Prepared for:

Rijkswaterstaat

Lessons from New Orleans for the Western Scheldt Estuary

Comparison between Mississippi Delta and the Western Scheldt
Estuary

Report

February 2008
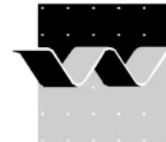
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Deepak Vatvani (Editor)

Report

February 2008

WL | delft hydraulics

Client:	Rijkswaterstaat

Title:	Lessons from New Orleans for the Western Scheldt Estuary

Abstract:

The Dutch Rijkswaterstaat has commissioned WL | Delft Hydraulics, as part of the long-term research program "Lange Termijn Verkenningen Westerschelde – Onderzoek en Monitoring" (LTV O&M), to conduct a preliminary study and identify lessons to be learned from hurricane-induced flooding of New Orleans, applicable to the Dutch-Flemish situation.

This desk study is based on currently-available information, reports and model studies, augmented by general knowledge of tide and surge propagation in the Scheldt Estuary and the Mississippi Delta. Brief comparative analysis of the important and major flooding events and the wind forcing that caused these events in the deltas, respectively Katrina hurricane event for the Mississippi delta and the 1953 storm event for the Western Scheldt, were carried out. Similarities and differences between the two deltaic systems and of the events are reviewed.

Based on these comparisons it is concluded that the similarities between the Mississippi delta and the Western Scheldt estuary are in essence related to their uses. Otherwise, the hydrodynamics, the morphology and the weather systems of these areas differ to a large degree. Despite the fact that both areas are both subject to coastal flooding originating from meteorological forces, there are important differences in storm surge characteristics affecting the two areas. These differences are important because they present the physical boundary conditions for solutions to prevent and prepare for flood disasters.

Finally, it is concluded that some gaps yet exist in our knowledge and capability for reliable short- and long term prediction of the effects of human intervention on natural processes and on risk of flooding, be it positive or negative. For further improvement of the Dutch flood prevention measures these knowledge gaps should be adequately addressed. An effort is made to identify the gaps through five concrete research topics that need to be studied in the near future.

References:	

Ver	Author		Date	Remarks	Final Internal Review	Approved by	
	Deepak Vatvani		11-02-2008		J. Dijkman	T. Schilperoort	

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Contents

1   Introduction

1.1   Background

After the catastrophic flooding of New Orleans following the passage of hurricane Katrina in 2005, Dutch private sector, technological institute and Dutch government specialists have supported United States (US) local and federal agencies' efforts to restore, rebuild and protect the disaster-stricken areas against future flooding. Some of the activities were carried out as a part of the Memorandum of Agreement between the Dutch Ministry of Verkeer en Waterstaat and the US Army Corps of Engineers. One of the objectives of the Dutch government in this context is to learn from the US experience due to following reasons:

1. The Dutch flood risk management strategy is also completely dependent on a system of dykes and dams.
2. The Scheldt Estuary has also been extensively modified over time due to natural processes accelerated by human activity.

The Dutch Rijkswaterstaat has therefore commissioned, as part of the long-term research program "Lange Termijn Verkenningen Westerschelde – Onderzoek en Monitoring" (LTV O&M), WL | Delft Hydraulics to conduct a preliminary study to identify lessons to be learned from hurricane-induced flooding of New Orleans, applicable to the Dutch-Flemish situation.

1.2   Objectives of the study

Based on the description above, the present study will focus on the following important questions:
- How does the flood-risk situation in the Mississippi-Delta compare to the situation along the Scheldt Estuary?
- Are there useful lessons to be learned for the Dutch situation from the New Orleans flooding due to Hurricane Katrina in August of 2005?

Aspects that will be considered in this report are differences and similarities between the morphology of the Scheldt Estuary and the Mississippi delta, and in the flooding events of 1953 in the Netherlands and of 2005 in New Orleans. This report will not address flood warning, evacuation or emergency response issues, or ecological impacts of the respective flood events.

1.3   Study approach

This preliminary desk study is based on currently-available information, reports and model studies, augmented by general knowledge of tide and surge propagation in the Scheldt Estuary and the Mississippi Delta.

Recent comparisons showed that the consequences of the 1953 flood event in the Netherlands was of the same order of magnitude as the flooding caused by Katrina in New Orleans (see table below). From the data in this report we can also conclude that the recurrence intervals for both events are roughly equivalent, i.e. once in 300 to 400 years. Consequently, both flood events will be used as the basis of discussion.

Table 1   Some of the characteristics of the 1953 flood event in the Netherlands and the 2005 Katrina flooding in New Orleans (Source: Kok M, Theunissen R, Jonkman S.N, Vrijling J.K. ,2006)

	1953 floods – Netherlands	New Orleans 2005
Number of inhabitants in the flooded area	250.000	500.000
Number of fatalities	1835	1100
Flooded area	2000km^2	260km^2
Direct economic damage	Fl 1,5 billion (in 1953 guilders)	US $ 30 billion
Number of dyke breaches	140	30

The recent insight to the New Orleans flooding situation was gained through the 'Dutch Perspective' Project in 2007 involving a consortium of Dutch firms and organizations. Information was also obtained from interviews with local US experts, including expert opinion, detailed description and interpretation of flooding processes that took place in New Orleans in 2005. Furthermore, data from the Interagency Performance Evaluation Task Force (IPET) report that studied the failure of the New Orleans Hurricane Protection System during Katrina have also been used, especially for the description of the storm event.

For the system in Western Scheldt, input for this report was derived from numerous past studies conducted in the Netherlands and Belgium, including Jeuken *et. al.* (2007), Asselman *et. al.* (2007), Haecon (2006), Marchand (2006), Wang *et. al.* (2002), Gerritsen (1999), van der Spek (1994), Coen (1988), and others.

Finally, in this report the quantities "high water level" and "storm surge" will be often mentioned to specify the increase in the water level caused by a storm event. These terms are illustrated in Figure 1 below.
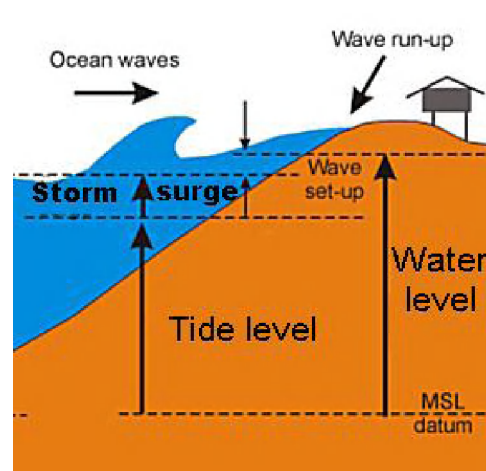

Figure 1   Quantities contributing to (high) water level (http://www.mfe.govt.nz/publications/climate/ chatham-islands-climate-change-jun05/html/figure-43.html)

Lessons from New Orleans for the Western Scheldt Estuary
Comparison between Mississippi Delta and the Western Scheldt Estuary

Z4511

February 2008

1.4 Contributors to this study

Several experts from various institutes have contributed to this study, listed as follows:

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Lessons from New Orleans for the Western Scheldt Estuary
Comparison between Mississippi Delta and the Western Scheldt Estuary

Z4511

February 2008

2 Overall review of the two systems

2.1 Mississippi Delta system

2.1.1 Area Description

A brief description of the Mississippi Delta, including natural and manmade systems, is subsequently provided.

Figure 2   Aerial photography of the Mississippi delta (source: GoogleEarth)

The Mississippi River is the second longest river in the United States, with a length of approximately 2340 miles (3766 km) from its source in Minnesota to its mouth in the Gulf of Mexico, about 100 miles (160 km) downstream from New Orleans. The river has an annual discharge average rate of between 7000 to 20000 m³/s. The length of the Mississippi delta, shown in the picture above, is approximately 140 kilometers.

The vast majority of the delta is in its natural state, i.e. undeveloped, albeit morphologically altered by decades of Mississippi River channelization and levee construction upstream, and by construction and maintenance dredging of navigation channels and the Port of New Orleans as well. Built-up areas include the Metropolitan area of New Orleans, predominantly rural areas of Plaquemines Parish, and small towns on the barrier islands. Human activities in the delta area include the important navigation industry, commercial

fishing, recreation, and a wide variety of activities related to the oil and natural gas industries.

Subsidence of the Mississippi 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. Except for isolated recent freshwater diversion projects, the supply of fresh water, nutrients and sediments to the delta has been blocked by construction of levees along the Mississippi River upstream. At the current rate, approximately one-third of pre-1900 coastal Louisiana will have subsided into the Gulf of Mexico by 2050.

