levels are found at Plaquemines East were the hurricane surge hits the high grounds and levees of the Mississippi ridges, which in the IPET-report are indicated as topographical control features. Due to this relatively high resistance as compared to the open and flooded marshlands, the surge level tends to increase at that location. Also, high levels are found at East-facing levees of New Orleans.

The values listed in Table 20 are used to draft a preliminary design of the engineered protection system, composed of levees and gates, around the metropolitan area of New Orleans. In more detail, this concerns the measures listed in chapter 4.1 of this report, aimed at the direct protection of incorporated values (see also Figure 7).

Table 20 Reference hurricane surge design levels and significant wave heights (1/10,000 return period)

basin	location	surge sevel		significant wave height	
		(feet)	*(meter)*	(feet)	*(meter)*
Pontchartrain	Lake Pontchartrain	20	*6.0*	11.8	*3.6*
	Lake Borgne	23	*6.9*	13.6	*4.1*
	Plaquemines East	28	*8.4*	16.5	*5.0*
Barataria	North	16	*4.8*	9.4	*2.9*
	Middle	18	*5.4*	10.6	*3.2*

I.2 Effect of measures on hurricane design surge levels

In order to analyze the effect of hurricane control or reduction measures in the Pontchartrain and Barataria basin a number of scenario's and strategies were considered in the current planning effort covering a realistic range of possibilities. These are:

- Autonomous development
- Current Situation
- Marshland Stabilization
- Marshland Creation
- Semi-Open Basin with surge reduction
- Basin Closure with gated levee barriers

For each of these scenarios new 1 in 10,000 years hurricane design surge levels are estimated on the basis of expert judgment and crude assumptions. Again, linear relations are assumed between surge levels and return period.

Autonomous Development

This scenario assumes that all salt-water marshes in the basin are lost and that New Orleans is an island surrounded with (shallow) water. This represents a "do nothing" scenario to materialize in the next 100 years or so. Under the same wind conditions, more open water will increase surge levels in the upper regions of the basins. Based on indicative calculations with Delft3D (see Appendix D) the overall effect seems to be in the order of 4 feet increase as compared to the present situation. All calculations consistently show the continued loss of marshlands (vegetation) has a considerable effect on the propagation of surges but reliable calculations are still beyond the present state-of-the-art.

Current Situation

Hurricane Katrina provided (real time) surge information, which will be used to estimate hurricane surge levels, but at the same time significantly changed "the current situation". Hurricane Katrina destroyed marshlands and changed them into open water. The question obviously is what exactly the current situation in terms of marshlands is. Because Hurricane

Katrina provided most data on surge levels and waves, the calculated current situation therefore represents the marshland situation as is was prior to Hurricane Katrina.

Marshland Stabilization

Additional coverage of the salt water delta area with a closed and healthy blanked of vegetation will with no doubt reduce surge levels, although it is still very difficult to predict how much exactly. It is assumed that an overall reduction of 2 feet could be achieved implementing an extensive stabilization program. The difference between the autonomous "do nothing" scenario on the one hand and a maximum stabilization effort is therefore estimated to be 6 feet. The option of marshland stabilization is therefore an important measure to reduce flood risks. However, marshland stabilization does not provide a reliable alternative for engineered solutions as Hurricane Katrina demonstrated. Severe hurricanes damage marshlands leaving more open water for the next one passing.

Marshland Creation

Marshlands are an effective means to reduce surge level and wave heights at a certain location. This is in particular true for fresh water (cypress) marshes with full grown bushes and trees. Based on indicative calculations by the project team (see section Appendix D2) it is assumed that the potential reduction of surge levels is about one foot per mile of closed and healthy fresh water swamp in front of the location. Beside surge reduction, fresh water swamps will significantly reduce the wave height approaching the location and hence the wave loading on levees. In the current planning calculation, a 50% reduction was used in wave height as compared to an open foreshore.

Semi-Open Basin with surge reduction

This scenario for the Pontchartrain Basin includes the construction of a surge reduction levee (a relative low and overflowing levee, about 12 feet high) and gated structures in the two passes. The effect is estimated at 3 feet reduction as compared to a situation without surge reduction.

For the Barataria Basin the reduction is estimated to be 6 feet again assuming 12 feet high overflowing levees. No gated structures are assumed in this scenario.

Basin Closure with a Gated Levee Barrier

Closing Lake Pontchartrain during a Hurricane event with a gated levee barrier will reduce the design water level behind the barrier significantly. The barrier however will not prevent local wind surges generated at the lake itself.

Due to the spatial extent of Hurricane Katrina, days before the hurricane passed; an increasing strong wind from the East raised the water level of Lake Borgne with about 3 feet and that of Lake Pontchartrain with about 1 foot. Hours before Hurricane Katrina hit the shore, Lake

Pontchartrain rose to about 3 feet when water was pushed in from Lake Borgne through the Rigolets and Chef Menteur passes (see section Appendix D2).

The effect of an early closed barrier during Hurricane Katrina would have prevented the rise of Lake Pontchartrain and would have reduced the experienced surge level by about 3 feet. Under worse conditions (i.e. 1 in 10,000 years) the effect of a barrier is estimated to be a 5 feet reduction as compared to a situation without a barrier.

A gated levee barrier in the Barataria Basin (following the alignment of the Intracoastal Waterway) will prevent the surge entering the upper part of the basin and will therefore reduce the Hurricane Design Surge Level to virtually zero. Some wave overtopping may occur but this will not significantly raise the water level behind the barrier.

I.3 Overview of design surge levels

The tables in this section provide an overview of estimated 1 in 10,000 hurricane design surge levels and significant wave height for four locations (see Figure 136) used for the planning design of levees around New Orleans.

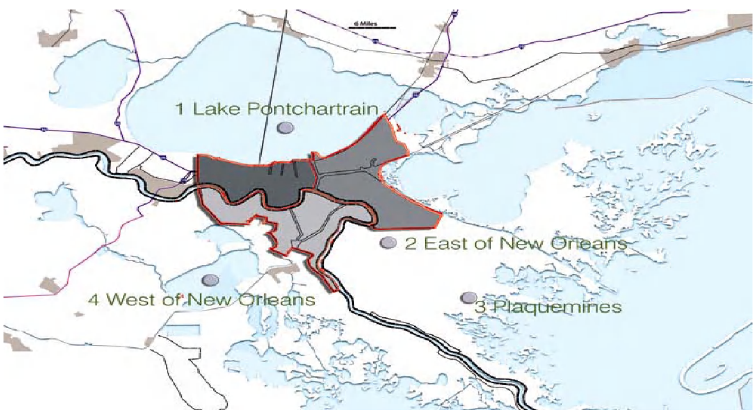

Figure 136 Locations for which surge and wave heights were estimated for various scenario's.

Table 21 Hydraulic design parameters (1 in 10,000) Lake Pontchartrain, North of New Orleans

	hurricane surge design level	**significant wave height**
Autonomous	21 feet	13 feet
Current Situation	17 feet	10 feet
Open		
Marshland Stabilization	15 feet	9 feet
Semi-Open		
Open Levee Barrier	12 feet	7 feet
Closed		
Gated Levee Barrier	10 feet	6 feet

Table 22 Hydraulic design parameters (1 in 10,000) area East of New Orleans

	hurricane surge design level	**significant wave height**
Autonomous	26 feet	16 feet
Current Situation	22 feet	13 feet
Open		
Marshland Stabilization	20 feet	12 feet
Marshland Creation	15 feet	5 feet
Semi-Open	no significant effect	
Closed	no significant effect	

Table 23 Hydraulic design parameters (1 in 10,000) Plaquemines

	hurricane surge design level	**significant wave height**
Autonomous	29 feet	17 feet
Current Situation	25 feet	15 feet
Open		
Marshland Stabilization	23 feet	14 feet
Marshland Creation	18 feet	5 feet
Semi-Open	no significant effect	
Closed	no significant effect	

Table 24 Hydraulic design parameters (1 in 10,000) area West of New Orleans

	hurricane surge design level	**significant wave height**
Autonomous	19 feet	11 feet
Current Situation	15 feet	9 feet
Open		
Marshland Stabilization	13 feet	8 feet
Marshland Creation	7 feet	2 feet
Semi-Open		
Open Levee Barrier	7 feet	4 feet
Closed		
Gated Levee Barrier	0 feet	0 feet

J Costs of structural measures and strategies

This appendix provides background information on how cost estimates for individual structural measures and the various strategies were derived. Cost items include all materials, construction, land acquisition, etc. The final costs of measures can be considered as budget needed for the owner. Taxes have not been included. Unit prices for labor, fuel and materials are according to the values in The Netherlands on January 1, 2007. Where appropriate, unit prices have been converted to US market prices which are about 20 to 40% higher than comparable prices in the Netherlands.

J.1 Cost of levees

The basis for cost calculation is formed by unit prices, for example the costs for the removal of 1 m^3 of soil, the cost of purchasing and installing of 1 m of strip drain, the cost for purchasing and installing of 1 m^3 of asphalt on top of a levee, etc. In the next step, quantity estimates result in the amounts of materials of various kinds needed for a particular measure. Multiplication of unit prices and quantities and considering an addition 10% over the total sum for construction details, leads to the estimation of the Direct Costs. This estimate of Direct Cost is then increased by application of the following multiplication factors, which leads to the estimated costs of the built structure (Total Construction Costs).

(1) ***Direct Costs*** based on unit prices and quantities plus 10% contingencies:

- a factor of 1.45 (45%) on (1) for construction overheads;
- a factor of 1.10 (10%) on (1) for construction profit and risk

(2) ***Total Construction Costs***

Next, where applicable, the cost of land acquisition is estimated and added to the Total Construction Costs to find the total costs of the project.

(3) ***Total Project Costs***

These costs are then increased by applying the following multiplication factors, which leads to the final cost estimate of a structure.

- a factor of 1.30 (30%) for Project Contingencies; and
- a factor of 1.19 (19%) for Program Management, Owners Design and Supervision.

(4) ***Total Owners Costs***

These overheads and other allowances are based on USACE information made available to the team. The unit prices used in the levee cost estimates are Dutch unit prices applicable for the Dutch market only. However, there are marked differences between the Netherlands and the USA, in particular affecting the market prices for aggregates and sand.

For levees, the above cost estimate leads to the total owners (investment) costs for 1 km of levee. Multiplication with the estimated length of the levee leads to the total investment cost for the stretch of levee. The above described method is applied for all projects that involve the upgrading of existing levees or the construction of new levees.

This method was applied for in total 40 levee design cases for various levee stretches and various scenarios regarding wetland development (autonomous development, existing situation, marshland stabilization and marshland creation). Each of these cases was analyzed for return periods ranging from 100; 500; 1,000; 5,000; 10,000; 100,000 to 1,000,000 years. The height of the levee was selected based on the surge levels and significant wave information as summarized in Appendix I. This Appendix also contains an example of a basic levee design and cost estimate for purpose of evaluation.

J.2 Cost of structures

The cost of structures was calculated by applying the method, software and unit prices used by Rijkswaterstaat for design studies and government budget reservations for infrastructure projects. A simplification was made by not applying the probabilistic method the software offers. Instead, only deterministic calculations were made in the context of the current project. The various assumptions are summarized in the following listing.

References
- "New Orleans - Rough drafts and quantity calculations", d.d. 14-02-2007 (author: G.A. Beaufort)
- Level of prices : 1-1-2007
- Reference databases: Becel1205b / LBK1206

Direct Costs
- **General**
  - all costs in Euro
  - all quantities in metric system
  - construction is situated in Dutch context
- **Surge Barrier**
  - temporary double-walled cofferdam (L=width of construction+14m, h=20m, w=10m)
  - all piling barge driven (permanent cofferdams shore driven)
  - small earthwork in place of construction
  - bottom protection in armor rock (no asphalt penetration needed)
  - steel sector gates (40m: 2 x 500t; 15m: 2 x 200t)
- **In- and Outlet Structures for Free Flow**
  - temporary double-walled cofferdam (L=width of construction+15m, h=20m, w=10m)
  - all piling barge driven (permanent cofferdams shore driven)
  - small earthwork in place of construction
  - bottom protection in armor rock (no asphalt penetration needed)
  - Steel plane gate doors (150t per door)
- **Sediment and River Water Inlet Structures**
  - temporary diafragma cell-wall cofferdam (L=width of construction+20m, h=30m, w=21m)
  - all piling barge driven (permanent cofferdams shore driven)
  - small earthwork in place of construction
  - bottom protection in armor rock (no asphalt penetration needed)
  - Steel plane gate doors (103ton per item)
  - Steel stop log closure beams (550ton per 2 items)
  - Steel fencing screen (56ton per item)
- **Other assumptions**
  - the construction sites are accessibile for heavy equipment
  - minimum 2 years blocking of shipping channels is allowed

Allowances
- 10% for forseen further detail of work

Indirect costs
- 15% Mob/demon, internal transports, site costs, staff
- 30% Overhead
- 10% Profit

Engineering
- 10% Contractor's engineering, research and supervision
- 19% Programme management

Contingency
- 20% Object contingencies for onforseen items on object scale
- 30% Project contingencies for unforseen items on programme scale

Other Expensenses (not part of construction of defined objects)
- **All excluded**
  some examples:
  - no land and compensation costs
  - no costs for permits and legal taxes
  - no costs for (temporary) road infrastructure
  - no costs for dikes infrastructure

Taxes
- Excluded

Margins
- Margins are estimated on +/- 30% for reason of high plan incertainty

The following table gives an overview of the structures for which this method was applied, which include surge barriers, sluices and diversion structures.

Cost estimate by: Rijkswaterstaat Bouwdienst

Project	**New Orleans**	Date:	1 oktober 2007
Document	**Estimate of costs**	File:	Cost estimate NewOrleans v0.06.xls
Chapter	**Surge Barriers, In and Outlet Structures**	Estimator:	R. Treiture

Deterministic calculation

Item	Description	Direct Costs	Indirect Costs	Total of Forseen Costs	Unforseen Costs ...object ... project	SUBTOTAL
Costs of Construction						
1	Surge barrier (width=40m)	€ 26 840 000	€ 17 298 380	€ 44 138 380	€ 8 827 676	€ 52 966 056
2	Surge barrier (width=15m)	€ 13 475 000	€ 8 684 638	€ 22 159 638	€ 4 431 928	€ 26 591 565
3.1	In- and Outlet Structure for Free Flow (No. of openings: 10)	€ 43 450 000	€ 28 003 525	€ 71 453 525	€ 14 290 705	€ 85 744 230
3.2	In- and Outlet Structure for Free Flow (No. of openings: 15)	€ 64 350 000	€ 41 473 575	€ 105 823 575	€ 21 164 715	€ 126 988 290
3.3	In- and Outlet Structure for Free Flow (No. of openings: 25)	€ 105 600 000	€ 68 059 200	€ 173 659 200	€ 34 731 840	€ 208 391 040
4.1	Sediment and River Water Inlet Structure (No. of openings: 1)	€ 13 750 000	€ 8 861 875	€ 22 611 875	€ 4 522 375	€ 27 134 250
4.2	Sediment and River Water Inlet Structure (No. of openings: 2)	€ 23 650 000	€ 15 242 425	€ 38 892 425	€ 7 778 485	€ 46 670 910
4.3	Sediment and River Water Inlet Structure (No. of openings: 3)	€ 33 550 000	€ 21 622 975	€ 55 172 975	€ 11 034 595	€ 66 207 570
4.4	Sediment and River Water Inlet Structure (No. of openings: 4)	€ 43 450 000	€ 28 003 525	€ 71 453 525	€ 14 290 705	€ 85 744 230
4.5	Sediment and River Water Inlet Structure (No. of openings: 5)	€ 53 900 000	€ 34 738 550	€ 88 638 550	€ 17 727 710	€ 106 366 260
4.6	Sediment and River Water Inlet Structure (No. of openings: 10)	€ 103 400 000	€ 66 641 300	€ 170 041 300	€ 34 008 260	€ 204 049 560
4.7	Sediment and River Water Inlet Structure (No. of openings: 20)	€ 203 500 000	€ 131 155 750	€ 334 655 750	€ 66 931 150	€ 401 586 900
Total Costs of Construction		**€ 728 915 000**	**€ 469 785 718**	**€ 1 198 700 718**	**€ 239 740 144**	**€ 1 438 440 861**
Engineering						
10% Contractor's engineering, administration, research and supervision		€ 144 000 000	€ -	€ 144 000 000	€ -	€ 144 000 000
19% Programme management		€ 270 000 000		€ 270 000 000		€ 270 000 000
Total costs of Engineering		**€ 414 000 000**	**€ -**	**€ 414 000 000**	**€ -**	**€ 414 000 000**
Land and Compensation Costs		€ -	€ -	€ -	€ -	€ -
Other Expenses		€ -	€ -	€ -	€ -	€ -
SUBTOTAL OF ESTIMATE OF COSTS		**€ 1 142 915 000**	**€ 469 785 718**	**€ 1 612 700 718**	**€ 239 740 144**	**€ 1 852 440 861**
30% Project Contingencies					€ 560 000 000	€ 560 000 000
Skewness (probabilistic calculation)						€ -
Compensation for Market Forces					**€ -**	**€ -**
TOTAL OF INVESTMENT COSTS (excluding taxes)		**€ 1 142 915 000**	**€ 469 785 718**	**€ 1 612 700 718**	**€ 799 740 144**	**€ 2 412 440 861**
Taxes						€ -
TOTAL OF INVESTMENT COSTS (including taxes)						**€ 2 412 440 861**
fluctuation band		nader te bepalen				**+-35%**

The following table illustrates the percentages of labor and fuel in the overall amounts.