Since its founding in 1718, the city of New Orleans has struggled against the annual flooding of the Mississippi River and the occasional storm surge flooding brought by tropical cyclones. Construction of private river levees to control flooding dates back nearly as far. Originally situated on the relatively high ground near the river, the city continued to grow and expand through the 20th century. Marshland north of the city was drained for development up to the shore of Lake Pontchartrain. Protected from the seasonal floods of the river, attention shifted to building levees along Lake Pontchartrain to the north and Lake Borgne to the east of the city.

During the past 40 years, as infrastructure and population expanded, the hurricane protection system was extended to protect important economic assets. Canal excavation over the past decades, mainly to support the oil and gas industries, is considered to be one of the most important causes of marshland loss and habitat destruction. This has altered estuarine hydrodynamics and flood levels, and has adversely affected coastal wetlands. Salt water intrusion has led to extinction of vegetation and consequent reduction of brackish marshland and freshwater swamps.

Loss of marshland has resulted in increased effective fetch for wind-generated waves and increased current velocities as well, further increasing the rate of marsh erosion. In addition, marsh browning disease and overgrazing by nutria, an invasive rodent species native to South America, is further reducing marshland area.

Anticipated future conditions

Without significant land stabilization, further loss of wetlands will continue, and land loss due to erosion, subsidence, and other factors will continue and possibly accelerate over the next 50 years. The wetlands buffer that now to a certain extent protects New Orleans from storm surges will gradually disappear if no measures are implemented. By 2050 the city will be closer and more exposed to storm surge and wave attack from the Gulf of Mexico. As barrier islands erode and wetlands are lost over the next 50 years, it is likely that higher salinity levels will occur at more inland locations leading to further degradation of marshland.

2.1.2 Storms statistics

Hurricanes have a historical expectation of a direct hit at any location along the Gulf of Mexico US shoreline on average every seven to twenty years (Blake, 2007). They also have

a historical expectation of Category Three or higher strength at landfall every fifteen to fifty years. Detailed estimates of return periods of hurricanes with different strengths are provided by the National Hurricane Center (NHC) which is a part of the National Oceanic and Atmospheric Administration (NOAA). Hurricane return periods are the frequency at which a certain intensity or category of hurricane can be expected within 75 miles of a given location. The following figures show the return periods of hurricanes along the Gulf Coast. For comparison with the Dutch storm frequency data, a table showing wind speed criteria for each hurricane category is displayed alongside Figure 3.

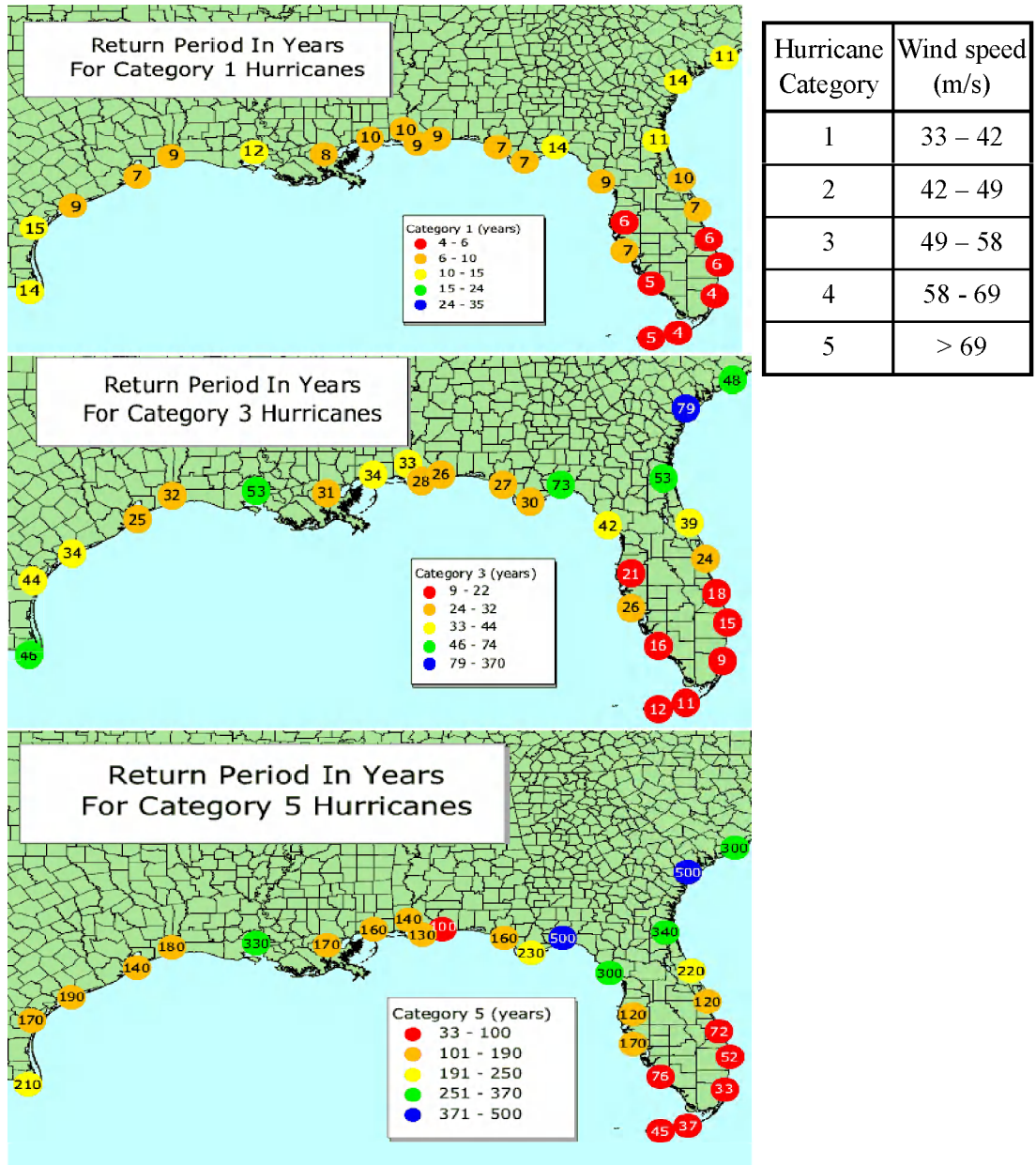| Hurricane Category	Wind speed (m/s)
1	33 – 42
2	42 – 49
3	49 – 58
4	58 - 69
5	> 69

Figure 3   Return period for hurricanes along Gulf Coast (source NHC)

Hurricane Katrina was a category 3 hurricane when it made landfall near New Orleans, an event shown in Figure 3 above to have a recurrence interval of approximately 30 years. However, this number is based the category classification that addresses only the wind force. Based on the joint probability of occurrence of all storm surge-related characteristics,

including central pressure, radius to maximum winds, propagation speed, track and local bathymetry, it has been generally-accepted that the recurrence interval for the Katrina event equals approximately 400 years. This result is based on work recently carried out to estimate the statistics and accompanying surge levels of hurricanes in the framework of USACE/FEMA's Joint Coastal Surge Study.

2.1.3 Katrina flood event

To investigate the failure of the New Orleans Hurricane Protection System (HPS) during Hurricane Katrina, the Interagency Performance Evaluation Task Force (IPET) carried out extensive studies, most of which have been completed or are nearing completion. The IPET report is widely regarded as the definitive state-of-the-art analysis of storm-surge flooding in Coastal Louisiana, flood risk, and structural integrity of the HPS. The IPET reports and supporting data can be downloaded from https://ipet.wes.army.mil/. The following excerpt provides an overview of the event, described in detail in Volume IV of the IPET Report.

Hurricane Katrina Description (excerpted from IPET report volume IV, 2006)

Hurricane Katrina, gradually intensified, from a Category 2 storm on the 26 August to a Category 5 storm on 28 August, 2005. The table below shows its wind characteristics from the 28th of August 1200 UTC, i.e. from the moment the hurricane attained its peak intensity.

Table 2 Hurricane Katrina Wind Characteristics from the 28th of August 1200 UTC
(condensed from IPET report volume IV, 2006)

Time (UTC)	North Latitude (deg)	West Longitude (deg)	Central Pressure (mb)	Max. Surface Wind speed (knots / m/s)	Radius to Max. Wind (nautical miles / km)	Saffir-Simpson Scale
28082005 1200	25.747	87.721	908	139 / 71	14 / 26	Category 5
28082005 1800	26.347	88.661	902	138 / 71	18 / 33	Category 5
29082005 0000	27.198	89.212	904	124 / 59	14 / 26	Category 4
29082005 0600	28.132	89.59	910	108 / 56	18 / 33	Category 3
29082005 1200[1]	29.479	89.575	923	102 / 52	36 / 67	Category 3
29082005 1800[2]	31.043	89.64	948	84 / 43	16 / 30	Category 2
30082005 0000	32.729	89.042	963	51 / 26	18 / 33	Tropical Storm
[1] = Landfall in Louisiana at 1100 UTC [2] = Final Landfall						

During the storm built up, the steadily increasing surface winds pushed water toward the Mississippi River Delta, and began to inundate the coastal wetlands of Southeast Louisiana east of the Mississippi River. By 1800 UTC on 28 August, when the storm was still 170 miles (274 km) away, water levels in Lake Borgne had reached 3 ft (0.9 m) above normal. In response to this, the water level in Lake Pontchartrain was raised to a level of 1 foot (0.3 m) above normal. Significant wave heights east of the Mississippi River entrance had reached almost 20 ft (6 m) in deep water and about 10 ft (3 m) just north of the barrier islands.

During the next 12 hours, despite decreasing intensity, the storm pushed the water levels in Lake Borgne towards 5.5 ft (1.7 m) above normal. Much of the wetland system, east of the Mississippi River Levees, was completely inundated. Along the southern shoreline of Lake Pontchartrain water level rose to nearly 3 ft (0.9 m)

above normal. By this time significant wave heights had reached almost 35 ft (10.7 m) at a location due east of the southern tip of the Mississippi River delta, in deep water. Finally, at around 0600 UTC on the 29th of August the rate of rise of both water level (reaching approximately 1 foot / hour) and wave height increased considerably in Southeast Louisiana. Before the final landfall, despite its decreasing intensity, the storm pushed a considerable volume of water against the Mississippi River delta and the east-facing levees along the Mississippi River, and in the "pocket" formed by the delta and the Mississippi coast. The storm then pushed this volume of water northward towards the Mississippi coast and into Lakes Borgne and Pontchartrain.

Local high winds tilted the water levels in Lake Pontchartrain and created high wave conditions on the downwind side of the lake. During this period wind direction in Lake Pontchartrain changed steadily from east to west, in the counter clockwise direction. In response to this, the region of maximum storm surge and high waves translated along the southern half of the lake, moving from west to east.

Additional discussion of Katrina event

Maximum water levels recorded during the hurricane in three areas of the delta between New Orleans and MRGO were as follows:
- In New Orleans and the IHNC the maximum surge ranged from 10 to 15 feet (3 to 4.5 meters).
- In Plaquemines Parish the maximum surge range was 15 to 20 feet (4.5 to 6 meters).
- Maximum surge level along the Gulf Intracoastal Waterway (GIWW) and MRGO was approximately 15 to 20 feet (5 to 7 meters).
- In the vicinity of Biloxi (east of the delta) the surge level was approximately 27 feet (8.5 meters).

With respect to its contribution to high water levels in New Orleans, the IPET-Report (Volume IV) concluded that MRGO increased surge levels at most 2 inches (5 cm) against the levees surrounding the city.

The wave height generated by the hurricane winds was significant and did contribute to the damage to the hurricane protection system. Increased water levels in Breton Sound and Lake Borgne, for instance, allowed considerable wave energy generated in the gulf to propagate over and through gaps between the barrier islands, across the inundated wetlands, to the hurricane protection system in these parishes. The long waves (> 12s) generated offshore were able to penetrate over the marsh area towards the HPS and caused significant overtopping.

A study carried out by a consortium led by the Netherlands Water Partnership (NWP) recently finalized a project entitled "A Dutch Perspective on Coastal Louisiana Flood Risk Reduction and Landscape Stabilization" (Dutch Perspective Project)[1]. This study, carried out with the help of the Delft-3D model, indicates a positive effect of wetlands on storm surge reduction, provided that a sufficiently wide band of wetlands (about 20 to 40 kilometres) is

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[1] This project studies long term options for flood risk reduction as well as options to stabilize and possibly restore the delta area.

present around the Metropolitan area of New Orleans. The frictional forces exerted by the wetlands also affect the spatial distribution of high water levels (see also section 5). The NWP study utilized a coarse model grid, and consequently the results should be considered indicative rather than precise.

However, analysis, under the Louisiana Coastal Protection and Restoration (LACPR) program using a higher-resolution model grid resolution and a projection of the degradation of the marshes into the future, indicate that the effect of marshes on the surge levels is marginal, i.e. smaller than suggested by the NWP Delft-3D model. Further studies to quantify the surge and wave-reduction potential of coastal wetlands are clearly warranted for planning and design of a systems approach to flood protection.

2.1.4 Summary of causes of levee failure in New Orleans during Katrina

Throughout the system, the high surge levels and wave heights generated by Hurricane Katrina exposed the hurricane protection system to considerable hydrodynamic forces and structural stresses.

In the city of New Orleans the canals are directly connected to Lake Pontchartrain. A movable floodwall, similar to the one in the access channel to the Port of Rotterdam in The Netherlands, did not exist. Along these canals the levees failed at four different locations.

In the 17th Street Canal, the floodwall was pushed aside rather than washed away by the high water. This situation resembles of the peat levee failure in Wilnis in the Netherlands in 2003, in that the failure mechanism was almost the same. The floodwalls at the canals in New Orleans are I-walls built upon sheet piles. Due to water pressure from the deeper sand layers and because the foundation of these I-walls were not placed sufficiently deep in the subsoil, the I-walls started to float when the water started to rise. This reduced shear strength and allowed water pressure to push the floodwall laterally, causing cracks between the I-walls and the levee embankment. Under-seepage through these cracks and the permeable sand layers below the foundation increased uplift on the walls, reducing their stability and resistance to sliding.

The increased flotation tendency of floodwalls in some locations was magnified by the lack of a buffer zone between the canals and the floodwall itself. The size of buffer zone in New Orleans has been decreasing due to loss of wetlands in the delta due to erosion. Reduction of wetlands area has in front of the levees also allowed piping to occur, an example of which is provided in the case of the London Avenue Canal. Piping was initiated by a crack that filled with water, and on the protected side of the I-wall, wave overtopping created scour trenches and eroded the levee. These two combined effects finally resulted in levee failure.

Another contributor to the levee failure was the overtopping design criteria for the levees. The levees were constructed to a uniform design height along their entire length. Due to heterogeneous soil conditions and other locally-varying conditions within the large Mississippi delta area, wave and surge heights – and consequently overtopping rates – also varied significantly along the floodwall. Lateral displacement of the I-walls provides further indication that design criteria and/or hydraulic boundary conditions were not sufficiently conservative.

Embankments constructed by hydraulic fill were found to be far more susceptible to erosion by overtopping in comparison to mechanically placed and compacted dry fill, i.e. using earthmoving equipment and dry sand transported using trucks. The latter method resulted in more homogeneous and better-compacted fill material. Another factor in levee failure is the embankment material itself. Levees built using clay were found to be far more resistant to erosion on the interior side than levees constructed primarily of sand.

Transitions and abutments between earthen levees and non-retaining structures, such as roads and bridges, are most often designed to resist frontal wave attack, and as a consequence can be more susceptible to oblique wave fields. These transitions can also affect local current direction and velocity, and some were found to have been responsible for scouring and washout of portions of the flood protection system, even when the structural integrity of adjacent levees and structures was otherwise sound.

2.1.5   Current state of New Orleans coastal flood protection system

Efforts to repair and restore the flood protection system to its originally-authorized levels of protection are in progress. So far the US Congress has only authorized and funded a 1 to 100-year level of protection. LACPR has to investigate various options to increase the protection level of this area up to category 5 hurricane events. Studies are currently underway and a comprehensive plan to avoid future coastal flooding disasters may emerge within one to two years.

The Mississippi River flooding of 1927 led to construction of higher and stronger levees to confine the river. Flood diversions were created to store excess flows and relieve downstream flooding. However, bayous providing natural flood storage were closed off to ensure sufficient downstream navigation depths during low-flow periods. The cumulative effect of these alterations was the diversion of fresh water and sediments otherwise distributed to marshlands along the river into the main navigation channel, with a single outlet into deep water through the Mississippi Delta birdfoot.

The current Congressionally-authorized flood protection level for the New Orleans Hurricane Protection System (HPS) is the 100-year event, roughly equivalent to Hurricane Betsy in 1965. The HPS in the Mississippi Delta around New Orleans is provided by a system of levees and floodwalls around (parts of) New Orleans and surrounding built-up areas, which according to IPET study was a protection system in name only.

Furthermore, land subsidence caused significant reductions on levee and floodwall heights, long reaches of which remained unnoticed over the years. In New Orleans, land subsidence has reduced the height and consequently level of flood protection afforded by significant portions of the levees and floodwalls comprising the HPS. Because these effects were gradual, they remained unnoticed over the years.