Cost estimate by: Rijkswaterstaat Bouwdienst

Project	**New Orleans**
Document	**Estimate of costs (pro rata)**
Chapter	**Surge Barriers, In and Outlet Structures**

Item	Description	Labour	Fuel	Steel	Concrete	Equipm.	Other	Σ
Costs of Construction								
1	Surge barrier (width=40m)	30%	4%	7%	8%	18%	33%	100%
2	Surge barrier (width=15m)	31%	4%	7%	8%	19%	31%	100%
3.1	In- and Outlet Structure for Free Flow (No. of openings: 10)	32%	4%	9%	10%	19%	27%	100%
3.2	In- and Outlet Structure for Free Flow (No. of openings: 15)	31%	4%	8%	10%	19%	27%	100%
3.3	In- and Outlet Structure for Free Flow (No. of openings: 25)	31%	4%	8%	10%	19%	28%	100%
4.1	Sediment and River Water Inlet Structure (No. of openings: 1)	42%	3%	15%	13%	18%	9%	100%
4.2	Sediment and River Water Inlet Structure (No. of openings: 2)	41%	2%	15%	14%	18%	10%	100%
4.3	Sediment and River Water Inlet Structure (No. of openings: 3)	41%	2%	14%	14%	18%	11%	100%
4.4	Sediment and River Water Inlet Structure (No. of openings: 4)	41%	2%	14%	14%	18%	11%	100%
4.5	Sediment and River Water Inlet Structure (No. of openings: 5)	41%	2%	14%	14%	17%	11%	100%
4.6	Sediment and River Water Inlet Structure (No. of openings: 10)	41%	2%	13%	15%	17%	11%	100%
4.7	Sediment and River Water Inlet Structure (No. of openings: 20)	41%	2%	13%	15%	17%	12%	100%
	Average values	37%	3%	11%	12%	18%	18%	100%
Total Costs of Construction								
	Standard Skilled Labour rate	37.00 €/hr						
	Fuel (gasoil)	0.78 €/Ltr						
	Steel (UNP)	1242 €/ton						
	Steel (Pile sheets)	850 €/ton						
	Steel (Reinforcement steel)	930 €/ton						

The table on the following page provides an example of the cost calculations that were carried out, in this case for a 40 m wide surge barrier.

Cost estimate by: Rijkswaterstaat Bouwdienst

Project:	**New Orleans**	Date:	1 oktober 2007
Document:	**Estimate of costs**	File:	Cost estimate NewOrleans v0.06.xls
Object:	**Surge barrier (width=40m)**	Estimator:	R. Treiture

recources of the estimate per category						input probabilistic calculation			
code	description	quantity	unit	unit rate	total	quantities		prices	
						% L	% U	% L	% U
Surge barrier (width=40m)									
	Site preparation								
	Building site								
L31COFFA	Temporary double-walled cofferdam L=12+8m W=10m	200	m	€ 8 755	€ 1 751 000	10	10	30	30
Q220321GR	Gravel	1 440	m3	€ 60	€ 86 400	20	20	10	10
Q42OWB	Colloidal concrete	4 320	m3	€ 126	€ 542 921	30	30	10	10
Q210199	Dry pumping building site	28 800	m3	€ 1.00	€ 28 800	20	20	30	30
Q218134	Permanent pumping	50	week	€ 1 000	€ 50 000	20	20	30	30
	(Sheet)Piling								
	Cofferdams permanent								
Q410413AZ26LS	Material sheet pile steel AZ26 (155kg/m2)	2 240	m2	€ 142	€ 317 296	5	5	20	20
Q410413AZ26D	Sheet piling steel AZ26 (155kg/m2) onshore	2 240	m2	€ 17	€ 38 394	5	5	20	20
Q562199AZ26	Anti corrosion sheet pile steel AZ26 coastal area	720	m2	€ 67	€ 47 999	5	5	20	20
Q411699D	Tie-rod anchorage for cofferdam L=15m	56	items	€ 1 381	€ 76 712	10	10	20	20
Q	0		0	€ -	€ -				
	Sheetpiles permanent under								
Q410413PU06LS	Material sheet pile steel PU6 (75kg/m2)	2 580	m2	€ 71	€ 182 535	5	5	20	20
Q410413PU06N	Sheet piling steel PU6 (75kg/m2) barge driven	2 580	m2	€ 43	€ 111 662	5	5	20	20
Q	0		0	€ -	€ -				
	Foundation piles								
Q410101N400	Driven piles precast prestressed concrete #400 barge driven	7 560	m	€ 81	€ 610 621	5	5	20	20
Q411102M	Cutting pile heads	280	items	€ 14	€ 3 970	5	5	20	20
	Earthwork								
Q2201	Excavating with dragline and barge transport	8 640	m3	€ 6.56	€ 56 678	30	30	20	20
Q	0		0	€ -	€ -				
	Bottom protection								
Q520101	Armor rock	54 000	ton	€ 32	€ 1 728 000	20	20	20	20
	Concrete								
Q42NWVL1	Cast-in-place reinf.concrete floor B35 d=1m or >1m	7 740	m3	€ 255	€ 1 971 533	5	5	20	20
Q42NWWD0	Cast-in-place reinf.concrete wall B35 d=1m or >1m	6 864	m3	€ 381	€ 2 615 870	5	5	20	20
Q42NWDK1	Cast-in-place reinf.concrete roof B35 d=1m or >1m	1 500	m3	€ 409	€ 613 178	5	5	20	20
	Steelwork								
T43 NS	Steel sector gates	1 000	ton	€ 10 000	€ 10 000 000	30	30	20	20
Q	0		0	0.00	€ -	30	30	20	20
Q	0		0	0.00	€ -	30	30	20	20
Q	0		0	0.00	€ -				
	Other								
F35	Driving and equipment	1 000	ton	€ 3 000	€ 3 000 000	30	30	30	30
Q43EPS	Emergency power supply	2	items	€ 105 000	€ 210 000	5	5	20	20
Q43RC	Remote control	1	items	€ 100 000	€ 100 000	5	5	20	20
Q880102	Building two level for operation (excl. pile foundation)	100	m2	€ 1 140	€ 114 000	20	20	20	20
eigen invoer	Miscellaneous	1	item	€ 142 430	€ 142 430	-	-	20	20
eigen invoer	-				€ -				
eigen invoer					€ -				
eigen invoer					€ -				
	total Surge barrier (width=40m)			€ 24 400 000					
	allowances for forseen further detail of work	10%	pct	€ 24 400 000	€ 2 440 000	50	50		
	total of direct costs				€ 26 840 000				
	Mob/demob	5%	pct	€ 26 840 000.0	€ 1 342 000	50	50		
	Transports + Site costs + Staff	10%	pct	€ 26 840 000.0	€ 2 684 000	50	50		

J.3 Cost of upgrading an entire levee ring

Based on cost estimates for 1 km of levee and cost estimates for structures required, for each of the levee rings in New Orleans (and Plaquemines) cost estimates were derived for upgrading an entire levee ring. The levee rings used for planning purposes are New Orleans North, New Orleans East, New Orleans South and Plaquemines.

Table 25 provides an example of such calculation for just a single levee ring, in this case Levee Ring New Orleans South for the Autonomous Development case in which marshes further deteriorate. The table specifies the length of the various levee stretches. The cost calculation assumes a fixed cost of in this case €400 million for water management items including costs for new pumping stations, related drainage canals and sluices. The example also shows that the cost of raising levees along the Mississippi River are included in the overall costs. Note that also costs are included for small return periods that is in the same order of magnitude of the existing situation (about 1:100). This is because the basis levee design maintained in the current project assumes that levees are covered with an asphalt layer in order to safely deal with overtopping waves and maybe also overflow, which is not the case for the existing levees.

The table can also be used to get an impression of the order of magnitude of the cost per kilometer of new levees and upgrading levees. For example, that table shows that for a 1/1,000 design, 1 km of new alignment for a levee on the East side of New Orleans, the cost amount to €67.2 million, which is equivalent to close to $145 million per mile. These are all-in owner costs.

Table 25 Example of the cost calculation for Levee Ring 3 in New Orleans (West bank), for various return periods, for the Autonomous Development case in which marshes further deteriorate (all costs in million euro)

Return Period in years	***50***	***100***	***500***	***1,000***	***10,000***	***100,000***	***1,000,000***
East Alignment							
New Alignment (28 km)	51.4	54.5	64	67.2	*80.8*	95.3	110.6
Subtotal	€ 1,439	€ 1,526	€ 1,792	€ 1,882	€ 2,262	€ 2,668	€ 3,097
West Alignment							
Upgrade existing levees (30 km)	16.9	18.8	24.8	26.9	*35.6*	47.6	55.3
New Alignment (30 km)	23.3	25.6	33	35.6	*46.4*	61.2	70.8
Floodgate ICW (2)	90.0	90.0	90.0	90.0	*90.0*	90.0	90.0
Subtota	€ 1,386	€ 1,512	€ 1,914	€ 2,052	*€ 2,640*	€ 3,444	€ 3,963
Additional Works							
Water Management							
Subtota	€ 400	€ 400	€ 400	€ 400	*€ 400*	€ 400	€ 400
***Mississippi Levees** (86 km)*	0.0	0.0	4.0	7.0	*14.0*	22.0	31.0
Subtota	€ 0	€ 0	€ 344	€ 602	*€ 1,204*	€ 1,892	€ 2,666
Total	**€ 3,225**	**€ 3,438**	**€ 4,450**	**€ 4,936**	**€ 6,506**	**€ 8,404**	**€ 10,126**

J.4 Costs of measures for a closed system

To further illustrate the cost calculation, Table 26 presents the cost calculation for measures to provide a closed defense system for the Pontchartrain and Barataria Basins. For the Pontchartrain Basin, two alternatives are taken into account: an alignment along the C90 highway (on the land bridge) and an alignment along the I10 interstate, which over a considerable length would ask for a dam in Lake Pontchartrain. Although following different routes, both alignments are similar in length. The costs of levee construction are a significant part of the overall barrier scheme as the closures need to be constructed over a considerable length. The choice we made for this strategy is to construct overtopping levees; e.g. high enough to prevent massive overflowing but resistant to wave overtopping.

Table 26 Cost of measures for closed system in the Pontchartrain and Barataria Basins (all costs in million euro)

PONTCHARTRAIN				
PontLB2	Gated levee barrier along Interstate 10			
		Unit	**Unit Price**	**Costs in million euro**
Dam 27 ft water	18	km	33.9	**€ 610**
Dam 27 ft land	18	km	25.1	**€ 452**
Gate structure	1,500	m	0.7	**€ 1,050**
Navigational gate	1		60.0	**€ 60**
Total				**€ 2,172**
PontLA2	Gated levee barrier along C90			
		Unit	**Unit Price**	**Costs in million euro**
Dam 27 ft	36	km	25.1	**€ 605**
Gate Rigolette	1,300	m	0.7	**€ 910**
Gate Chef Menteur	200	m	0.8	**€ 160**
Navigational gate	1		60	**€ 60**
Total				**€ 2,034**
BARATARIA				
BARL	Gated levee barrier along Intracoastal Waterway			
		Unit	**Unit Price**	**Costs in million euro**
Dam 27 ft	53	km	30.5	**€ 1,617**
Gate structures	1,000	m	0.7	**€ 700**
Navigational gates	2		60	**€ 120**
Total				**€ 2,437**

J.5 Costs of possible strategies

This section provides an overview of the costs of possible strategies. Table 27 thru Table 32 specify the costs for the Autonomous Development case and Strategies 1 thru 5, respectively. Table 33 presents the costs for the Preferred Strategy. The cost estimates for all strategies and the Autonomous Development case all assume a flood protection level for the three levee rings in the metropolitan area of New Orleans of 1 in 1,000.

The tables divide the total costs over the various (groups of) measures included in the strategies. Where relevant, the tables also specify the number of culverts and diversion, and the number of square kilometers in the various marshland stabilization and marshland creation measures.

The total costs is expressed as Net Present Value. The tables also present a split of the total costs over one-time investments for structures and wetland creation and annual costs for wetland stabilization. This assumes that all structures and wetland creation can indeed be considered as one-time investments, and annual maintenance costs for these measures are ignored. Marshland stabilization it considered as an effort that is maintained for 50 years with annually a limited budget. This is of course a rough distinction between one-time investments and annual costs, but is considered acceptable for use in comparing possible strategies.

Table 27 Costs of measures for the **Autonomous Development case** (flood protection level 1 in 1,000) with a distinction between one-time investments for structures and wetland creation and annual costs for wetland stabilization.

	Cost in million $	***Cost in million €***
Protected City measures	$15,120	*€ 11,200*
Ring levees Plaquemines	$1,485	*€ 1,100*
Total (Net Present Value)	**$16,605**	*€ 12,300*
One-time investments for structures and wetland creation	$16,605	*€ 12,300*
Annual cost for wetland stabilization	$0	*€ 0*

Table 28 Costs of measures for **Strategy 1**: Open defense system with marshland stabilization (flood protection level 1 in 1,000) with a distinction between one-time investments for structures and wetland creation and annual costs for wetland stabilization.

	Cost in million $	***Cost in million €***	**remarks**
Protected City measures	$11,475	*€ 8,500*	
Ring levees Plaquemines	$1,485	*€ 1,100*	
Culverts in existing Barataria interstate + railway	$68	*€ 50*	5 culverts
Fresh Water Diversions	$203	*€ 150*	3 diversions
Marshland Stabilization Pontchartrain	$3,402	*€ 2,520*	1,800 km^2
Marshland Stabilization Barataria	$2,835	*€ 2,100*	1,500 km^2
Total (Net Present Value)	**$19,467**	*€ 14,420*	
One-time investments for structures and wetland creation	$13,231	*€ 9,800*	
Annual cost for wetland stabilization	$312	*€ 231*	

Table 29 Costs of measures for **Strategy 2**: Open defense system with marshland stabilization and marshland creation (flood protection level 1 in 1,000) with a distinction between one-time investments for structures and wetland creation and annual costs for wetland stabilization.