The US has no national legal framework, no continuing legal authority or assured funding of flood protection system maintenance, upgrades or improvements. As a consequence, the severe subsidence of the system was either undetected or unmitigated, and HPS design standards – based on statistics more than 40 years out of date and failing to account for the large loss of wetlands during this time – were clearly inadequate.]

2.2   The Scheldt Estuary

2.2.1   Brief description

The trans-national Scheldt estuary (Figure 4) extends from the upper reaches near Gent in Belgium to the lower reaches and the mouth at Flushing (Vlissingen) in The Netherlands. In its Dutch part, called "Westerschelde", the estuary is a meandering multiple channel system, with inter-tidal islands and inter-tidal flats at the inner side of channel bends. In its Belgian part, called "Zeeschelde", the estuary is a single meandering channel, with inter-tidal flats at the inner part of bends, but without inter-tidal islands. The upper parts of the inter-tidal areas along the shores of the estuary host fauna and flora-rich salt marshes.

The estuary is of economic importance as a major shipping artery, hosting the Port of Antwerp, as well as providing an access route to the Port of Rotterdam via the Rhine-Scheldt canal. The total population of the Scheldt catchment amounts to 10 million (ICBS). In the area itself a total population of around 300,000 people resides in the Netherlands and less than 1 million people in Belgium. This includes the city of Antwerp with a population of around 450,000 (2003).

Figure 4   The (Western) Scheldt-estuary (source: flyer from the project PROSES)

The Eastern Scheldt formed the main mouth of the river Scheldt until the Middle Ages. In the 14th century it lost this function to a tidal channel which formed a vast marsh area which gradually became connected to the Scheldt River north of Antwerp and evolved into the current river mouth. In the 17th century the Scheldt estuary was highly branched with extensive inter-tidal flats and marsh areas having large storage capacity. Since then the system gradually developed into the funnel-shaped estuary of the present days. A vast marsh area, called the Verdronken Land of Saeftinghe, was then formed. In 1867 the closing of the Kreekrak channel definitely separated the Easter Scheldt from the river Scheldt.

Both morphology and tidal characteristics have changed with time (van der Spek, 1994). Following Coen (1988), the tidal range near Antwerp increased considerably: from about 3.2 meters in 1650 to 5.2 meters in present days. The propagation speed of the tidal wave also increased. In 1650, the distance Flushing-Antwerp was covered by the wave crest in about 4.5 hours; at present it is covered in about 2 hours due to decrease in the storage areas. Another factor which has influenced the changing of the estuary characteristics is the rise of the sea level. Since 1650 the mean sea level is 0.5-1.0 m higher and it continues to rise. Another study (Kramer, 2002) similarly concluded that the changes in the tidal behavior between the year 1000 and 1800 are caused primarily by changes in the geometry and the sea level rise. The higher tidal dynamics that is the direct effect of the rising tide level and shortening of the propagation time has reduced the inter-tidal and brackish area in the estuary.

Recent (years to decennia) changes occurring after 1950, i.e. since the poldering was stopped and sand extracted from the system, have been extensively monitored. Between 1955 and 2002, the total sub tidal area in the Western Scheldt has decreased by 35%. However, a direct causal relationship between poldering and land loss has not been established (Kuijper et.al., 2004). Gerritsen et al (1999) analysed the relation between the changes of the tide and the morphological changes in the Western Scheldt. Field observations show that the amplification of the tide in the estuary has become stronger in time. As the following figure shows, the ratio between the amplitudes of M2 tide in the inner part of estuary and at the mouth is considerably increased in the period after 1970. This change in amplification is related to the morphological changes in the estuary, although it is not fully clear which of the human interferences (land reclamation, sand mining, dredging and dumping related to deepening and maintenance of the navigation channel) has caused the relevant morphological changes due to the long response time of the system to the interferences.
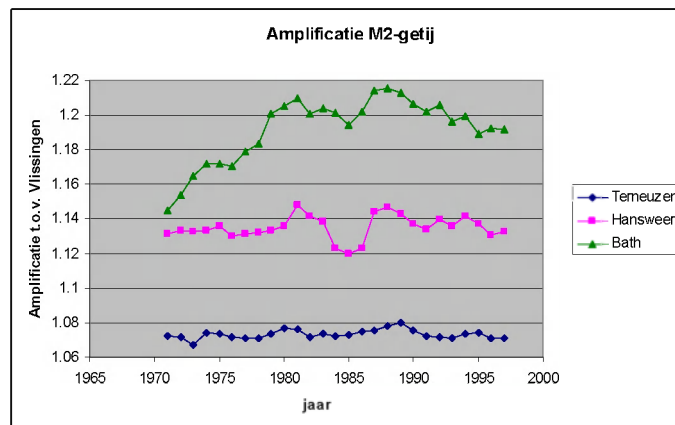

Figure 5   Amplification of the M2-tide (as a factor of the tide level at Flushing) at different locations in the Scheldt estuary

Analysis on the interaction between the morphology and the tide in the estuary (Wang et al, 1999, 2002) shows that the morphological changes under influence of the human interferences have a distinct influence on the tidal asymmetry in the estuary. Tidal asymmetry is an important factor influencing the residual sediment transport and thereby influencing the large scale morphological development. Although not fully understood yet, the recent turn from import (of sediment) to export of the estuary (Nederbragt and Liek,

2004, Haecon, 2006), is probably also related to the change of the tidal asymmetry in time. Export of sediment together with the ongoing sand mining in the estuary will cause the estuary to deepen gradually further.

The following factors contribute to flood potential in the Scheldt Estuary, leaving aside the effect of the sea level rise and the funnel shape of the estuary:
- Land reclamation that has significantly changed the surface area and the geometry of the estuaries,
- Land reclamation has thus resulted in a reduction of the basin volume, which also means that there is less space to absorb the impact of high water
- Navigation channel deepening and maintenance dredging reduces the travel time of the high water wave and increases the tidal level
- Erosion of salt marshes has potentially increased wave attack on the dyke system.
- Land reclamation has stopped the natural sedimentation process on large areas of the delta, to such an extent that the remaining large saltmarsh in the Western Scheldt has become one of the most elevated spots of the entire delta.
- Land reclamation leads enhanced subsidence of the reclaimed areas

Projected future conditions

There is an increasing demand to further deepen the channel in this estuary to allow larger ships enter the Port of Antwerp. Without careful consideration and appropriate remedial measures, the character of the estuary could potentially be altered from a multiple-channel to a single-channel system. The development strategy outlined in "Ontwikkelingsschets 2010 Schelde-estuarium" stipulates that deepening of the channel should be compensated by mitigation measures including wetlands expansion by landward relocation of flood defences.

The following goals for Western Scheldt development, to be realized by 2030, were formulated by the joint Dutch-Belgian LTV O&M project, under which this study is carried out:

- Provide adequate protection against flooding in the region, whereby an option to reconnect the Eastern- and Western Scheldt should be seriously considered.
- Maintain unimpeded access to the Port of Antwerp in the future, for which a study to maintain a tide-independent shipping depth up to 13.1 m will be conducted.
- Maintain healthy and dynamic natural ecosystems in the estuary

2.2.2 Extreme wind statistics

Extreme winds speed frequency statistics compiled for Flushing (Marechal, 2003) are summarized in Figure 6. The table below does not contain the recurrence frequency for the 1:4000 year. The wind speed value for the 1:4000 year frequency is equal to 35 m/s or 70 knots (Wieringa and Rijkoort, 1983).

Windspeed [m/s]	Recurrence Freq. [year]
17.8	0.5
18.9	1
19.9	2
21.1	5
22	10
22.8	20
23.8	50
24.5	100
25.3	200
26.2	500

Figure 6   Extreme wind statistics for Flushing (from S.E.M. Marechal, 2003)

The associated water levels for these wind recurrence frequency that has been adopted for a study "Inventory of historical water level in the Scheldt estuary" for Rijkswaterstaat (Asselman *et.al.*, 2007) is shown in the Figure below
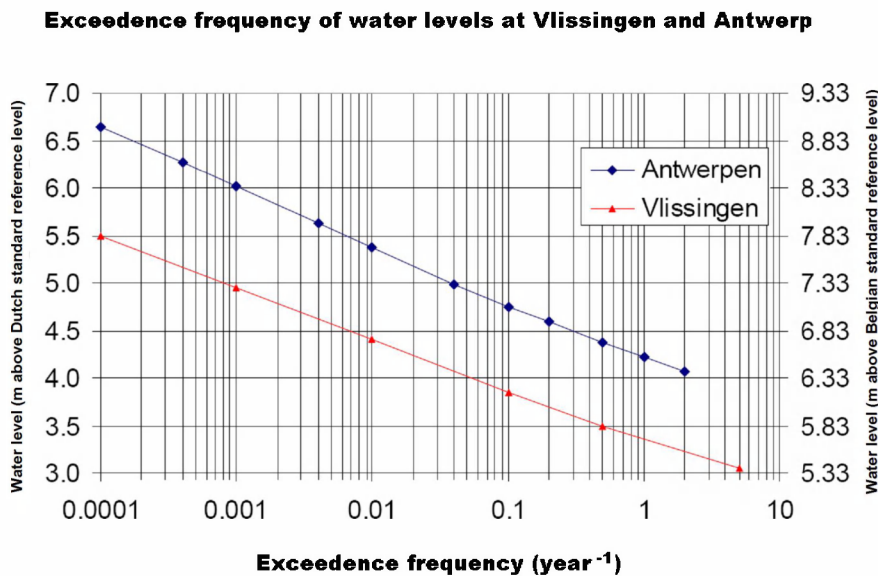

Figure 7   Exceedence frequency of water levels at Flushing (Vlissingen) and Antwerp

2.2.3 The 1953 flood event

On Friday, January 30th, a very severe storm moved over the North Sea. The strong north-westerly winds with wind-forces of 11-12 pushed the water in the North Sea in the direction of the English Channel. As the storm coincided with a spring flood tide, the water levels rose significantly. The spring flood tide occurred in the night of Saturday to Sunday at 5 am. However, many places were already flooded before high tide arrived. About 2 am, the first water flowed over the dykes. Dykes began to fail about an hour later. During the next low tidal period, the severe storm hindered the tidal movement, and water levels remained high. This resulted in even higher water levels during the second flood on Sunday afternoon. Figure 8 gives an overview of the areas that were flooded during the disaster. In total an area of approximately 2000km² were flooded. Water level in Antwerp reached up to a level of 7.7

m above the reference level. At Flushing, at the entrance of the Western Scheldt estuary, the water level reached approximately 4.5 m above mean sea level (MSL).
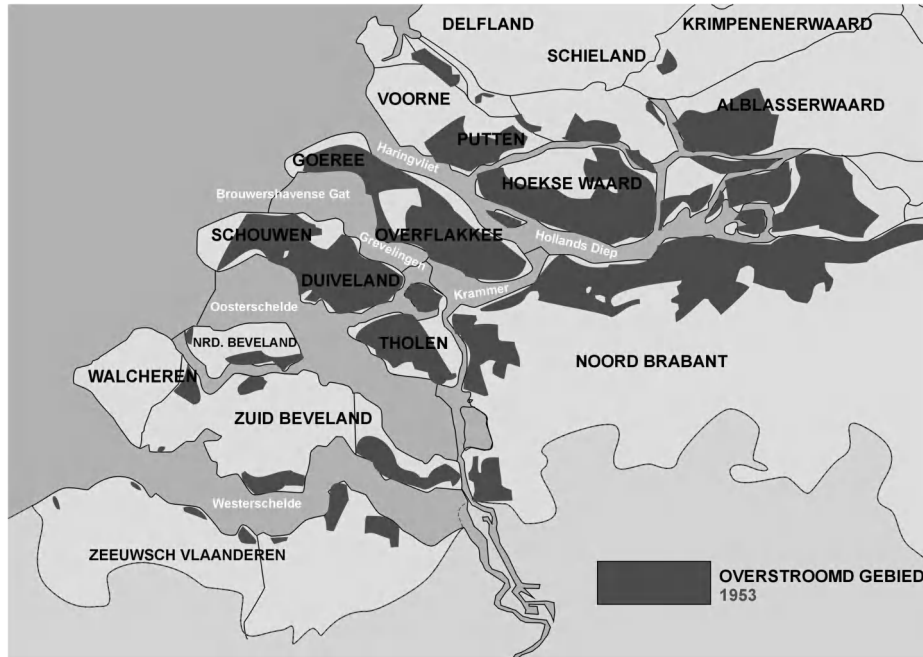

Figure 8   Overview of the flooded area during the 1953 storm (Source: Rijkswaterstaat)

The 1953 flood event in Zuid Beveland was simulated using the mathematical model Delft-1D2D. The actual breaches and the observed water levels were apllied as boundary conditions of the simulation (Asselman, 2003). Around 20 % of the total area of Zuid Beveland was inundated, i.e. 7500 ha or 75 km^2. (Rijkswaterstaat and KNMI, 1961). Nearly all breaches occurred along the southern sea dyke (bordering the Western Scheldt). Total inundated area in Zeeuws Vlaanderen was approximately 2880 ha, and was the least affected area of the Delta.

This disastrous flood caused more than 1800 fatalities and gave birth to the Dutch Delta Project, which led to the strengthening and raising of dykes, closing of some tidal inlets, and construction of storm surge barriers at the opening of the Eastern Scheldt (1986) and in the Nieuwe Waterweg (1997), the access channel to the Port of Rotterdam.
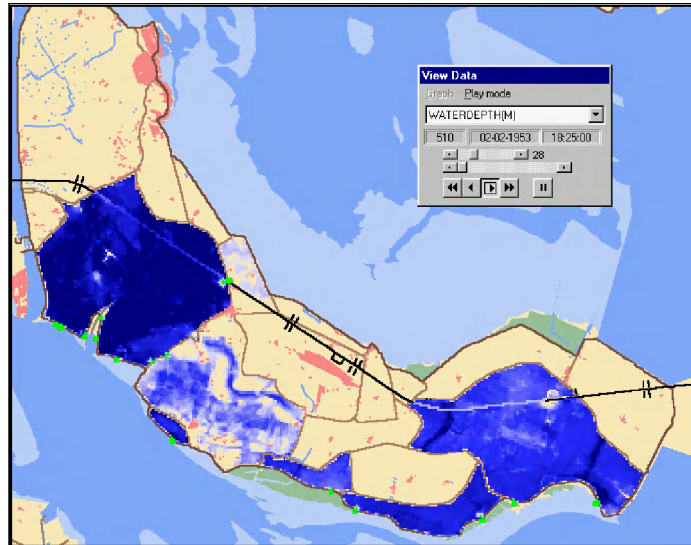
Figure 9   Delft-1D2D flood model result of Zuid Beveland during the 1953 storm.

The 1976 flood in Flanders

Because the high water level in the Western Scheldt estuary and Antwerp in 1976 were higher than in 1953, the event will be discussed in brief below.

Due to a north western storm water was pushed into the Scheldt River leading to dyke breaches at several locations along the river. More than 800 ha of the Zeeschelde corridor were inundated. In Antwerp water level of 7.31 m above TAW[2] was recorded. Especially the municipality of Ruisbroek was heavily affected (900 houses flooded).

2.2.4   Analysis of 1953 dyke breach

The analysis of the dyke conditions and maintenance practices before the 1953 flooding was discussed by Gerritsen (2005). By his account, historical practice determined dyke construction procedures, height and slope. Construction material was generally clay or less cohesive sandy clay, which was put on a clay foundation with subsurface of (sandy) clay, sand or even peat. The dyke height was simply the height of the highest recorded high water plus a safety margin of approximately one-half meter (Battjes and Gerritsen 2002).

Provincial supervision of the dykes existed more on paper than in fact. After the evaluation of the earlier flood that occurred in 1906, recommendations for the centralization of the polder boards in the southwest for coordinating dyke maintenance and dyke improvements were effectively resisted by the boards until 1945.

War-related construction in the period between 1940 and 1945 also affected the state of the dykes. Since the dykes were in now closed military areas, undermining by rabbits and moles increased. After the war, many of these weak spots were inadequately repaired by filling the holes due to higher prioritization of repair of war-damaged infrastructure.

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[2] TAW = Tweede Algemene Waterpassing (Belgian reference water level).

In 1953, the weakened areas described above often proved to be the locations where the dykes first failed. The collapse of most dykes initiated from the inside. The primary cause was wave overtopping, which led to penetration and subsequent saturation of the landward side with water. On steep slopes, this quickly led to sliding and collapse. The first visual impact of such a failure often was an along-crest crack at the landward side, as little as 10 cm wide. This absorbed the overtopping water, which seeped down and exited at the dyke toe. This erosion of the dyke base then led to sliding and overall collapse. Overall, the state of the dykes in 1953 left much to be desired with respect to height, slope, stability and structural integrity as well as their general state of repair.