	Cost in million $	***Cost in million €***	**remarks**
Protected City measures	$8,640	*€ 6,400*	
Ring levees Plaquemines	$1,485	*€ 1,100*	
Culverts in existing Barataria interstate + railway	$68	*€ 50*	5 culverts
Fresh Water Diversions	$203	*€ 150*	3 diversions
Marshland Stabilization Pontchartrain	$3,402	*€ 2,520*	1,800 km^2
Marshland Stabilization Barataria	$2,835	*€ 2,100*	1,500 km^2
Marshland Creation Pontchartrain	$ 810	*€ 600*	200 km^2
Marshland Creation Baratari	$ 608	*€ 450*	150 km^2
Total (Net Present Value)	**$18,050**	*€ 13,370*	
One-time investments for structures and wetland creation	$11,814	*€ 8,750*	
Annual cost for wetland stabilization	$312	*€ 231*	

Table 30 Costs of measures for **Strategy 3**: Open defense system with marshland stabilization and measure to minimize sediment loss (flood protection level 1 in 1,000) with a distinction between one-time investments for structures and wetland creation and annual costs for wetland stabilization.

	Cost in million $	***Cost in million €***	**remarks**
Protected City measures	$11,475	*€ 8,500*	
Ring levees Plaquemines	$1,485	*€ 1,100*	
Culverts in existing Barataria interstate + railway	$68	*€ 50*	5 culverts
Fresh Water Diversions	$203	*€ 150*	3 diversions
Marshland Stabilization Pontchartrain	$3,402	*€ 2,520*	1,800 km^2
Marshland Stabilization Barataria	$2,835	*€ 2,100*	1,500 km^2
Opening river bank for crevasse building	$68	*€ 50*	
Total (Net Present Value)	**$19,535**	*€ 14,420*	
One-time investments for structures and wetland creation	$13,298	*€ 9,800*	
Annual cost for wetland stabilization	$312	*€ 231*	

Table 31 Costs of measures for **Strategy 4**: Semi-open defense system with marshland stabilization and surge reduction measures (flood protection level 1 in 1,000) with a distinction between one-time investments for structures and wetland creation and annual costs for wetland stabilization.

	Cost in million $	***Cost in million €***	**remarks**
Protected City measures	$10,530	*€ 7,800*	
Ring levees Plaquemines	$1,485	*€ 1,100*	
Culverts in existing Barataria interstate + railway	$68	*€ 50*	5 culverts
Fresh Water Diversions	$203	*€ 150*	3 diversions
Marshland Stabilization Pontchartrain	$3,402	*€ 2,520*	1,800 km^2
Marshland Stabilization Barataria	$2,835	*€ 2,100*	1,500 km^2
Surge Reduction Levee Pontchartrain	$945	*€ 700*	
Surge Reduction Levee Barataria	$1,350	*€ 1,000*	

	Cost in million $	*Cost in million €*	remarks
Total (Net Present Value)	**$20,817**	*€ 15,420*	
One-time investments for structures and wetland creation	$14,580	*€ 10,800*	
Annual cost for wetland stabilization	$312	*€ 231*	

Table 32 Costs of measures for **Strategy 5**: Closed defense system with marshland stabilization (flood protection level 1 in 1,000) with a distinction between one-time investments for structures and wetland creation and annual costs for wetland stabilization.

	Cost in million $	*Cost in million €*	remarks
Protected City measures	$ 9,585	*€ 7,100*	
Ring levees Plaquemines	$1,485	*€ 1,100*	
Culverts in existing Barataria interstate + railway	$68	*€ 50*	5 culverts
Fresh Water Diversions	$203	*€ 150*	3 diversions
Marshland Stabilization Pontchartrain	$3,402	*€ 2,520*	1,800 km^2
Marshland Stabilization Barataria	$2,835	*€ 2,100*	1,500 km^2
Gated Levee Barrier Pontchartrain	$2,932	*€ 2,172*	
Gated Levee Barrier Barrataria	$2,746	*€ 2,034*	
Total (Net Present Value)	**$23,255**	*€ 17,226*	
One-time investments for structures and wetland creation	$17,018	*€ 12,606*	
Annual cost for wetland stabilization	$312	*€ 231*	

Table 33 Costs of measures for the **Preferred Strategy** (flood protection level 1 in 1,000) with a distinction between one-time investments for structures and wetland creation and annual costs for wetland stabilization.

	Cost in million $	*Cost in million €*	remarks
Protected City measures	$9,585	*€ 7,100*	
Ring levees Plaquemines	$1,485	*€ 1,100*	
Culverts in existing Barataria interstate + railway	$68	*€ 50*	5 culverts
Fresh Water Diversions	$203	*€ 150*	3 diversions
Marshland Stabilization Pontchartrain	$3,591	*€ 2,660*	1,900 km^2
Marshland Stabilization Barataria	$2,835	*€ 2,100*	1,500 km^2
Marshland Creation Pontchartrain	$810	*€ 600*	200 km^2
Marshland Creation Baratari	$608	*€ 450*	150 km^2
Marshland Creation Landbridge	$675	*€500*	
Total (Net Present Value)	**$19,860**	***€ 14,710***	
One-time investments for structures and wetland creation	$13,434	*€ 9,950*	
Annual cost for wetland stabilization	$321	*€ 238*	

Cost comparison between possible strategies

Table 34 allows a comparison between possible strategies of total costs, one-time investments for structures plus wetland creation, and annual costs for wetland stabilization. The Autonomous Development case has the lowest total cost (expressed in Net Present Value). This is not surprising, because this case assumes that no landscape stabilization measures are taken. The total costs of all strategies is roughly similar with $19 to $23 billion. The rough split between one-time investments for structures plus wetland creation and annual costs for wetland stabilization leads to the observation that the one-time investments for the Autonomous Development case are *higher* than these costs for the strategies. This is explained by noting that in the Autonomous Development case the levee system needs to be higher (and hence more expensive) than in the strategies that include wetland stabilization measures to offer the same flood protection level. The costs for stabilizing the wetlands leads to a reduction in costs for the levee system.

Table 34 Comparison between possible strategies of total costs, one-time investments for structures plus wetland creation and annual costs for wetland stabilization.

strategy	total costs (Net Present Value)	one-time investments for structures and wetland creation	annual cost for wetland stabilization
	(billion $)	(billion $)	(million $ / year)
Autonomous Development case	$16.6	$16.6	$0
Strategy 1: Open system; marshland stabilization	$19.5	$13.2	$312
Strategy 2: Open system; marshland stabilization and marshland creation	$18.1	$11.8	$312
Strategy 3: Open system; marshland stabilization and measure to minimize sediment loss	$19.5	$13.3	$312
Strategy 4: Semi-open system; marshland stabilization and surge reduction measures	$20.8	$14.6	$312
Strategy 5: Closed system; marshland stabilization	$23.3	$17.0	$312
Preferred Strategy	$19.9	$13.4	$321

The costs presented in Table 34 are realistic estimates to compare alternative strategies. As explained in the section J1 of this appendix, cost estimates are based on unit prices for materials and percentages for overheads, management and design. The unit prices for construction materials like concrete and steel are based on current (2007) US market prices. However, the cost for levee construction, marshland stabilization and marshland creation are based on efficient mining of nearby sources of (fine) sand and clays rather than on importing these resources from far away upstream borrow areas. A typical (Dutch) price for dredging and delivering of sediment from nearby sources is at about 4-6 US$ per cubic meter. The project team was informed that current market prices for sand in New Orleans are in the 15 US$ per cubic meter and higher range. The project team's cost estimates as compared to USACE must therefore be considered to be in the lower part of the range, meaning that the "actual" costs for a strategy could be 30-40% higher as indicated in Table 34. Considering the various strategies, adequate resource management and smart dredging could potentially safe billions of dollars. Rather design the work according available resources than relying on the importation of materials from upstream.

J.6 Consideration of the Lake Pontchartrain Barrier Plan

The option to develop de Lake Pontchartrain Barrier Plan should be compared with the alternative option to (further) raise the levees on the North side of the city of New Orleans along Lake Pontchartrain. Both alternatives, of course, aim at a similar protection level for the city, i.e. a safety level of 1/1,000 per year or better (see Appendix E), but characteristics differ.

When considering the costs of these alternatives, the following points need to be taken into consideration:

1. In case a barrier would be constructed, the existing Lake Front levees need still require upgrading to provide a better protection in the 1/1,000 to 1/5,000 range. These costs are estimated in the current study at around € 700 million.
2. Without a barrier, the costs of upgrading the Lake Front levees are obviously higher and amount to € 1,400 million.

Based on the current cost estimates, constructing a barrier would therefore save around € 700 million in Lake Front Levee costs. This conclusion, however, may change as a result of a more detailed study of the costs of raising the Lake Front Levee. It may be the case that the intensive land-use immediately adjacent to the existing levee and sometimes on both sides of the levee, will lead to higher costs than estimated in the current project.

The cost of the Lake Pontchartrain Barrier (gates and 27 ft dam) is estimated at about € 2 billion. Perhaps these costs could be reduced to around € 1.5 billion by reducing the height of the dam to say 10 feet allowing a certain amount of overflow. But the barrier option still would be far more expensive then upgrading the existing levees as shown in the table below

	no barrier	**with barrier 27 ft**	**with barrier 10 ft**
Upgrade Lake Front levees	€ 1,400 million	€ 700 million	€ 900 million
Barrier Plan	€ 0 million	€ 2,000 million	€ 1,500 million
Total Costs	**€ 1,400 million**	**€ 2,700** million	**€ 2,400** million

Obviously not only the costs of measures need to be taken into account when considering a choice between the alternative to develop the Barrier Plan or, alternatively, (further) raise the levees along the Lake Front. Other considerations include:

- **Flood protection for New Orleans.** The Lake Pontchartrain barrier would provide additional redundancy to the hurricane protection system (an extra line of defense), but this could possibly also be achieved with more simple means to strengthen the land bridge as a surge reduction feature.

- **Safety for the Lake Pontchartrain shore line.** The barrier provides hurricane protection for the larger area bordering Lake Pontchartrain including the shore of Slidell and Mandeville. These additional benefits are not included in the current analyses but could potentially change the overall feasibility of the Barrier Plan.
- **Impact of the barrier on surge levels outside the barrier.** In case the barrier is constructed and closed during a hurricane, it can be expected that hurricane surge levels will increase on the Gulf-side of the barrier, including part of the coastline of the State of Mississippi. This effect should be addressed as a negative impact of barrier construction. To quantify this effect, hydrodynamic calculations with a large number of hurricanes is required, each with different characteristics. Such analysis is unfortunately outside the scope of the current project. Hence, the project team is not able to weigh this aspect in an overall assessment of the feasibility of the barrier plan.
- **Speed of Construction.** In the Netherlands, the speed of construction of barriers was one of the strong arguments in favor of constructing barrier rather than upgrade existing levees. For example, barrier construction in the Eastern Scheldt was confined to a relatively “small” area at the mouth of the estuary, while existing levee alignment bordering the estuary stretched more than 200 kilometer. The Lake Pontchartrain Barrier still requires extensive levee construction (36 kilometers) on a small land bridge while saving on upgrading around 40 kilometer Lake Front levee. Regarding the speed of construction, the barrier plan does not seem to offer a major advantage when compared to the levee plan.
- **Water management.** A final point of consideration is that the barrier plan might offer advantages for water management when compared to the levee plan. Special reference is made to salinity control of Lake Pontchartrain. By manipulating the barrier also during normal weather conditions, the barrier could be used to better control salinity levels in the lake. It should be noted, however, that decommissioning and closing of the Mississippi River Gulf Outlet (MRGO) might take away any salinity issued on Lake Pontchartrain altogether.

All in all, the project team is not able to fully address the various aspects of the Barrier Plan versus the Levee Plan in the framework of the current project. Especially (1) the lack of information on possible flood damage in the area North of Lake Pontchartrain, (2) the effect of the barrier on surge levels along other parts of the Gulf coast (State of Mississippi), and (3) the lack of a reliable cost estimate for upgrading the existing lake front levee in New Orleans make a clear conclusion impossible at this stage. Especially the relatively simple hydrodynamic analysis carried out in the current project limits the level of detail of the study. Further study on this issue is highly recommended.

K Management and Maintenance

The Dutch perspective on LACPR is not confined to nature and technology. Management and maintenance of the present and future situation is essential for the performance of any coastal restoration and/or hurricane protection scheme.

K.1 Concepts of management and maintenance

Management considerations

Existing flood protection schemes must be maintained by management and maintenance. Improvement of structures or the entire scheme is needed if they show weaknesses or if they do not meet the (changed) functional requirements. Given the changing conditions, management and maintenance require monitoring: monitoring of natural conditions, but also monitoring of the surroundings or society is necessary.

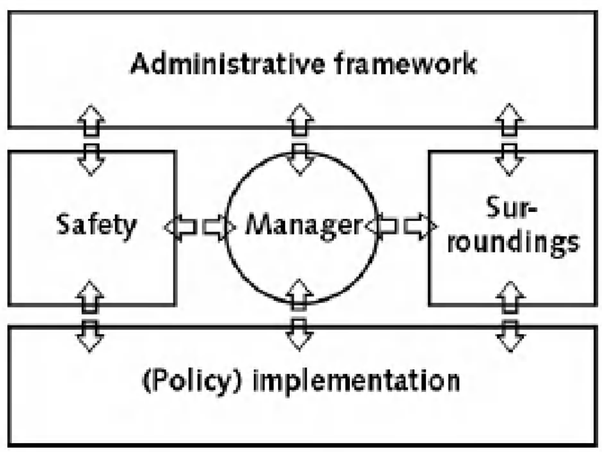

Figure 137 Managing flood protection schemes

New policies must be developed and implemented. And last but not least, the flood protection manager acts within an administrative framework.

Large infrastructural schemes such as flood protection schemes generally fulfill a number of functions. The main goal of management and maintenance is to ensure that the scheme performs to the required standards. This is called "functional quality". Not meeting these standards leads to (functional) failure. This type of failure needs to be distinguished from structural failure, which happens if the scheme loses its structural integrity. In general, management and maintenance is defined as the grand total of activities aimed at keeping the scheme at the required level of functional quality. In most cases this is a tougher demand than the structural integrity. Management and maintenance requires inspection, repairs, replacements and upgrade to ensure a longer lasting service time of the scheme.

Furthermore, it is vital to include future management and maintenance in the design philosophy of the scheme.

Design philosophy and risk-analysis

The design philosophy of flood protection measures is generally aimed at providing a certain predefined flood protection level. However this level of protection can be expressed in many ways and, to make things even more complicated, various design techniques can be applied.

For example, the required protection level offered by any flood protection measure can be defined in a number of ways, using:

- Natural events, such as "providing sufficient protection against a Category 5 hurricane" or "being able to withstand the maximum recorded water level".
- Statistical terms in combination with natural events, such as the "100-year flood" or the "1,000 years hydraulic load".
- Consequences, such as "the flooded area is limited to …. area" or "the number of casualties is limited to ….".
- Statistical terms in combination with consequences, such as "the yearly probability of damages exceeding …. is limited to …." or "the yearly probability of a number of casualties exceeding …. is limited to ….".

Dealing with natural hazards means dealing with uncertainties and probabilities. It is therefore inevitable that statistical terms and probabilistic design techniques are used to design flood protection measures. In order to assess whether a technical system, such as flood protection measures, meets the required standards, risk analysis can be applied.

The risk part of risk analysis incorporates the probability of various events and the consequences of these events. Generally speaking, risk is the product of probability and consequences. Any risk analysis is aimed at quantifying both factors. Uncertainties are generally included in assessing the probability of an event.

Such a risk analysis may focus on various items:

- Analysis of the technical system and its components;
- Probabilities and uncertainties of loads and strengths of the system and its components;
- Balancing the cost of an improved system and the expected damages of failure;
- Optimization of the system;
- Prioritization of measures to improve the overall performance of the system.

In any risk analysis it is important to discern the ultimate limit state (ULS – loosing structural integrity) and the serviceability limit state (SLS – loosing functional performance). If the risk analysis includes the consequences of any natural hazard this distinction will take place automatically. If a less complex risk analysis is performed, this distinction must be carefully preserved.