2.2.5 Post-1953 coastal flood protection

After the 1953 storm in the Netherlands, the government decided to undertake the Delta Project to protect the inhabitants of the Delta Region against a storm with a recurrence interval of 4000 years. A legal framework, was established in 1958 with the Dutch Flood Protection Law and the Delta Act, which prescribed the closure of most of the last open estuaries to increase the level of flood protection reduce costs of upgrading a considerable length of levees along these estuaries. It was in the 1970's that a growing environmental awareness pushed the need for less drastic solutions. One contentious issue at the time was whether to close the Eastern Scheldt Estuary and turn it into a freshwater basin. The decision at the time was to implement a gated solution to maintain the estuary in a semi-natural state – a technically challenging approach. Although driven by safety considerations, the Delta Project enabled the creation of additional freshwater 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 and brackish water estuaries, with the exceptions of Eastern Scheldt estuary and the Lake Grevelingen, were all converted to freshwater systems, effectively separating fresh and saltwater systems. Although the gated barrier in the Eastern Scheldt allows tidal flow in the estuary, it effectively blocks sediments and has artificially altered historical shoaling and erosion patterns. Furthermore, the Delta Act requires flood protection levels of service to be maintained by regular updating of hydraulic design criteria and periodic inspections of levees and floodwalls to ensure their capacity to meet updated design criteria.

After the 1976 flooding event in Belgium, the Flemish government adopted the Sigma-Plan, with similar aims as the Dutch Delta-plan for the Zeeschelde corridor, i.e. to prevent a repeat of the 1976 disaster.

3 Similarities and differences between the two systems

3.1 Similarities

From a historical perspective it is clear that the present state of the Mississippi Delta and that of the 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 have evolved beyond their natural state, and both deltas have adapted and continue to adapt to manmade conditions. In the Netherlands, the era of significant human intervention dates back to roughly the tenth century, and two centuries in the Mississippi Delta. In both deltas, flooding from rivers and the sea triggered swift and large-scale system modifications patterned after traditional flood protection solutions. Immediate action was required in the Netherlands and is likewise being contemplated for the next hurricane season in the US Gulf Coast, again primarily employing traditional approaches including levees, barriers and floodgates.
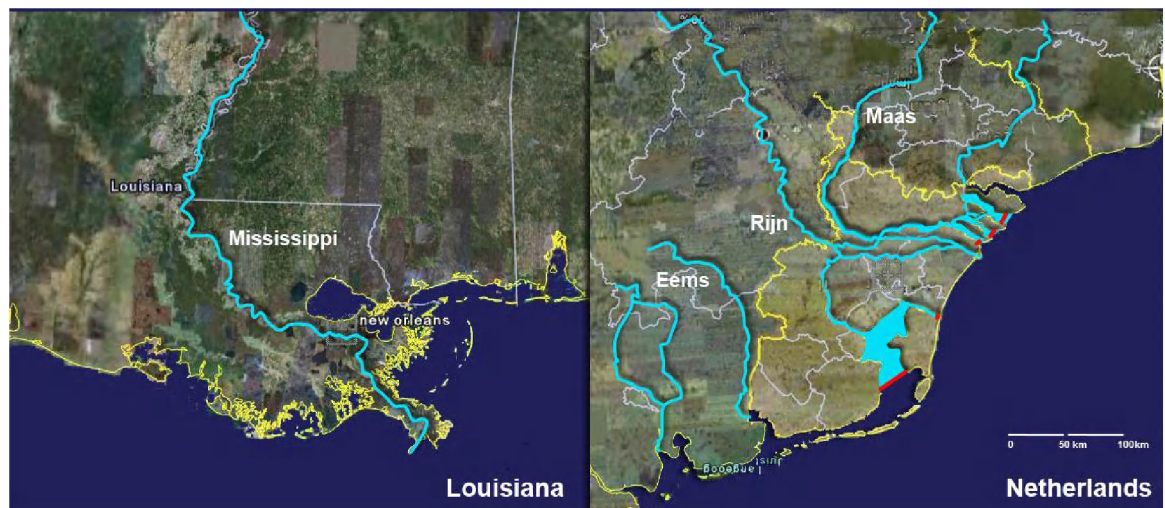

Figure 10   Mississippi Delta and the Netherlands, outlining fresh water bodies on similar scale. Image of the Netherlands oriented South and pointing upwards (source: Dutch Perspective report - Kevelam D, DHV)

To summarise, some of the similarities between the two systems are as follows:
o   Adapted by human intervention
o   Similar longitudinal dimensions and funnel-shaped features
o   Sensitive to surge amplification due to topography and dredging
o   In direct contact with the open sea
o   Horizontally confined by dykes
o   Subject to major coastal flooding with similar recurrence intervals
o   Prone to flooding, potentially exacerbated by climatic and geologic changes including sea level rise and subsidence, and human alteration including channelization, erosion/aggradation, and/or channel widening, deepening or realignment.

3.2   Differences

Significant differences between the two systems are briefly described below, with terms 'WS' used to denote the Western Scheldt Estuary, 'MD' the Mississippi Delta including the Port of New Orleans, 'IHNC' the Inner Harbor Navigation Channel, and 'MRGO' the Mississippi River Gulf Outlet.

- WS is a natural estuary altered to a much lesser extent by maintenance dredging for navigation purposes than the MD with the Port of New Orleans, IHNC and MRGO.
- WS has larger transverse spatial scale, whereas both systems have comparable longitudinal dimensions
- WS is a mesotidal (tide dominant) system, whereas MD is a microtidal (wave dominant) system
- WS has a larger maximum and average depths than MD, especially when looking at the eastern part of the MD (Lake Borgne, IHNC, Lake Pontchartrain)
- The depth of the Mississippi river in MD is between 15 – 70 meters, while the range of depth in the entire WS is between 2 – 20 meters
- The river discharge of the Mississippi river is 50 to 150 times larger than the discharge of Scheldt river in WS
- WS, as the only open-sea access to Port of Antwerp, experiences much greater shipping traffic volume and tonnage than MD
- The meteorological threats for the Mississippi are hurricanes, while the threats for the Western Scheldt estuary come from storms-surges combined with high tides.
- Wind speeds associated with hurricanes in MD are much greater than for storms experienced in the WS, and consequently storm surges of a magnitude that occur in WS relatively infrequently may occur in MD fairly often
- MD is surrounded by wetlands that flood due to hurricane storm surges. During Hurricane Katrina, a large portion of the storm surge that reached the city of New Orleans flowed over these wetlands. The Western Scheldt is mostly surrounded by polders, which are protected against flood during storm surges.
- Flood protection of the WS is supported by a comprehensive legal and institutional framework with assured funding, whereas planning and execution of MD flood protection measures is relatively ineffective due to fragmented institutions and inadequate and/or uncertain funding.
- Design of flood protection systems in the WS and the Netherlands is risk-based, whereas in the US standards-based (i.e. 1:100 year event) design criteria are used.

4   Conclusions / Lessons learned from Katrina flooding event for the Scheldt Estuary

In the comparison of the Mississippi delta and the Western Scheldt estuary the similarities in the physical system have been discussed. However, it must be stressed that the hydrodynamics, the morphology and the weather systems of these areas differ to a large degree. Despite the fact that both areas are both subject to coastal flooding originating from meteorological forces, there are important differences in storm surge characteristics affecting the two areas. These differences are important because they present the physical boundary conditions for solutions to prevent and prepare for flood disasters.

An example, to stress the importance of the physical differences, is the effect of the large tidal range in the Western Scheldt in case of a dyke breach. When the hinterland is low-lying with respect to the tides (and that is the case for a major part of polders that flank the estuary) and such a breach does occur, the area will not simply flood, it will also developed into a tidal basin. The in- and outgoing flood and ebb currents will rapidly erode the original breach into a deeply incised tidal channel. The closure of such a channel during flooding will be complicated, even with today's advanced equipment. The strong and opposing currents complicate any construction work. In the Mississippi Delta such a breach will not develop into a tidal channel, because of the small tidal range, which makes the closure of the breach (although still far from simple) less complicated. This difference may make it worthwhile to invest more in prevention in Zeeland, and more in damage repair in Louisiana.

Moreover, the current legal and institutional frameworks for design, maintenance, repair and improvement of flood protection works differ in fundamental ways. As a consequence many of the lessons to be learned from the flooding of New Orleans caused by Hurricane Katrina-in 2005 are more a product of differences than similarities between US and Netherlands approaches to coastal flood protection.

Risk-based design, by accounting for social preferences, economic benefits and costs, and adaptability to non-stationary climatological conditions, is clearly preferable to standards-based design. In the US, for example, levees, floodgates and river flood protection works are often designed to protect against lesser floods, i.e. 100- to 500-year events, than comparable high-hazard dams, design of which is commonly based on the probable maximum flood (PMF). The PMF effectively constitutes the upper limit of statistical flood extremes, and as a result many dams in the U.S. provide much higher levels of protection than levees relative to potential consequences of failure.

A strong and integrated legal and institutional framework, coupled with assured and adequate levels of funding, are essential to design, maintenance, inspection, repair and improvement of flood protection systems. The institutional commitment requirement extends not only to structural flood protection measures, but also to long-term restoration and protection of coastal ecosystems and natural flood defenses. The differences in the physical conditions (the hydrodynamic forcing and the sediment sources and sinks) however, would require very different designs in the two situations. This means that the

locations for successful restoration projects differ and also that the design of such project must differ.

The similarities in the Mississippi delta and the Western Scheldt estuary are in essence related to their uses. For the Western Scheldt, the main functions of the estuary are flood protection, navigation and preservation of coastal ecosystems – similar in these important respects to the Mississippi delta. The two functions potentially in conflict are navigation and flood protection, because navigation requires unrestricted access for ships and therefore unrestricted flow of water, while protection against flooding requires flow restriction. Balancing these two functions in the future are challenges to both the estuary and the delta.

Lessons from New Orleans for the Western Scheldt Estuary
Comparison between Mississippi Delta and the Western Scheldt Estuary
Z4511
February 2008

5   Recommendations for further studies

From the discussions in the previous chapters and from other studies, it can be concluded that some gaps yet exist in our knowledge and capability for reliable short- and long term prediction of the effects of human intervention on natural processes and on risk of flooding, be it positive or negative.

These knowledge gaps can best be illustrated by posing specific questions listed below. We recommend that these questions be addressed in the near future to further improve the Dutch flood prevention measures.

A. **Can (re-)construction of wetlands and marshes provide significant immediate and long-term benefits to coastal flood protection?**

Related questions are as follows:
- Can the effects of various coastal restoration measures be reliably quantified?
- Is it possible to identify optimal locations and minimum configurations for sustainable wetlands?

The (re-)construction of marshland can reduce the impact of storms by the reduction of the wave height near the flood defences ('natural wave breakers'), by a reduction of the wind speed ('wind breakers') and possibly through the reduction of flood levels

The recent New Orleans study conducted by the NWP consortium indicated that restoration of freshwater and coastal wetlands has the potential to significantly reduce surge levels near the city of New Orleans, as shown in Figure 11 below. However, these preliminary Delft3D results also indicate that flood reduction is highly dependent on the storm characteristics including storm size, strength, track and speed of forward motion. Due to frictional effects water levels may increase along the transitional area between marshland and water.

Here we must also stress that the positive effect of the wetlands on the surge levels is not supported by the recent studies carried out by LACPR using a more detailed hydrodynamic model. Because this issue could play an important role in the discussions on flood risk reduction, the conservation and possibly restoration of wetlands, we strongly recommend carrying out studies on the possible immediate and long-term benefits of wetlands on coastal flood protection.
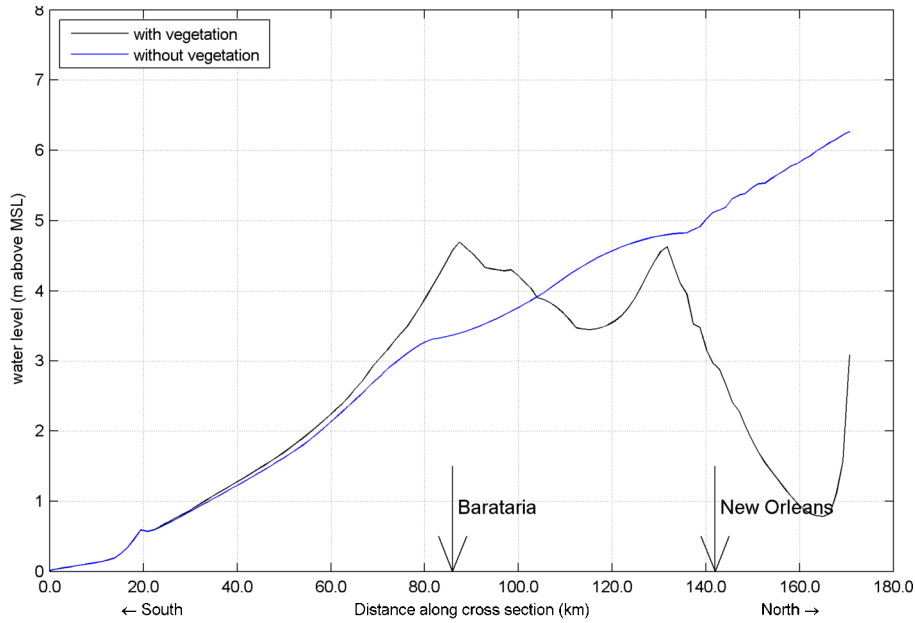
Figure 11   Effects of vegetation on maximum surge levels (excluding the tide level) along a North-South
               cross section of the model crossing Brataria and New Orleans

B. How does variation in storm parameters scenarios affect flood protection system design criteria?

A recent study to assess the effect of failure of the dykes under design water level conditions (probability of occurrence 1:4000), conducted by WL | Delft Hydraulics for the eastern part of Zuid Beveland using the Delft-1D2D computer model, indicates that relatively small changes in water level can significantly alter flood patterns and flood depths (Jeuken et al., 2007). Figure 12 shows sample stage hydrographs applied to dyke breach simulations. The series represent alternative water level scenarios used by the Dutch and the Belgian for an identical event. The shapes of the series are similar, but not identical. The maximum level differs by 10 to 20 cm.
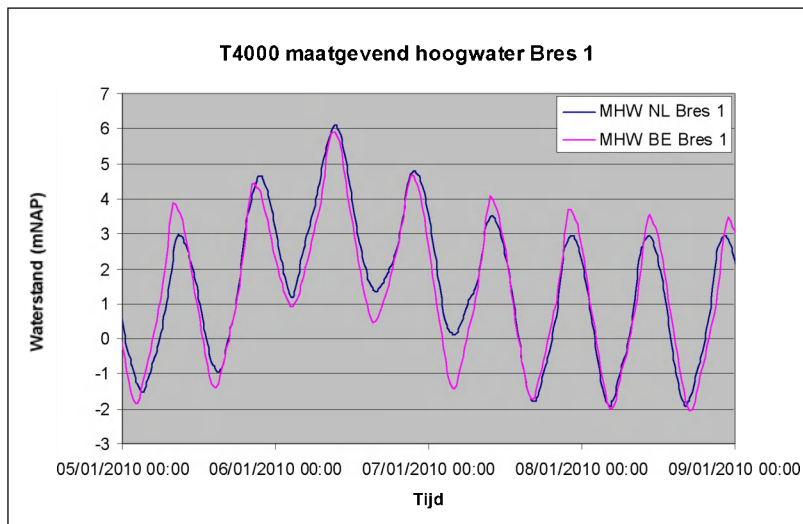

Figure 12   Time series of water levels applied to the flooding model of the eastern part of Zuid Beveland
               (source: Asselman et. al., 2007)

Lessons from New Orleans for the Western Scheldt Estuary
Comparison between Mississippi Delta and the Western Scheldt Estuary

Z45 I I

February 2008

While the hydrographs are similar, the impacts differ significantly. Figure 13 shows the computed maximum flood extent and maximum water depths using both conditions. A relatively small increase in the water level scenario produced significantly higher flood levels and flooded areas. In the Dutch scenario, few of the secondary dykes are overtopped. In the Belgian scenario, however, more secondary dykes are overtopped and much more area floods. If, for arguments sake, we assume that each scenario represents a minor variation in storm dynamics, than it is essential that the design parameters be tested against a multitude of (small) variations in the storm scenarios applied to derive these parameters. In short, insight in the return periods of flood levels at a location can only be obtained by simulating the flood levels for a large number of historical or synthetic storms with different features (size, track, radius, etc.) instead of using a single typical storm event. Single events such as the so-called Standard Project Hurricane were previously used as the basis for design in the U.S, and such approaches continue to be applied in the Netherlands as well. From simulations of multiple storm ensembles can return period of specific flood elevations at specific locations be estimated with reasonable confidence.
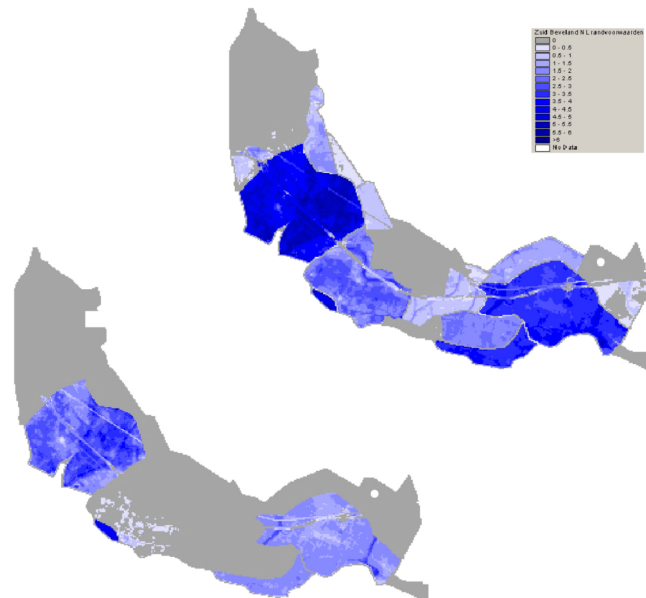

Figure 13   Maximum computed water depths the eastern part of Zuid Beveland, using the Dutch (top) and Belgian (bottom) water level time series (source: Asselman *et. al.*, 2007).