Assessing the protection level of any flood protection scheme starts with the system as a whole. This system is constructed using a (large) number of components, each with its own threats, loads, failure modes and so on. A fault tree or an event tree (Figure 138) can be used to illustrate this behavior of the flood protection scheme.

Preparing an event or fault tree requires a lot of craftsmanship and knowledge about the behavior of the flood protection scheme. The technique of preparing an event or fault tree is largely a supporting technique for the designer. The designer remains responsible for the description and likelihood of the various failure modes. Literature studies, empirical data, interviews and so on may prove to be helpful to quantify the various events or failures.

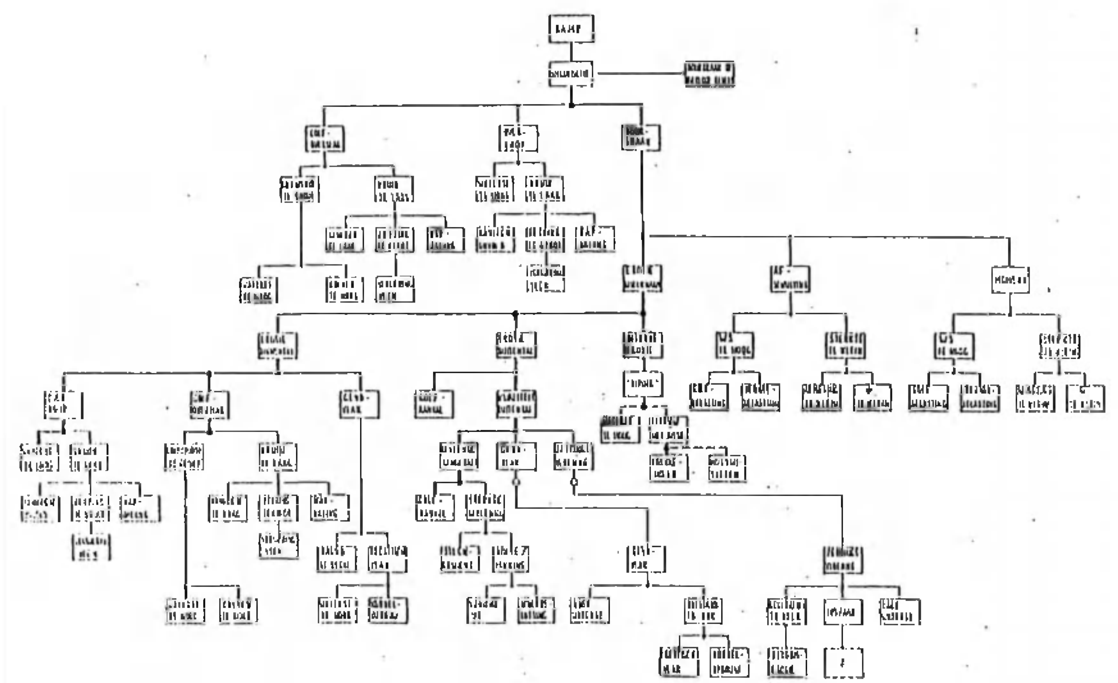

Figure 138 Example of an event tree

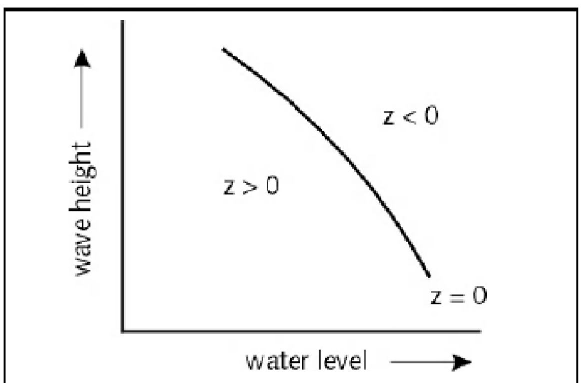

Figure 139 Reliability function (this example is for two stochastic functions only)

To derive a probability of failure two methods can be applied. The first method is using experience or intuition by estimating the probability of failure. The second method is to perform a probabilistic calculation. This second method requires a model to describe the behavior of the scheme or component. Based on this behavior a so-called reliability function is derived. The probability of failure equals P(Z<0). Such a reliability function is dependent on water level, crest level, slopes and so on. Most of these variables have a stochastic character.

For estimating the probability of failure, several techniques can be used:

- Level III: including the full probability density functions;
- Level II: a simplified method in which the probability density functions are replaced using normal distributions;
- Level I: a further simplified method using characteristic or design values for the various variables and (partial) safety factors. Strictly speaking this method does not yield a probability of failure but, depending on the application and the design philosophy, such a method can be applied very effectively.

Calculating the probability of failure of a flood protection system automatically leads to the question "How safe is safe enough? ". This question can be answered from at least two points of view:

- Individual risk, indicating the risk for an individual.
- Societal risk, indicating the risk for the society as a whole.

Each of these points of view will lead to its own conclusions.

Further information on design philosophy in general can be found in the Fundamentals on Water Defense laid down by the Dutch Technical Advisory Committee on Water defense (1998).

Changing conditions

Changing conditions will force the responsible authorities to evaluate and re-evaluate both the technical and functional state of the solutions. The changes arise from:

- Nature: sea level rise, climate change;
- Structural: settlement, structural degradation;
- Society: economics, population.

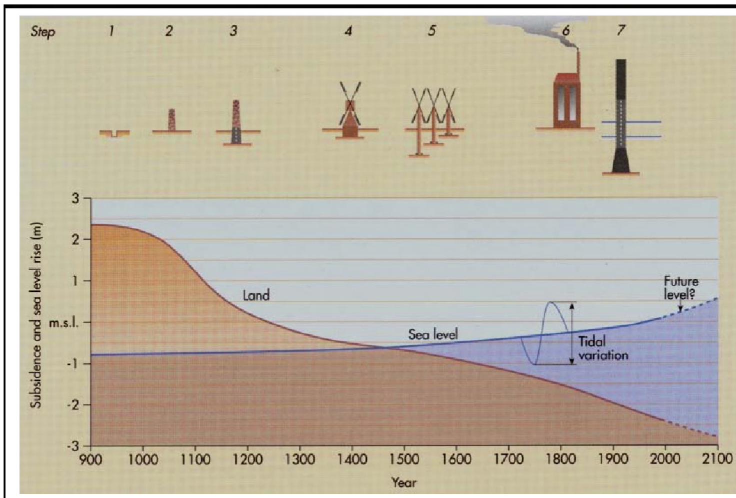

Figure 140 Sea level rise and settlement (over time)

The event or fault trees mentioned before share one common drawback: the probability of an event occurring or not leads to a rather binary approach. However in flood protection most of the mechanisms have a more continuous character. Most of the parameters determining both the probability of failure and the consequences of failure will vary in time.

Sea level rise will lead to an increased probability of failure, settlement of levees will lead to increased probability of failure and urban development will lead to increased damages in the case of a flood. This means that these developments which will take place over time will have to be addressed in the design philosophy. A lifetime approach in the design of a flood protection system is therefore necessary and this is where the relation between design and management & maintenance becomes clearly visible.

Strategy, tactics and operations

To describe this relation in more detail, it is essential to discern strategic, tactical and operational maintenance. Operational (day-to-day) and tactical (everything for the next 5-10 years) maintenance are both focused on the technical quality of the solution. Operational maintenance is not meant to combat changing conditions, except for the structural degradation. Tactical maintenance considers all changing conditions except for the societal conditions. Strategic maintenance is focused on the matter: how safe is safe enough, given the changes in society?

Further information on the distinction between strategic, tactical and operational maintenance can be found in Jorissen et al (1994).

Maintenance concepts

Maintenance concepts may vary depending on the properties of the solutions, the costs of maintenance, the predictability of failure, the consequences of failure and so on. In general two main classes of maintenance strategies can be discerned: corrective maintenance and preventive maintenance. Corrective maintenance means that the object will be repaired after failure. This strategy is applied if the consequences of failure of the object are relatively small. In hydraulic engineering this strategy is not applied very often because of the large consequences of failure. However, this assumption is not valid for all components of hydraulic infrastructure. Therefore, more and more components are maintained using the corrective maintenance strategy, which is in most cases extremely cost-effective.

Several preventive maintenance schemes are available. The most advanced and generally the most cost-effective option is based on the actual condition of the object. However this requires an accurate description of the behavior of the object (= deterioration model). Preventive maintenance always requires a form of inspection as well as repair. Costs of inspection have to be taken into account when deciding on a maintenance strategy. Other options are time-based and/or load-based. Time-based preventive maintenance is based on fixed intervals. These intervals may be based on experience or modeling. An intermediate form of preventive maintenance is load-based. According to this strategy, maintenance is carried out, for example, based on the number of passages through a shipping lock.

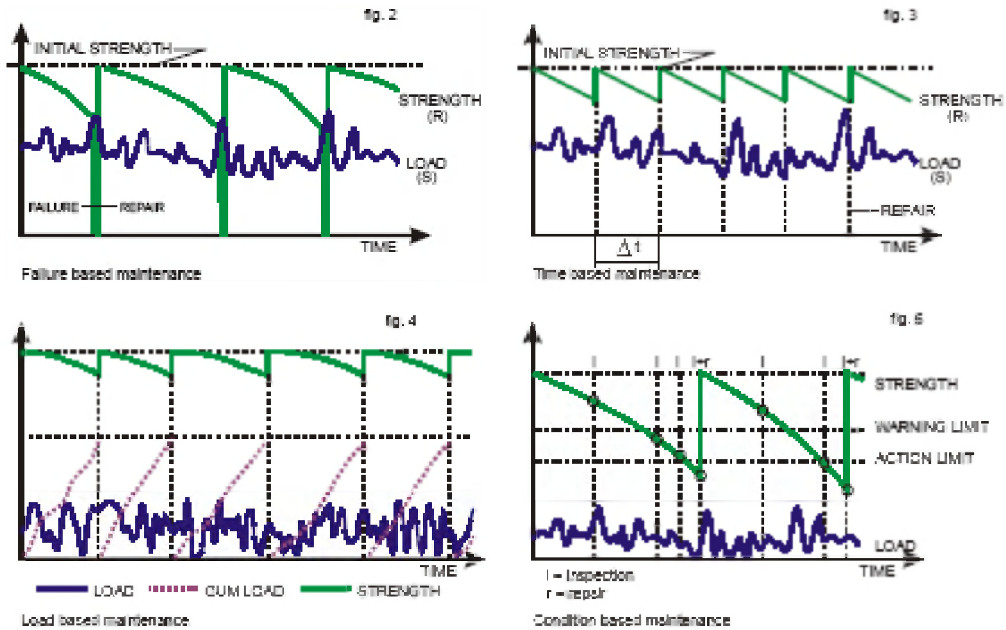

Figure 141 Maintenance concepts

Research and monitoring is aimed at improving the deterioration models and inspection techniques in order to apply the conditions-based preventive strategy to the vital components of the object as much as possible. If possible, corrective maintenance is preferred for the other components. These maintenance strategies are described further in the papers by Vrijling et al (1992) and Jorissen et al (1994).

K.2 Dutch perspective on management and maintenance

K.2.1 The present situation in The Netherlands

General

Figure 142 Flood prone areas in the Netherlands

Large parts of the Netherlands are threatened by floods, both coastal and riverine of origin. Obviously the North Sea poses a threat with storm surges entering this shallow sea from the Northwest. However also the major rivers Rhine and Meuse entering the Netherlands from the East and Southeast may cause flooding. About 60% of the population lives in flood-prone areas and around 70% of the Gross National Product (€450 billion in total) is earned in these areas. Throughout the centuries flooding and protection against flooding have always been major issues for spatial planning and urban development.

Not only in extreme situations do such floods impose a problem on the Dutch. Some parts of the Netherlands lie so low (up to 18 feet below MSL) that water management requires daily measures such as drainage, pumping, storage and discharging into the sea or rivers.

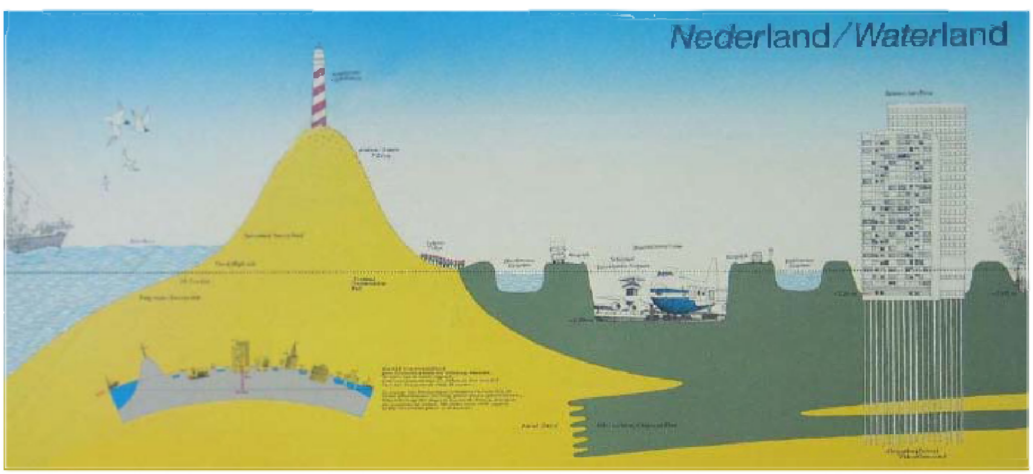

Figure 143 Cross-section

Figure 144 Primary flood protection structures

The flood-prone areas are protected by so-called primary flood protection structures such as levees, dunes, barriers and other type of structures (such as locks). The total length of these structures adds up to 3,558 kilometers (2,211 miles).

The total length of additional flood protection structures, largely meant for internal drainage purposes, adds up to a tenfold of this figure.

Flood protection

Looking back over the centuries its has always been the case that major steps in flood protection have been taken following a flooding disaster ("no policy beats a calamity"). Even in the 20th century it took the 1916 and 1953 floods before the present flood protection system could be realized.

Figure 145 Extent of the 1916 flooding

The flooding in 1916 of the so-called "Zuiderzee area", when even Amsterdam was flooded due to a storm surge on the North Sea, caused a 20-mile long dam to be constructed, which was completed in 1932. After that land reclamation works were carried out, including large polders such as the Wieringermeer, Noordoostpolder, and Flevoland.

The biggest disaster in recent history is the flooding in February 1953. Large parts of the Southwest of The Netherlands were flooded and 1,836 people died. In retrospect, this disaster led to a major step forwards. This step was the Delta plan, which was developed after the flood and had two main features: shortening of the coastline by closing off the estuaries and introducing flood protection standards for flood protection infrastructure.

Figure 146 Extent of the flooding in 1953

Closing off the estuaries meant building large dams and barriers, including the Eastern Scheldt and Maeslant barriers. Only the most Southern estuary, the Western Scheldt, remained open because of the harbor of Antwerp. The Delta plan shortened the Dutch coastline by more than 700 kilometers (434 miles).

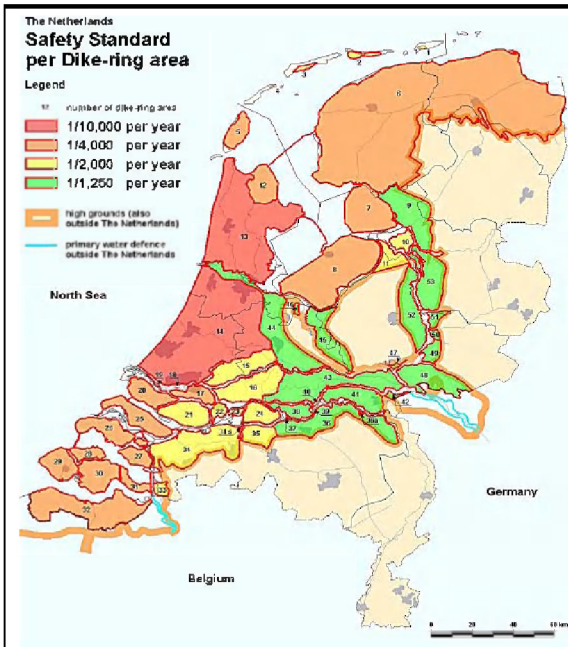

Figure 147 Flood protection standards for primary flood protection infrastructure

The flood protection standards were derived on an economic basis, essentially following the same method as applied in Appendix E of this report. The required flood protection level of the primary flood protection structures ranges from 1/10,000 per year to 1/1,250 per year. These figures stand for the inverse of the return period of the design hydraulic loads.