Following hurricane Katrina, the significance of storm parameter variation on flood frequency has been understood quite well in the US, and much has been accomplished in development of empirical simulation techniques and optimal sampling methods for joint probability estimation. In a joint effort of USACE and FEMA (the Joint Coastal Surge Study), these approaches have been refined to produce a suite of 152 storms for detailed simulation and estimation of flood levels for different return periods. Consequently we recommend to perform a study on the effect of variation in storm scenarios on the Dutch flood protection design conditions on a similar line as the US approach.

C. Does enlargement of estuaries result in a significant surge reduction?

Provision of storage buffers by selective lowering of dykes to reduce peak storm surge levels is consistent with strategies for storage and attenuation of riverine floods. In rivers the water volume in the storage basins is relatively large compared to the water volume contained in the discharge peaks. It is not currently known whether such a surge reduction strategy is feasible for wind-generated (as opposed to precipitation-induced) flood waves in an estuary in contact with the open sea. Questions that need to be addressed include required storage volume, optimal location and adaptability to different storm surge characteristics. Contrary to river floods, flood volume associated with wind-generated waves on the open sea is practically unlimited in comparison to river basin runoff due to precipitation. Hence the questions how significant the surge reduction would be in case the storage buffers of estuaries are enlarged.

D. How much surge amplification due to funnelling effects can be expected in the Scheldt Estuary?

It is widely recognized that the funneling effect that in all likelihood amplified the surge in New Orleans could likewise affect the Scheldt Estuary, with different storm parameters producing different impacts. We propose to study and quantify effect in the Western Scheldt estuary for different storm conditions.

Figure 14   Funnel effect that may enhance the storm surge levels (source top picture: Carter N T and Stern C V, 2006).

E. Would the integrated 2D modelling approach applied for New Orleans yield different results for the Netherlands?

Most of the recent studies that have been carried out to investigate the impacts of Katrina in New Orleans have been are performed using advanced, high resolution two-dimensional (2D) models (ADCIRC+STWAVE, Delft2D-FLOW + WAVE + Vegetation). The models incorporate multiple important parameters that can interact with one another in a single 2D model: flood wave propagation, wind-driven waves, astronomical tides, storm surge hydrodynamics, bathymetry, topography and hydraulic resistance. To our knowledge, in the Netherlands this type of modeling approach has never been applied in a fully integrated fashion. This can be explained by the fact the Dutch approach is geared towards prevention rather than post-facto simulation of flood events. However, it can be argued for the Dutch situation that, if flooding is to be allowed under certain conditions or when a dyke breach occurs, the interaction between these parameters will need to be properly considered for accurate simulation of flood levels. Increased understanding of these effects combined, through integrated 2D modeling approach, could yield new insights to the prospective effectiveness of flood protection alternatives in the Netherlands.

6   References

Asselman N, Coen L, Diermanse F, Groeneweg J, Jeuken C, Peeters P, Pereira F, Sperna Weiland F, Vanlede J, Viaene P (2007), *Sterkte-zwakte analyse van de methoden waarmee de maatgevende condities en de fysische gevolgen van overstromingen langs het Schelde estuarium worden bepaald in Nederland en in Vlaanderen*, Koploperproject LTV-O&M-Thema Veiligheid - deelproject 1 & 2, WL | Delft Hydraulics report for Rijkswaterstaat no. Z4384.

Asselman, N E M (2003), *HIS simulatie Delta 2003* (in Dutch). WL|Delft Hydraulics report no. Q3329.

Battjes J A, Gerritsen H (2002), Coastal modelling for flood defence, Phil. Trans. R. Soc. A, Volume 360, Number 1796, pp. 1461-1475.

Blake E S, Rappaport E N, Landsea C W, NHC Miami (2007), *The Deadliest, Costliest, And Most Intense United States Tropical Cyclones From 1851 To 2006 (And Other Frequently Requested Hurricane Facts)*, NOAA Technical Memorandum NWS TPC-5, April 2007.

Carter N T and Stern C V (2006), **Mississippi River Gulf** *Outlet (MRGO):Issues for Congress,* CRS Report for Congress, Congressional Research Service - The Library of Congress, August 2006 (http://www.ncseonline.org/NLE/CRSreports/06Sep/RL33597.pdf).

Coen I (1988), *Ontstaan en ontwikkeling van de Westerschelde, Water,* Vol. 43, pp.156-162 (in Dutch).

Dijkman J (editor), (2007), *A Dutch Perspective On Coastal Louisiana Flood Risk Reduction And Landscape Stabilization,* Netherlands Water Partnership Report For International Research Office Of The U.S. Army.

Gerritsen H, Wang Z B and van der Weck A W (1999), *Morfologische interpretatie van de veranderingen in het getij van de Westerschelde,* WL | Delft Hydraulics, Rapport Z2671.

Gerritsen H (2005), *What happened in 1953? The Big Flood in the Netherlands in retrospect,* Phil. Trans. R. Soc. A.

Haecon (2006), *Actualisatie van de zandbalans ven de Zee- en Westerschelde,* Haecon (Soresma), report 1249760008/lvp.

IPET (2007), *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System,* Final Report of the Interagency Performance Evaluation Task Force, Volume III, IV and V.

Jeuken C, Hordijk D, Ides S, Kuijper C, Peeters P, de Sonneville B, Vanlede J, (2007), *Inventarisatie historische ontwikkeling van de hoogwaterstanden in het Schelde estuarium ,* Koploperproject LTV-O&M-Thema Veiligheid - deelproject 2, WL | Delft Hydraulics report for Rijkswaterstaat no. Z4384.

Kok M, Theunissen R, Jonkman S.N, Vrijling J.K. (2006) *Schade door overstroming: ervaringen uit New Orleans*, TU Delft / HKV publication, ISBN-10: 90—77051-00-7.

de Kramer J (2002) Waterbeweging *in de Westerschelde, een literatuurstudie*, ICG-rapport 02/6 (produced as part of the project 'Zeekennis' for RIKZ).

Kuijper C, Steijn R, Roelvink D, van der Kaaij T, Olijslagers (2004) P, *Morphological modelling of the Western Scheldt*, Report Z3648 from WL | Delft Hydraulics prepared for RIKZ.

Marchand M, Crosato A, Klijn F (2006), *Flood risk analysis for the river* **Scheldt** *estuary*, EU-FLOODSite project report number   T25-06-01.

Marechal S E M (2002), *Downtime analyse van een exposed containerterminal, Case study: Westerschelde Container Terminal, Vlissingen*, Masters Thesis, Technische Universiteit Delft, October 2002.

Nederbragt G and Liek G-J (2004), *Beschrijving zandbalans Westerschelde en monding*, Rapport RIKZ/2004.020, Rijkswaterstaat, Rijksinstituut voor Kust en Zee/RIKZ.

USGS, (2007) *Historical and Projected Coastal Louisiana Land Changes: 1978-2050*, Open-File Report 03-334.

Van der Spek A (1994), *Large-scale evolution of Holocene tidal basins in the Netherlands*, PhD thesis, University of Utrecht, ISBN 90-393-0664-8.

Wang, Z B, Jeuken C, Gerritsen H, de Vriend H J, Kornman B A (2002), *Morphology and asymmetry of vertical tide in the Westerschelde Estuary*, Continental Shelf Research, Volume/Issue 22/17 pp. 2599-2609.

Wang, Z B, Jeuken C, and de Vriend H J (1999), *Tidal asymmetry and residual sediment transport in estuaries*, WL | Delft Hydraulics, Report Z2749.

Wieringa J en Rijkoort P J (1983). *Windklimaat van Nederland*, KNMI, Staatsuitgeverij, Den Haag 1983.