The 10,000-year return period is applicable for the areas with the highest economic values at stake and the most densely populated areas (which also includes most of the major cities such as Amsterdam, Rotterdam and The Hague).

Surroundings

Although floods have been dominant in the history of the Dutch, the acceptance of floods has changed significantly over the centuries. In the mind of the general public there is no such thing as an "inevitable flood". This is in sharp contrast compared to the situation in the 19^{th} century and before. Floods were considered to be "an act of God".

Another important development is the enormous increase in the consequences of floods. In the 19th century the flood plain of the major rivers was flooded fairly regularly.

There were even a number of relief structures designed to create floods in the lesser populated or lesser important areas to protect important cities further downstream when a flood happened. At present such a relief structure would create enormous damages due to the increased population and ongoing developments.

On the other hand, it has become more and more difficult to built and maintain large infrastructural elements in this densely populated country. Lack of space in the urban areas is a limiting factor in designing and constructing new levees. Also the historical, natural and cultural values of the existing infrastructure are increasingly considered to be worth saving.

The changed public perception of floods, the increased risks, the limited options for large-scale infrastructural measures and the increased appreciation of existing infrastructure are the key challenges for the present flood protection manager.

Policy

Figure 148 Main policy elements

The flood protection manager in the Netherlands however is helped by a clear policy. The main elements of these policies are:

- Spatial planning
- Coastal management
- River management
- Structural management
- Information and research
- Emergency management

For each element of this flood protection policy there are specific goals set:

- Spatial planning: "water proofing" urban developments;
- Coastal management: to maintain the coastline at the 1990 position and to compensate for sand-losses in the foreshore;
- River management: to develop and maintain a river bed able to discharge the design discharges (with a return period of 1,250 years) safely; this means that the water levels during these floods are equal to, or lower than, the 1996 design values;
- Structural management: to maintain and reconstruct flood protection structures in order to meet the legally-prescribed flood protection standard;
- Information and research: to research the relevant natural, technical and societal developments and to disseminate the results in a comprehensive set of national guidelines;

- Emergency management: to prepare emergency management plans and to have an emergency management organization standing by.

Traditionally, the elements of spatial planning and emergency management have always been the weakest links. Especially after 1953, when vigorous flood protection standards were introduced and structures were built to meet these standards, the general public and most of the administrative bodies too considered flooding risks to be insignificant. The focus on so-called preventive, structural measures (dams, barriers, levees and dunes) resulted in a neglect of non-structural measures.

However, worldwide catastrophic flooding events and some minor flooding events in the Netherlands have led to a change in this opinion. Nowadays the topics of spatial planning and emergency management are the priorities to improve the preparedness of all the administrative bodies involved. Obviously, this also requires a much greater awareness and commitment of the general public too.

With regard to spatial planning the municipalities are obliged to involve the water boards in the process of developing municipal zoning plans. This allows the water boards to address the water management or more specifically the flood protection issue at an early stage.

With regard to emergency planning the local and regional authorities (municipalities, water boards, and provinces) have been improving their preparedness over the last decade. However, this preparedness is mostly limited to potential regional flooding problems. Extreme floods, threatening the nation, have not been addressed in the context of emergency management. The focus was always on preventive measures. However, recently the Rijkswaterstaat has taken the initiative in dealing with flooding disasters on a national scale.

The flood protection policy is well embedded in a general water management policy. This policy is based on integrated water management. The Netherlands form an important part of the catchments of four main European rivers: the Rhine, Meuse, Scheldt and Ems. The Dutch water systems are a mixture of natural systems (rivers and sea) and human interventions (canalization, locks, levees, and barriers). About 60% of the land surface needs protection against flooding. An extensive system of primary flood defenses provides an excellent standard of protection against flooding from the rivers and sea. However, water systems provide other, essential functions, such as:

- Transport;
- Surface water and groundwater for agriculture and industry;
- Ecological values;
- Recreational use;
- Drinking water supply.

The main policy goal for water management is therefore:

To have and to preserve a safe and habitable country and to maintain and develop resilient water systems which allow a sustainable use.

Integrated water management is the key to accomplishing this ambitious goal. By managing the water system (water, bottom and banks) as a whole based on assigned functions the Ministry of Transport, Public Works and Water Management focuses on realizing reference situations in the national water systems. Agreements are made with regional and international partners to reach a similar approach for entire catchment areas.
In a functional approach the first step is to assign one or more functions to a water system. The number of possible functions can be very large; the Netherlands chose 13 functions. The most common or primary functions are printed in Italics. The national management plan includes a detailed list of assigned function for each water system.

Functions		
Flood protection	Fisheries	Hydropower
Discharge of water, ice and sediment	Bank recreation	Drinking water
Transport	Recreational fishing	Commercial fishing
Water quality and ecology	Cooling water	Sand and gravel mining
Recreation		

Administration

Delivering the flood protection policy is the responsibility of public authorities. Flood protection management involves a number of these authorities. In fact all types of administrative bodies (national, regional, and local) are involved. The national government (Ministry of Transport, Public Works and Water management unless stated otherwise) is responsible for:

- Setting the policy;
- Legislation;
- Issuing voluntary guidelines for design and mandatory guidelines for safety assessment;
- Financing the reinforcement of primary flood protection structures (due to new flood protection standards, to increased hydraulic loads associated with the protection standards and/or to new knowledge of failure mechanisms);
- Financing management and maintenance of the coast, rivers and large barriers;
- National crisis management (Ministry of the Interior);
- Management and maintenance of the coast, rivers and large barriers (Rijkswaterstaat).

The water boards are responsible for:

- Management and maintenance of the majority (90%) of the primary flood protection structures and all regional flood protection structures;
- Financing management and maintenance (local taxation).

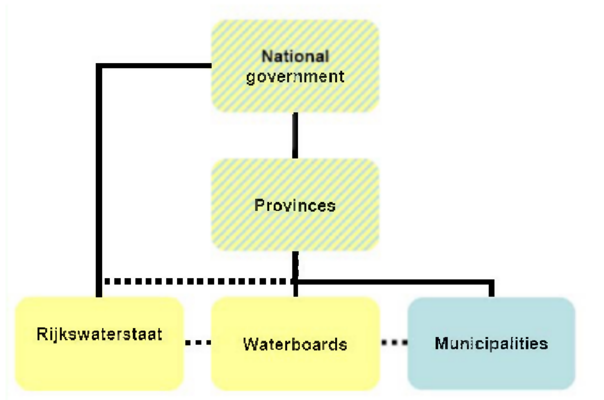

Figure 149 Administrative bodies involved in flood protection

The provinces supervise both water boards and municipalities on a regional level. The provinces are also responsible for spatial planning and regional crisis management. With respect to flood protection, the municipalities are responsible for local crisis management.

Water boards

Central government and the provincial and municipal authorities are familiar bodies and most people have some idea about what they do. The water board is less well known, which is only to be regretted, since water boards carry out essential tasks to keep the country habitable. The Netherlands cover about 34,000 square kilometres where land and water meet. A large proportion of the land is artificial. This originally water and wetland area has been reclaimed, drained and cultivated by people. It has become suitable for habitation, building, agriculture and horticulture, industry and recreation. The Dutch seem to take these activities for granted and seldom realize the potential risk of the low location of the country. More than 50% would be inundated if there were no dunes and dams to protect property and goods against storms at sea and high water in the rivers. The Dutch feel safe. The care for flood protection and water management is business-as-usual. However, without continuous operating and maintenance of the many levees, locks, pumping stations, flood barriers, canals and ditches, the safety of more than nine million people in the Netherlands would be at stake.

The water boards are largely responsible for the essential aspects of regional water management. Nowadays this goes a lot further than constructing levees and operating pumping stations. The activities of the water boards are now also related to licensing discharges, treatment of urban wastewater, conservation and restoration of water systems, guiding water use etc. Water boards are responsible for balancing the different interests in water management. This is done in co-operation with central government, provincial and municipal authorities and stakeholders. Water boards are public authorities. Unlike provinces and municipalities, water boards have limited, legally-defined tasks:

- Flood protection: maintenance of infrastructure (dunes, levees);
- Water management:
  - water quantity: drainage and irrigation, ensuring that it is kept at the appropriate levels;
  - water quality: combating water pollution and improving the quality of the surface water;
- Treatment of urban wastewater;

- (Sometimes) management of inland waterways and rural roads.

Stakeholders elect their own representatives in the water board assembly. Unlike general democracies where political representatives are elected, water boards can be characterized as "stakeholder democracies". Categories of stakeholders (residents, landowners, owners of property) choose their representatives in the assembly. Dutch water boards have their own financing structure. They raise taxes to carry out their tasks. Two basic taxes are distinguished:

- the water system tax (for flood protection and dry feet) and
- the water pollution levy (for wastewater treatment and water quality management).

Both taxes recover the costs of water boards. In this respect the boards are self supporting.

A remarkable solution for making use of external funds is the Netherlands Water Board Bank. This financial institution was created by water boards at a time when individual water boards were not eligible for loans from private banks. In 50 years of existence the Bank has evolved into a reputable bank.

The Dutch water boards are united at provincial level and at national level. In this way, they are able to communicate with their main counterparts. The organization at national level is called the Association of Water Boards. The Association is the counterpart of ministries, the parliament and international institutions.

Finally, it should be mentioned that the water boards have undergone an enormous merging in the past 50 years. The number of water boards has gone down from circa 2,500 in 1950 to 12 at the moment. This process of merging has three main reasons. Firstly, the flood of 1 February 1953, during which 1,836 people lost their lives and enormous financial damage was brought about. This disaster marked the end of many small water boards. Secondly, the handing over of water quality control, including waste water treatment, to the water boards from 1970 onwards. After all, the responsibility of building and managing costly sewage treatment plants calls for firm administrative and financial support. Thirdly, the government's policy of setting up integrated water management, which means that the various responsibilities, i.e. surface water and groundwater in both quantitative and qualitative terms, should be looked at in their mutual connection and, therefore, preferably brought together in one organization (the so-called "all in-water boards").

Financing

Generally speaking the required budget for flood protection in The Netherlands is raised by taxation. Taxation on a national level raises the budget for all reinforcement works and for management and maintenance of the coast, the river and a limited number of barriers and levees. Taxation on a local level is used to cover the costs of management and maintenance of the vast majority of levees (90% of the primary flood protection structures and all regional flood protection structures).

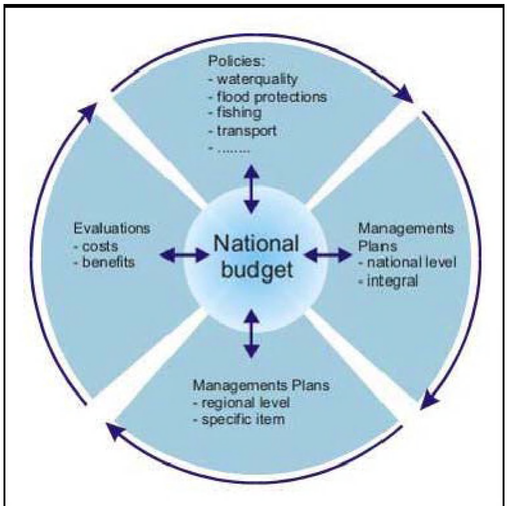

Figure 150 National water management plan

The national budget for water management in general and flood protection in particular is allocated based on national water management plans. These plans include both (re)construction and management & maintenance of infrastructure. In these plans the link between policy, measures, costs and benefits is described.

Distributing the available national budget requires prioritization. This process is always difficult, but is absolutely essential to maintain pressures such as cost awareness and cost effectiveness. In the Netherlands prioritization is carried out from three different viewpoints:

1) Political agreements (priority 1);
   a) Priority based on functions;
   b) Flood protection and discharge of water, sediment and ice;
   c) Transport using national water systems;
   d) Water quality and ecology;
   e) Transport using regional water systems;
   f) Other functions;
2) Priority based on type of measures (priorities 2 and 3):
   a) Fixed maintenance before variable maintenance;
   b) Projects under construction before new tenders.

This prioritization sequence within the national budget means that flood protection measures are indeed one of the key priorities in water management.
The budget of the water boards is raised by local taxation by the water boards. The water boards are allowed to raise taxes only for water management purposes. The provinces strictly supervise both the amount and destination of the taxation. Nevertheless, this local taxation is a very efficient and effective method. Taxes are raised for a very specific purpose from a very specific population. And to complete the circle: that population is directly represented on the water board based on their taxation volume (and therefore their level of interest).

Water board taxation (figures for 2004, in € per year)		
Charges based on property	Charge for undeveloped land	€60 per hectare (10,000 m^2)
	Charge for buildings	€39 per household
	Charge for residence	€39 per household
Water pollution charge (€50/unit)	Small business (1-3 units)	€50-150
	Business (< 1,000 units)	< €50,000 (based on accommodation)
	Business (> 1,000 units)	> €50,000 (based on water consumption)
	Household (3 units)	€150

Safety assessment

A separate legal instrument has been developed especially for the function of flood protection. Since 1996 the Flood Protection Act has described the flood protection standards and the safety assessment procedure attached to these standards.

In short:

- The national authority (ministry) issues guidelines to assess the quality of flood protection structures every five years;
- The guidelines contain the most recent information on hydraulic boundary conditions and technical criteria;
- The flood protection manager (water board and Rijkswaterstaat) make these safety assessments and report the results to the provinces;
- The provinces in their turn integrate the reports of the flood protection manager and report to the minister;
- Finally, the minister reports to both houses of parliament.

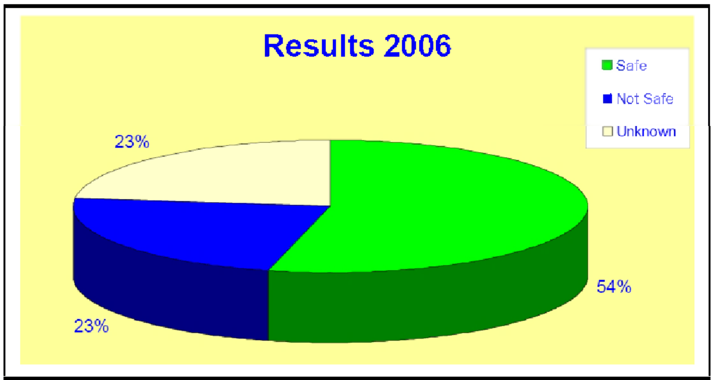

Figure 151 Result of safety assessment for 2006

The Flood Protection Act of 1996 enforces a safety assessment of all primary flood protection structures every 5 years. The results of the second national safety assessment still show a large fraction of uncertainty, largely due to insufficient information on in particular geotechnical aspects. The 23% that does not meet the standards are well-known stretches: coastal embankments (revetments) and geotechnical problems (dating from the reinforcement program without geotechnical research). The total of the required reinforcement program according to these results will add up to €1.6 billion.

Developments

Three developments will enhance the future flood and water management policy and practice in the Netherlands:

- Changes in flood protection philosophy;
- More attention for spatial planning and crisis management;
- International and especially European policies (and legislation).

Flood protection structures in the Netherlands have never been stronger: the probability of encountering floods has substantially declined since the last flooding in the Southwestern part of the Netherlands in 1953. However, the risks of casualties and of economic damage from flooding have become much greater since this event.

This controversial situation is the result of a growing discrepancy between the existing set of design standards for the height and strength of dams, levees, and coastal defenses set around 1960, and a steady social and economic development since that time. The average yearly economic expansion since 1960 has been twice as high as expected at that time and the population at risk in the Netherlands has more than doubled. In the period between 1960 and the present, the design standards have not been corrected for the increased economic value and population.

Compared to other risks, the societal risk of flooding (the probability of large numbers of casualties) in the Netherlands appears to be several orders of magnitude larger than the sum of the societal risk of other known external hazards (e.g. industrial hazards and plane crashes). A further increase in flood risk is expected both due to climate change (increased sea level rise and higher river peak discharges), and further economic and social development. To adapt the required flood protection level an update of the risk-based protection standards is essential. It is also essential to incorporate another type of flood protection measures in the equation: non-structural measures such as spatial planning and crisis management.

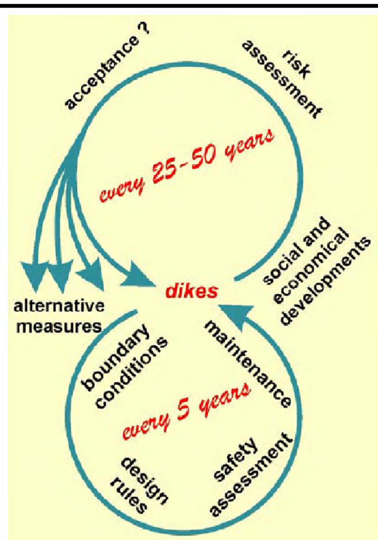

Figure 152 Safety and risk

In order to reduce the societal risk of flooding, strategies to reduce the probability and/or to reduce the number of fatal victims are appropriate. A further strengthening of levees would reduce the probability of a flood. However, one of the reasons for the increased societal risk is the growth of housing and infrastructure projects in low-lying areas. So far, potential strategies to guide housing and other spatial developments in order to avoid undue increase of risk have not been used in the Netherlands.

Policy requires a system of response mechanisms when floods occur. An evaluation of the present situation has given cause for concern: small-scale, unrealistic training opportunities, emergency plans showing shortcomings and poor cooperation in some cases between managers of flood defenses and disaster-response organizations.

Figure 153 Coastal sediment system

Another important development is the increased international dimension. National borders do not limit floods and any other natural event. Especially in river systems the need for harmonizing measures is important, since various countries share the same river causing the flood. However also in coastal systems, the natural system has to be the basis for analyzing and developing measures. The continuity of sediment transport along the North Sea shores is an excellent example.

Future weak coastal links

A number of locations on the Dutch seashore will fail to meet the protection standards in the near future. As a proactive action the Ministry of Transport, Public Works and Water Management asked the provinces to come up with solutions in which both the safety aspect and "enhancing the spatial quality" were addressed. The Ministry made a budget of €740 million available as the estimated amount needed for the flood protection measures of the reference design. The provinces initiated a project organization with all authorities participating. So far, the provinces have come up with a number of integrated plans. The main problem however has been to find the required additional funds. In urban areas, the larger local municipalities were able to contribute. However in the more rural areas, additional funds were harder to find. National budgets for recreation and/or nature development are potential options, but the difficulty for the provinces is to coordinate or to combine these budgets in the plans for the weak links. This process is still ongoing at the moment. Around the summer of 2007 the Ministry of Transport, Public Works and Water management will assess the provinces` plans based on the protection requirements and the additional (with respect to the €740 million) funding.

K.2.2 Present situation around the North Sea

Not only the Netherlands are threatened by coastal flooding in the North Sea area. Neighboring countries such as Belgium, Germany, Denmark and England all face to some extent the challenges from living on the sea shore.

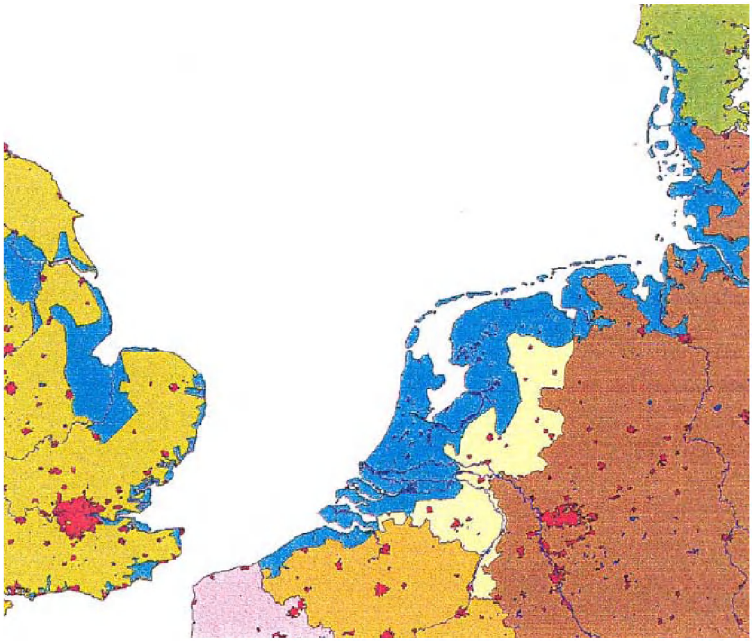

Figure 154 Coastal flooding around the North Sea

Rijkswaterstaat has participated in the COMRISK project (www.comrisk.hosted-by-kfki.baw.de). The objective of this project was to improve coastal flood risk management through the transfer and evaluation of knowledge and methods as well as pilot studies. One of the subprojects was specifically aimed at:

- Providing a comprehensive analytical framework as a tool to properly assess policies and strategies;
- Making an inventory of different levels (strategic, institutional, instrumental and operational) of coastal risk management in relation to the current national policies of the countries and regions in the North Sea Region involved in the COMRISK project;
- Making an assessment of current national policies in terms of legal, social, technical, financial, socio-economic, ecological and managerial aspects (including the Integrated Coastal Zone Management - ICZM - principles for sustainability).

It showed that a wide range of flood protection policies has been developed in the countries and regions depending not only on the scale of the potential flooding problem (ranging from 70% to less than 1% of area and/or of GNP). The legal, social, financial, socio-economic, ecological and managerial context is very decisive. This has resulted in various flood protection policies (criteria, standards, legislation, operation and management):

- UK: generally cost-benefit analysis (although indicative protection standards exist), permissive legislation, mix of centralized and de-centralized operation and management;
- Denmark: population at risk, technical standards, permissive legislation, centralized operation and management;

- Germany: technical standards, permissive legislation, centralized operation and management (at state level);
- Belgium: technical standards, permissive legislation, centralized operation and management (at the level of Flanders);
- The Netherlands: legal flood protection standards, prescriptive legislation, mix of centralized and de-centralized operation and management.

Country	Flood prone area (km^2 and %)	Capital at risk (€ billion)
England and Wales	2,200 (5%)	250
Denmark	< 1%	No data
Germany	3%	No data
Belgium	11,000 (18%)	No data
The Netherlands	25,000 (70%)	2,000

K.2.3 Present situation in New Orleans

General

The area of greater New Orleans is surrounded by water: the Mississippi River, the Gulf of Mexico, and large lakes such as Pontchartrain and Borgne. Combined with the low lying, densely populated areas, this leads to significant potential flooding risks. These risks are continuously growing because of sea level rise, settlement, urban development and coastal erosion. During Hurricane Katrina large areas of the New Orleans area were flooded.

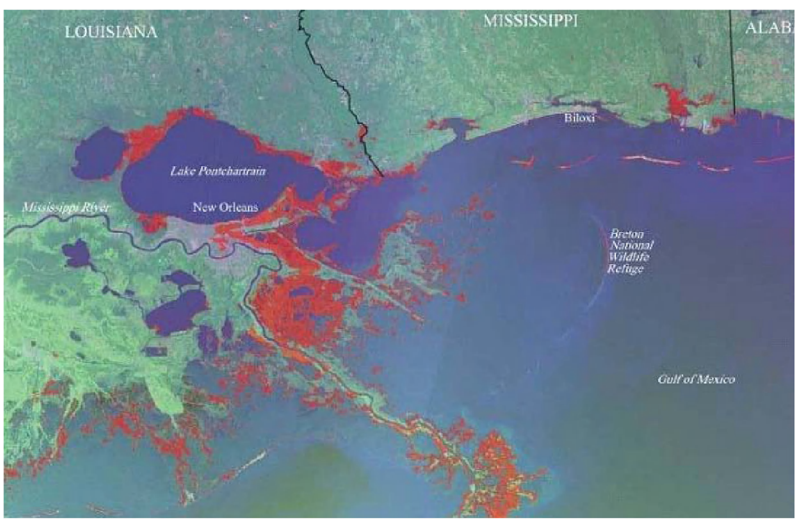

Figure 155 Flooding during Hurricane Katrina

During the flood more than one million state residents were displaced, over 1,400 people died, over 200,000 homes were damaged and approximately 200 square miles of marshes were destroyed.

Flood protection is provided by river levees and hurricane protection schemes. The internal drainage is provided by a large number of pumping stations.

Figure 156 Levees and pumping stations

The internal drainage is important because of the characteristics of the urban area of New Orleans: low lying areas with hardly any storage areas.

In order to prevent flooding during rainfall nearly all the rain has to be discharged into Lake Pontchartrain via three major outfall canals.

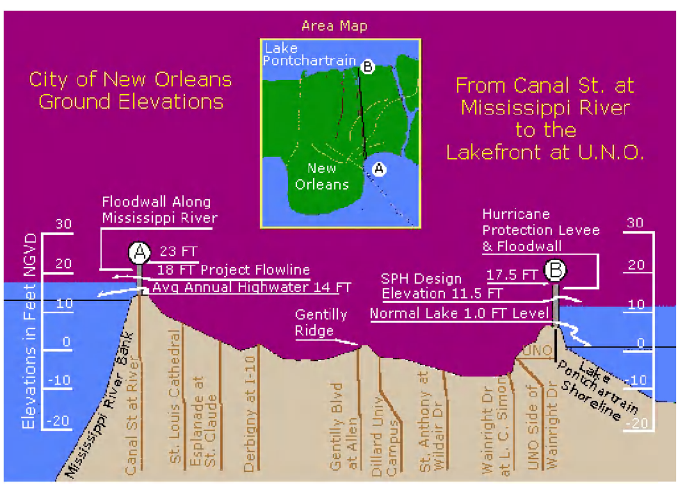

Figure 157 Cross-section

The flooding during Hurricane Katrina had two main causes: overtopping of earthen levees in the Eastern parts of the city and geotechnical failure of the flood wall (I-wall) in the centre of the city.

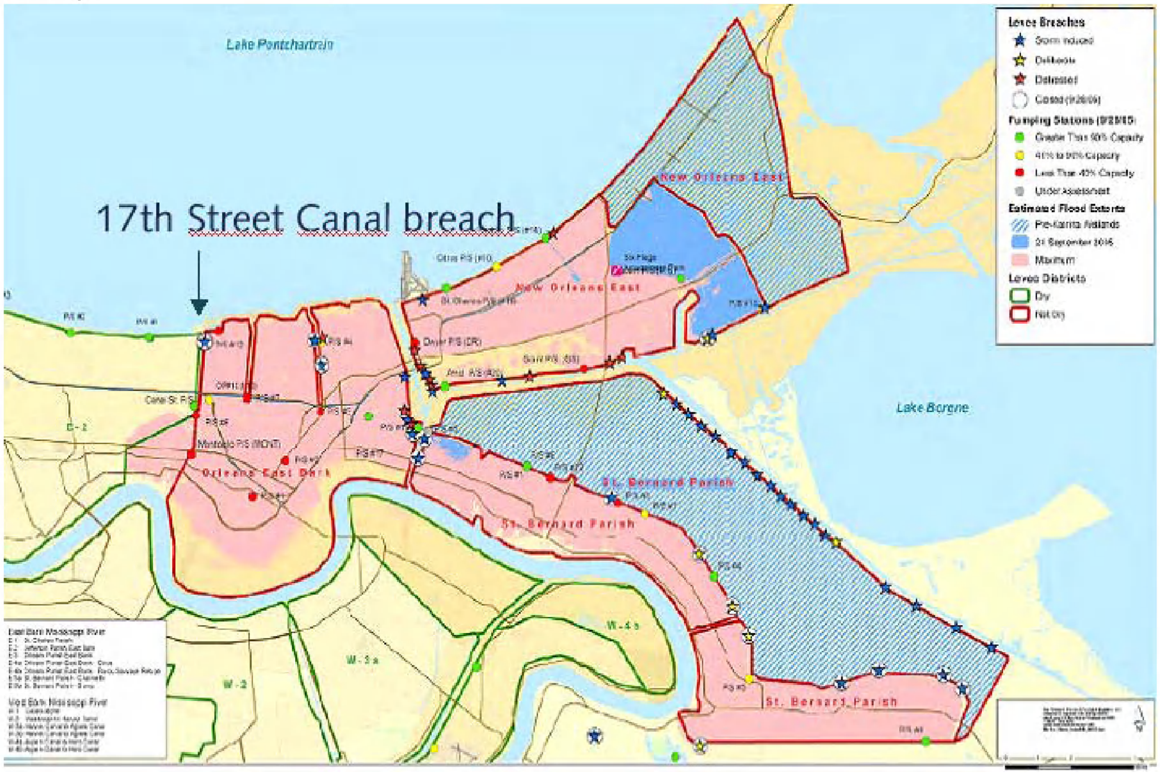

Figure 158 Map showing principal features of the main flood protection rings or "polders" in the New Orleans area and the various breaches that occurred during Hurricane Katrina (indicated by the blue stars). (Modified after USACE, 2005)

Policy

With regard to flood protection and coastal management, local government in the U.S. is responsible for land use and zoning decisions that direct floodplain and coastal development. However, numerous federal and state flood policies and programs influence local, and individual, decision-making. Federal government funds flood control structures and projects, manages a flood insurance program, provides disaster assistance and generates essential data through mapping and other efforts.

The federal role in flood control began in the late 19th century. Prompted by devastating floods in the Mississippi River basin, Congress created a commission to oversee the development of a levee system to control the river's flow. The Mississippi River flood of 1927 and floods in the mid-1930s led to federal flood control investment. The Flood Control Act of 1936 declared flood control to be a "proper" federal activity in the national interest. State and local governments are responsible for sharing (sponsoring) the construction cost of federally-funded flood control infrastructure and for its operation and maintenance. State and local entities may construct flood control infrastructure independently from the federal government, and are responsible for land use and zoning decisions guiding development in floodplains and coastal areas.

By the 1950s, it had become clear to Congress that the federal response to flood risk through structural flood controls and post-disaster assistance for flood victims was not good enough.
Pre-disaster funding via insurance began to look like an attractive alternative to flood control structures or disaster assistance. The National Flood Insurance Act of 1968 enabled the creation of the National Flood Insurance Program (NFIP). Coverage is available to all owners and occupants of insurable property in a participating community. Managing flood risk through insurance was expected to greatly reduce the reliance on federal disaster relief assistance because participating communities were expected to adopt and enforce building and other standards that could greatly reduce losses from a 100-year flood. However, the residual flood risk behind levees or downstream of dams remains largely unaccounted for in the NFIP and often is not incorporated into individual, local, and state decision-making.

A fundamental question being raised in the aftermath of Hurricanes Katrina and Rita is: do current federal policy, programs, and practices result in an acceptable level of aggregate risk for the nation? And if not, how can acceptable levels be reached? A similar development has taken place in many other countries. A good example is the United Kingdom (in particular: England and Wales). The flood protection policy in the late 20th century was very much based on local cost-benefit analysis. The national government only participated in protection schemes if the benefit-cost ratio was larger than 2. However, after a large series of riverine floods creating large-scale damage and disruption, a more national policy has been developed. This is not to the same extent as in the Netherlands with the legally prescribed flood protection standards following the catastrophic flood of 1953. In both countries, however, the debate on how to deal with low probability-high risk events is ongoing.

At the regional level of the State of Louisiana, coastal management increasingly became an issue over the last decades of the 20th century. Wetland loss in coastal Louisiana has reached catastrophic proportions, with current losses of 25-35 square miles per year. The disappearance of Louisiana's wetlands threatens the enormous productivity of its coastal ecosystems, the economic viability of its industries, and the safety of its residents. Coastal Louisiana is important to the local and national economies because of oil and gas production and its international seafood and recreation industries; in addition it is the number-one port complex in the nation. The infrastructure that supports these activities is interwoven with the unique ecosystem created by the Mississippi River in South Louisiana. Additionally, major flood control and river control civil works structures located in coastal Louisiana play an important role in providing for its habitation.

Increasing environmental awareness has led many to recognize the relationships of local and national development to losses being incurred by Louisiana's coastal wetlands and barrier shorelines. In 1998, the State of Louisiana and its Federal partners approved a coastal restoration plan entitled *Coast 2050: Toward a Sustainable Coastal Louisiana*. That document presented strategies jointly developed by Federal, State and local interests to address Louisiana's massive coastal land loss problem. For the first time, solutions were proposed to address fundamental ecosystem needs in order to prevent the loss of this natural treasure. By implementing this plan's regional ecosystem strategies, it is envisioned that a sustainable ecosystem will be restored in coastal Louisiana, in a large part by utilizing the same natural forces that initially built the landscape.

While the ultimate goal for coastal restoration under the Coast 2050 plan is to implement strategies throughout coastal Louisiana, the Barataria Basin is in dire need of immediate attention. On February 18, 2000, the USACE and Department of Natural Resources of the State of Louisiana (LADNR) signed a historic agreement to initiate large-scale action to restore this basin. The Barataria Basin has tremendous potential for restoration because of nearby sediment resources in coastal bays, the Mississippi River, and in Federal and State waters of the Gulf of Mexico. USACE and State initiated the Louisiana Coastal Area study, which will develop plans to submit to the United States Congress requesting authorization and construction funding for ecosystem restoration in the Barataria Basin under the Water Resources Development Act.

Administration and finance

The USACE (the civil works section, to be more precise) is responsible for delivering the national policy on navigation, flood control and coastal restoration. The involvement of USACE flood control construction is predicated on the project being in the *national interest*, which is determined by the likelihood of widespread and general benefits, a shortfall in the local ability to solve the water resources problem, the national savings achieved, and precedent and law. Over the last century, many of the communities most prone to riverine flooding have been protected by significant investments in flood control infrastructure. Many of the current questions and concerns revolve around the following topics:

- Whether the level of protection is sufficient if all consequences are considered (e.g., intensity and spread of urbanization, concentration of oil processing and distribution infrastructure);
- Whether flood threat and vulnerability have changed (e.g., as the result of increases in ocean temperature; coastal wetlands losses; and the reliability of aging levees and dams); and
- How sufficient is the hurricane and storm protection for the nation's coastal communities.

The USACE works within the (financial) framework provided by Congress. The evaluation and recommendation of a flood control project by USACE involves multiple steps. After an initial reconnaissance study that is funded by federal government, current policy is for the cost of the follow-on feasibility study to be split 50% federal - 50% non-federal; flood control and storm protection construction is generally split 65% federal - 35% non-federal. When Congress authorizes USACE to construct a project, the authorization is generally based on a report by the Chief of Engineers. In that report, it is typically recommended to build one of the alternative plans studied in the agency's feasibility report, consisting of an evaluation of alternative plans, benefit-cost analysis, engineering analyses, and environmental impact assessments. The benefit-cost analysis of a project may result in a recommended plan for flood control infrastructure providing for protection greater than or less than the 100-year flood. Local project sponsors can request that a "locally preferred alternative" be built, instead of the plan identified by the benefit-cost analysis. The NFIP creates incentives for communities to support flood control alternatives providing at least the 100-year level of protection, but the program provides few incentives for more protection.

For some local leaders and communities, the financial capital required to cost-share an USACE flood control project may represent a barrier to pursuing greater protection. The benefit-cost analysis focuses on the national economic developments and does not constitute a comprehensive risk analysis, because the consequences considered are largely limited to property damage, leaving out other potential consequences, such as loss of life, public health problems, and economic and social disruption. The Water Resources Development Act of 1986 (up for Congress now) requires USACE to address the prevention of loss of life in the formulation and evaluation of flood control projects. The Act will also authorize a number of coastal restoration and hurricane protection projects (such as the Barataria Bay).

To give an idea of this, the overall budget for the USACE (Civil Works) for the fiscal year 2008 is approximately $5 billion of which nearly 50% is to be spent on operations and maintenance.

The State of Louisiana has a number of authorities responsible for delivering the flood protection and coastal restoration policy:

- Department of Natural Resources (DNR);
- Department of Transport and Development (DoTD);
- Coastal Protection and Restoration Authority of Louisiana (CPRA).

Generally, the State finances its activities by taxation and general funds from federal government. However, the policy goals formulated on flood protection and coastal restoration require funds far beyond this level. The coordination of state and federal funds is therefore necessary.

On a local level the levee boards and the municipalities play a major role.

The levee boards have recently been consolidated. This process has led to two levee boards, one on each side on the river: the West bank and East bank. These levee boards are responsible for management and maintenance of the levees. The levee boards have two "chains of command". The general supervision of the levee boards is carried out by the State of Louisiana. From a technical perspective, the USACE conducts a yearly inspection of the state of the levees together with officials from the levee board. If necessary, this inspection may lead to an incident report by the USACE to the water boards. The ultimate consequences of such an incident report may be that the USACE does the required reinforcement works at the levee board's expense. The levee boards finance their activities by local taxation.

The municipalities (parishes) are responsible for managing the sewage system and internal drainage. The internal drainage largely depends on a large number of pumping stations taking the water out of the "bowl of metropolitan New Orleans". There is however one exception: the former levee board in St Bernard Parish was responsible for internal drainage and this responsibility has been transferred to the consolidated levee board (East).

Taskforce HOPE

Directly after the floods due to Hurricane Katrina and Rita a number of emergency operations started involving a number of taskforces. Taskforce Unwatering completed the draining of the city on October 11, 2005.

Taskforce Hope was/is aimed at:

- Repairing the damage flood protection and internal drainage works before June 1st 2006 (start of the hurricane season; cost of $1.5 billion);
- Raising all levees to the originally authorized level before September 1st 2007 (cost included in the $1.5 billion mentioned above);
- Completing the authorized hurricane protection system before September 1st 2007 (cost of $500 million);
- Realizing a 100-year protection level for the urban areas by 2010 (cost of $6 billion). Any further increase of protection levels is being studied by LACPR.

CPRA and LACPR

Prior to the Hurricane Katrina and Rita floods, the State of Louisiana and the USACE had already formulated strategic goals on coastal restoration. After the floods the state created the Coastal Protection and Restoration Authority of Louisiana (CPRA) and authorized it to prepare a comprehensive master plan for a sustainable coast. CPRA is charged with coordinating the efforts of local, state and federal agencies to achieve long-term and comprehensive coastal protection and restoration. The main challenge is to integrate flood control and wetland restoration. In February 2007 a draft master plan was completed. Four main objectives were formulated:

- To reduce risk to economic assets;
- To restore sustainability of the coastal ecosystem;
- To maintain a diverse array of habitats for fish and wildlife;
- To sustain Louisiana's unique heritage and culture.

The final master plan has been presented to Louisiana legislature in April 2007.

Directly after the Hurricane Katrina and Rita floods the USACE prepared a Category 5 report to come up with an indication of the measures required to protect the greater New Orleans area against a Category 5 type of hurricane. Following this study Congress authorized the USACE to prepare a plan on Louisiana Coastal Protection and Restoration (LACPR) in close co-operation with the State of Louisiana. Both the Louisiana legislature and the United States Congress provided legislative directives to investigate and integrate the use of manmade structural, natural environmental, and public policy related measures. The LACPR project will integrate flood control, coastal restoration, and hurricane protection objectives into a consistent and interoperable plan. Based on the federal directive, the purpose and scope of this project is as follows:

- The **purpose** of the project is to identify a plan for increased protection against storm surge equivalent to a Category 5 hurricane within South Louisiana.
- The **scope** is to address the full range of flood control, coastal restoration, and hurricane protection measures needed for comprehensive Category 5 protection in South Louisiana.

The planning for LACPR is to have a final report ready by the end of 2007. A preliminary report was finished in June 2006.

The main challenge for the future lies in the integration and coordination between federal and state efforts.

K.3 Management and maintenance for LACPR

K.3.1 Multiple lines of defense

One of the important goals of LACPR is to provide a robust coastal flood protection scheme, based on a combination of measures.

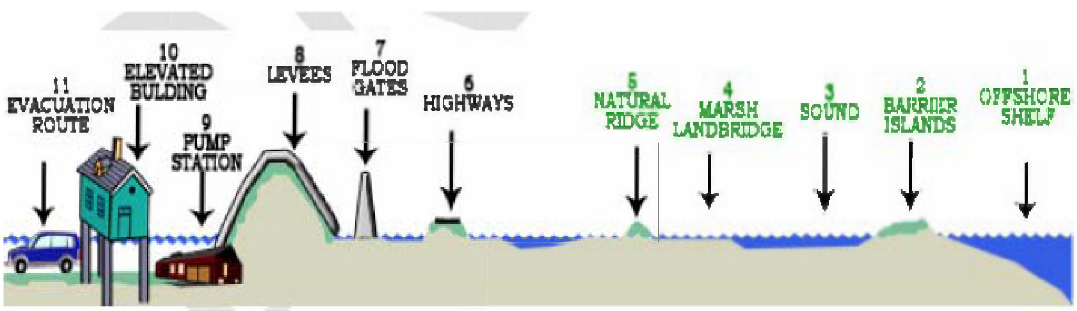

Figure 159 Multiple lines of defense

The Dutch perspective on LACPR also features a combination of measures. The main elements of these measures are:

- Levees around metropolitan areas;
- Marshland stabilization and development;
- Levees and barriers to close off the estuaries;
- Non-structural measures included in all options.

The main components used to develop these strategies are:

- Protected City: a series of interlinked levees directly around the metropolitan area of New Orleans. This system can be considered like a levee-ring area very similar to the Dutch situation. The Protected City measures also feature an option with a barrier in the Mississippi River.

- Pontchartrain and Barataria basins: for these two basins three main alternatives have been developed, being a levee/barrier-option; surge reduction measures; and marshland stabilization and development. These alternatives can be used in combination.
- Non-structural measures.

Three strategies were developed using these components:
- Open estuary system: this protects the metropolitan area of New Orleans with levees; stabilizes and develops the marshland; creates a shortcut in the Birdfoot and includes non-structural measures to reduce personal and economic risk;
- Semi-open system: this is equal to the open system with enhanced surge reduction measures (using passive measures);
- Closed system: this is equal to the semi-open system with structures (levees and barriers) to close off the estuaries.

Elements	Open	Semi-open	Closed
Protected City	Ring levee	Ring levee	Ring levee
Pontchartrain basin	Marshland stab/creation	Marshland stab/creation + passive surge reduction	Marshland stab/creation + levees/barriers
Barataria basin	Marshland stab/creation	Marshland stab/creation + passive surge reduction	Marshland stab/creation + levees/barriers

The topic of management and maintenance will be described using the semi-open strategy as a starting point. The other strategies may require some additional comments on management and maintenance.

K.3.2 Strategic and tactical goals

From the viewpoint of management and maintenance the strategic and tactical goals of the flood protection scheme need to be interlinked (also the operational goals need to be interlinked, but that topic will be dealt with later). The Dutch concept of safety assessment (every 5 years) including the risk assessment (every 25 to 50 years) can easily be transferred to the proposed strategies for the Louisiana coast and the New Orleans area.

The strategic goals are flood risk reduction and landscape stabilization in order to enable socio-economic developments. First of all, it must be realized that these goals cannot be reached in a short period of time; it is realistic to say that it will take decades (30-50 years) to reach them. This inevitably leads to the conclusion that during that period the strategic goals may already have to be adapted once or twice. This is a very important aspect in developing the management and maintenance strategy.

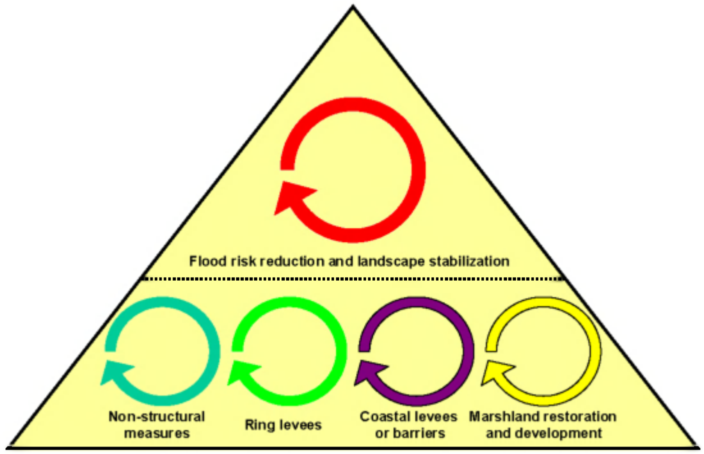

Figure 160 Strategic and tactical planning

The strategic goals are accomplished by the four types of proposed measures. Each of these measures has its own characteristics.

The non-structural measures can be implemented relatively quickly and are mostly logical "no-regret" measures. Due to its nature this type of measures however needs to be updated regularly. A yearly routine of practice, evaluation and adaptation is adequate.

The ring levees are meant to protect metropolitan areas from flooding. Depending on the required protection level (ranging from 10^{-5} to 10^{-2} per year) (re)construction of these embankments with a total length of several hundred kilometers will take approximately 5 years depending on the available budget. Also these measures can be described as "no regret" measures to be taken right away. The planning period for these levees should be somewhere between 50 and 200 years depending on the type of structures applied. Structures that are easily adapted can be designed using a short planning period, whereas the longer planning periods are required for (elements of the) structures that cannot be adapted easily.

The coastal levees and/or barriers will probably take more time to design because the uncertainties in the performance and/or the complexity of the design. It will probably take a number of years to come up with a design that fits in with the strategic goals of the scheme. During this research and design period a number of large-scale pilot projects can be tested in practice.

Finally, the marshland restoration and development is a long-term measure. It will take decades to "create" significant developments. Also, the uncertainties attached to these measures are even greater than for the coastal levees and/or barriers. Large-scale tests in the field of these measures are definitely required.

The tactical goals for the various measures need to be projected onto the strategic time span of 50 years. The combined effect of these measures changes over time (except for the non-structural measures).

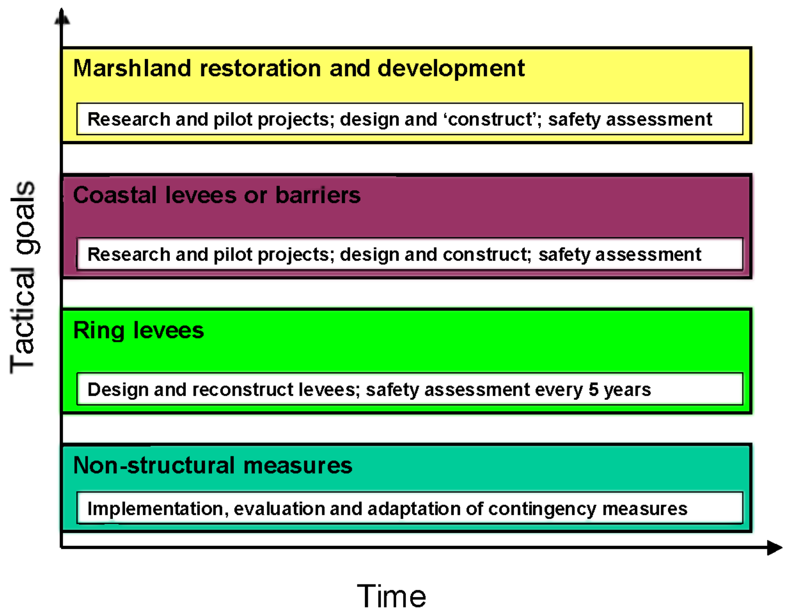

Figure 161 Tactical planning elements

After construction, the ring levees will slowly deteriorate due to the combined effect of sea level rise and settlements. That effect can be compensated for once the measures "coastal levees" or "marshland restoration and development" start to be implemented. However, this requires assessing the actual performance of the various measures regularly. For the levees a 5-year period is considered to be adequate.

K.3.3 Operational goals

Operational goals are to be derived from the tactical goals. The operational goals are largely determining the regular maintenance budget.

K.3.4 Integration and coordination

The multiple line of defense approach is only as robust as the quality of managing and maintaining the separate lines. In addition to this, the need for integrating and coordinating the activities of the various authorities involved is paramount.

The key discussion on management and maintenance is to find a fitting balance between the role and actions of the various authorities involved. Obviously, this study is not aimed at changing the way the U.S. authorities are organized. However, based on the Dutch, European and American experiences, a number of relevant criteria for the optimal management and maintenance situation can be derived:

1. An adequate planning level;
2. Involving local authorities;

3. Spatial and functional integration; and
4. Clear responsibilities.

The first two criteria seem to be contradictory. First of all, it is necessary to have a planning level matching the scale of the natural system and the processes taking place. For example, the Mississippi River and the coast of the Gulf of Mexico need to be treated as a whole. On the other hand, flood protection measures need to be taken at the lowest level possible in order to keep local authorities involved and committed to their tasks. The local authorities are able to commit local residents and to find optimal solutions based on costs and benefits of flood protection measures.

The third criterion is based on the ability to integrate the various functional demands in a spatial framework.

The fourth criterion is a clear separation of responsibilities including the need for checks and balances.

A number of sub-criteria can be developed from these four criteria:

1. An adequate planning level:
   a) planning based on the natural systems involved, i.e. the river and the coastal system;
   b) planning based on functions assigned to these systems such as flood protection, navigation, …;
2. Local authority:
   a) legislation, which gives (local) water authorities the authority to carry out their duties, to raise money and to enforce their rights;
   b) taxation of the people in the jurisdictional area of the water authority for generating income to carry out its duties;
   c) representation of stakeholders in the water authorities, to create stakeholder commitment and to ensure democratic decision-making;
   d) funding of large capital for major investments, which is mainly found within the private sector;
   e) institutional development, addressing trained staff and tools such as accurate cadastral and financial administration, needed to allow for effective and efficient operation;
3. Spatial and functional integration:
   a) functional integration;
   b) spatial integration;
4. Clear responsibilities, including checks and balances.

K.3.5 Recommended situation

Based on the criteria the recommended situation for management and maintenance of the future flood protection scheme in the greater New Orleans area can be described as follows:

- A political commitment to strategic management goals and the framework for tactical management goals and measures;

- Design and implementation of the specific tactical measures within the approved framework;
- Regular update of tactical planning (once every 1-5 years, depending on the type of measures);
- Funding for operational management and maintenance.

Given the responsibilities of various authorities involved it seems to be necessary to establish two interlinked "chains of command", leading to both federal and state government.

Item	Authority	Responsibilities
Integration/coordination	State	Risk management
Protected City	Levee board	M&M ring levee
Coastal management	USACE/State	M&M coastline
Coastal levees/barriers	USACE	M&M levees/barriers
Birdfoot/river management	USACE	River management
Non-structural measures	Municipality/State	Spatial planning

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L Dutch water management, conceptual approach and lessons learned

This appendix provides an overview of approaches and lessons learned in Dutch water management with focus on the Rhine-Meuse-Scheldt estuarine delta area

The Layer Model, introduced in the National Spatial Planning Strategy (2005) of the Netherlands, is proposed as a model for the analysis, integrated design and (participative) planning of land use, water management and civil engineering works as well as for communicating about these matters. This approach aims to produce management plans that consider all three layers in an integrated fashion and the land use to be future-oriented, sustainable and efficient.

The Layer Model distinguishes three layers. Each layer influences the spatial considerations and choices with respect to the other two layers. Each layer will change in time, but the pace of changes differs. The slower the pace of change the more careful the implementation of changes should be considered, because these changes will influence the future for a long time. The *essence* of the Layer Model lies in the difference in dynamics between the layers. These dynamics determine the order of designing and planning land use.

The following layers are defined (see Figure 162):

- Ground layer. Soil, (ground)water and flora and fauna in those environments. Changes take place in time spans of centuries (50 to 500 years) and are large scale and steadily going on. Wrong decisions will lead to unsustainability and large management efforts and costs in the future.
- Networks. All forms of visible and invisible infrastructure: waterways, civil-engineering works as levees, sluices, locks, etc., roads, railroads, pipe-lines. Changes take place in time spans of 25 up to 100 years.
- Occupation. Spatial patterns due to human use. Spaces for living, working and recreational activities. Changes take place relatively fast in periods of 10 to 25 years.

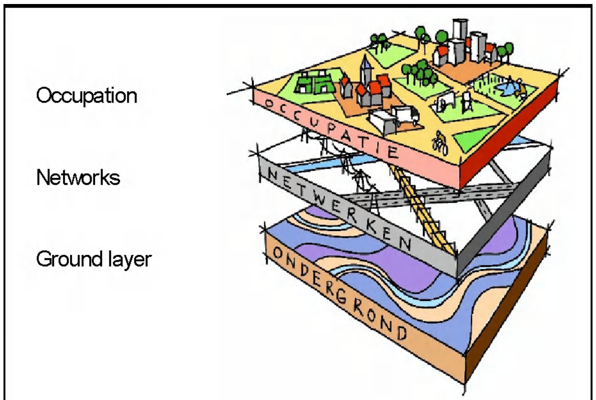


Figure 162 Layer Model

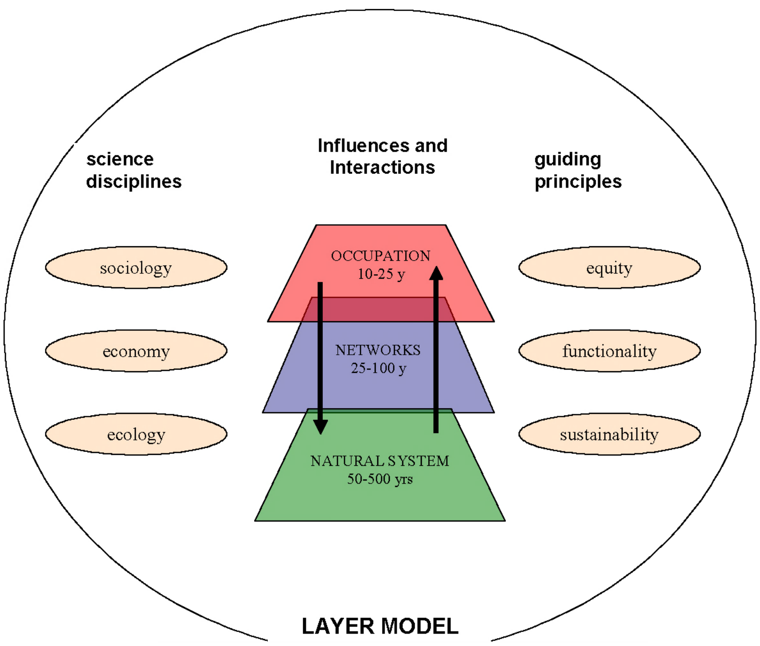
Besides these layers the political dimension is of importance. Integrating the different paces of change with policy objectives is a great challenge in spatial planning.

In analyzing and designing of spatial planning much consideration should be given to the properties and functions of the ground layer and the network layer, as well as the structural significance of both layers. Because these layers determine for the greater part the sustainability of land use and related management efforts and costs now and in the future.

In the planning stage, the processes in the different layers need to be considered in relation to each other. This will prevent conflicts now and in the future between different land use functions and will also create greater coherence in the measures to be taken. After all, intervention may (or better should) serve more than one policy objective at the same time.

The *advantages* of applying the Layer Model are:

- the model raises awareness about the complexity and forces to a broader integrated perception of matters;
- the model provides insight in integrated solutions;
- the model provides an overview of interests at stake, as well as the actors and stakeholders;
- the model allows a distinction between levels of scale within a problem: national, regional and local; and
- the model provides insight in consequences of choices made.



Link National Spatial Strategy: http://international.vrom.nl/docs/internationaal/engelsesamenvattingnr.pdf

The most important lessons learned from Dutch water management all have to do with influencing the basic natural processes in the ground layer. This is not a surprise, because a lot of civil-engineering measures have deeply influenced the natural processes that shape the Dutch landscape. Practically all natural processes in the Delta of the Netherlands are influenced by man: tides, salinity gradients, transport of (sometimes polluted) sediment and nutrients. This affected biotic processes in many ways and created new landscapes.

The Delta Project, implemented following the 1953 flood disaster, very well succeeded in reducing flood risks to the agreed level. It also resulted in substantial improvements in water management, realizing a tide-free navigation link between the ports of Rotterdam and Antwerp (Belgium), the supply of fresh water to agriculture in the region, providing roadways between the islands, and opening up the islands for recreation purposes.

Before executing the Delta Project the Delta area consisted of several estuaries, a transition area of the rivers Rhine, Meuse and Scheldt to the North Sea with gradual transitions from fresh to salt water and with tidal influences. An area dominated by dynamic equilibria between sedimentation and erosion. Through land reclamation areas behind levees were withdrawn from these dynamic equilibria. Subsidence of reclaimed land by settling and draining of ground layers of peat and clay and lacking of further natural sedimentation led to frequent flooding during the last centuries. The last flood of 1953 with 1836 deaths and tremendous economic damage was the starting point of planning and executing the Delta project to secure the protection against flooding of the area.

During the execution of the Delta project (1958 – 1997) plans were changed through increasing environmental awareness. Instead of closing off the sea inlet of the Eastern Scheldt a storm surge barrier was built, finished in 1986. A second storm surge barrier was built in the main shipping way The New Waterway to the port of Rotterdam, finished in 1997.

The Delta project has - in spite of the ecologically induced adjustments of the original plans - changed the former multiple estuary into strictly separated water systems. Not only land has been fixed by levees but also water systems have become fixed in place. During the years it has become more and more apparent that the loss of the dynamic estuarine conditions (tides mixing with incoming river flows carrying sediments, organic matter and nutrients) has ecological disadvantages leading to socio-economic effects concerning the utilisation of the water systems.

In short, the main negative impacts and possible solutions are:

- The artificial fresh lake Volkerak-Zoom suffers from blue-green algae blooms due to incoming nutrient-rich river water. Studies are being carried out to restore estuarine conditions. Results are pointing in the direction to make it a salt water lake with as much water circulation and tidal fluctuations as possible.
- The artificial brackish Lake Veere suffered from with blooms of sea lettuce, green algae and lack of oxygen in the deeper parts due to inflow of nutrient rich water from agricultural land surrounding the lake. In 2004, a culvert to the tidal Eastern Scheldt became operational to flush the lake with salt water. Since then water quality has improved considerably. Studies are carried out to adjust management of unnatural water level (high in summer and low in wintertime to improve the drainage of surrounding agricultural land) to further improve the ecology of the lake.
- The artificial salt Lake Grevelingen copes with lack of oxygen in the deeper parts and changes in bottom fauna due to lack of water circulation. The situation has improved by building a culvert to the North Sea, but the lake is still slowly deteriorating. Studies will be undertaken to improve water quality and ecology by enlargement of the culvert with the

North Sea and using a culvert with the Eastern Scheldt. Combination with a tidal energy plant will be studied as well.
- The Haringvliet barrier closed off a tidal inlet and controls the riverflow of Rhine and Meuse. It causes sedimentation of polluted material in the Biesbosch and Haringvliet and Hollands Diep. Migrating fish are now blocked by the barrier which also creates an abrupt change from fresh to salt water. By 2009, the Haringvliet sluices will be opened a little bit to restore fish migration, enabling fishes to swim up and down the rivers Rhine and Meuse. To avoid negative side-effects for fresh water supply due to salt water intrusion, various modifications of irrigation water and drinking water intakes are necessary. New modifications to the ground layer now clearly conflict with the network layer that has been adapted to it.
- A still unsolved side-effect of the storm surge barrier in the Eastern Scheldt is the steadily proceeding erosion of the tidal flats and salt marshes. This process affects the protected habitat of tens of thousands of birds, and is caused by the disturbed hydro-morphological equilibrium due to the oversized tidal channels and reduced water exchange through the barrier. It remains unsure whether or not this development will have to be accepted or that measures can be taken to mitigate the undesirable effects, for example by means of nourishment of the intertidal areas.
- Shoreline erosion problems had to be solved in the stagnant lakes. Measures to protect the shorelines and adjoining shallow waters of the created lakes from erosion by continuous attack of wind driven waves were carried out in the seventies and eighties.

The necessity of finding solutions for these problems is strengthened (and required) by the implementation of the European Water Directive and the Birds and Habitat Directive. Both the ecological and water quality must be improved. The guiding principle behind the approach is responsibly repairing and strengthening the estuarine dynamics. The cohesion between the various bodies of water in a systems approach is essential here.

In addition to coping with the above mentioned negative impacts, also the following issues require attention:
- The effects of climate change will have to be anticipated and coped with: sea level rise, heavier storms, more intense rainfall, dryer summers, higher salt concentrations in (ground)water and seepage flows.
- How will the Delta waters be impacted when, in extreme conditions, excess river flow is stored in these waters when during a storm at sea the barriers are closed? A study for this function of Lake Volkerak-Zoom will be carried out the next years.
- Will a sea defense line of one high levee be sufficient in future? What are the possibilities and advantages and disadvantages of broader coastal zones with for example two levee lines and making use of natural sedimentation processes when still available?

The installed capacity of the various navigation locks in the dams of the Delta works will impose restrictions on shipping to and from the Delta area harbors in the future. The capacity will have to be enlarged in the future. Recreational sailing is also subject to the barrier effects of dams and locks. This puts a brake on economic growth of that sector.

Several other challenges have to be dealt with in this region. The pressure on the region from the surrounding urbanized areas is increasing. At the same time the number of inhabitants has recently dropped. Agriculture and aquaculture– historically an important economic bearer – requires modernization and renewal. Despite obvious attractive qualities such as water, nature and space, recreation is declining. Here too renewal and innovation are needed.

The lessons learned in short are:

- It is wise to bring flood defense measures in harmony with natural processes and the goods and services these processes provide us.
- Compartmentalizing of the Delta estuary leads to separation of water systems and reduction of natural water exchange. This diminishes resilience and flexibility for integrated water management and flood control. It may cause problems of erosion, sedimentation and water quality. And it may block water discharges needed in emergencies.
- Following this concept the best solution for the Dutch Delta estuary would be a more open system with large barriers and culverts not disturbing daily natural dynamics.
- Triggered by various incidents of intensive rainfalls in recent years and near river flooding in 1995, the need to continue raising public awareness about living with water in this low lying area became apparent. The Dutch have to accept and deal with the risk that the water poses in a novel way. Before the water may surprise the Dutch as an enemy again, it is important to anticipate and innovate in a timely fashion.

A former directors of Rijkswaterstaat Zeeland summarized it in this way: "*Mother Nature is the best engineer, think twice before you interfere*". This implies that when you act against nature you may keep encountering unwanted effects. So when you interfere or adjust former interferences be "eco-pragmatic": use natural processes in favor of sustainability and do not fight battles with natural processes that you can not win in the long run.

M Project team

The following individuals, listed in the order of the appendices they contributed to, have participated in this study:

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