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Coastal defence cost estimates

Case study of the Netherlands, New Orleans and Vietnam

Report of measurements and observations

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April 2010

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1 Background and objective

Background
A large and fast-growing part of the world's population lives in low-lying coastal zones. To sustain economic activities and living in these areas a wide range of coastal defence measures has been constructed. These coastal defence measures reduce the risk to economic values and populations in coastal zones prone to flooding. Coastal defence measures can even help to enable living in areas that are below sea level, for example in parts of the Netherlands and New Orleans.

Climate change, and more specifically sea level rise, poses a direct threat to these areas (Ericson et al., 2006; Nicholls et al., 2008). Sea level rise requires the coastal defence measures to be adapted to higher water levels and more intense hydraulic boundary conditions (such as waves and storm surges). The exposure of coastal zones and especially coastal cities to flooding was determined by Nicholls et al. (2008). However the risk of flooding and the costs of adaptation to sea level rise are greatly influenced by coastal defence measures. The study of Linham et al. (2010) builds upon Nicholls et al. (2008) to determine the risk and impact of flooding in port cities.

Objectives
This study is part of a global study on the costs of adaptation to the effects of climate change (Linham et al., 2010). It adds information from three specific case studies (the Netherland, New Orleans and Vietnam) to the global study. The case study areas are comparable by type of coast; all are low-lying deltaic coastal areas. This study investigates the unit cost estimates of coastal defence for the full range of hard and soft engineering measures, such as dikes/levees, sea walls, (beach) nourishments and other measures, for example storm surge barriers.

In considering the costs of coastal defence and adaptation to climate change different scale levels can be recognized (see Figure 1-1). At the highest level of detail specific information from actual projects and designs can be utilized. This requires detailed insight in the actual design and as built status of coastal defence projects. By combining information from individual projects, cost estimates can be provided for one enclosed coastal defence system, e.g. a dike ring or polder in the Netherlands or New Orleans. Cost estimates at a national level can be obtained by aggregating information from different defence systems. For example, Kok et al. (2008) report estimates of the costs of adaptation of the flood defences in the Netherlands to different levels of sea level rise. This is done by combining assessments of the response of different sub systems and dike rings to the sea level rise (see also section 2.1). Finally, estimates for different systems and countries can be aggregated to cost estimates at a regional, continental or even global level.

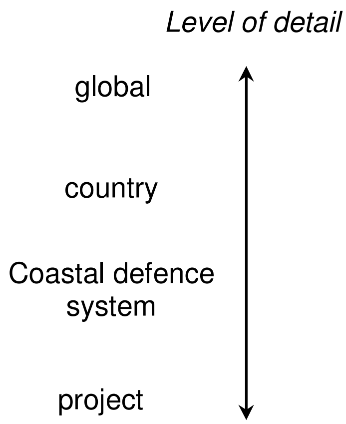


Figure 1-1: Different levels of detail for coastal defence cost estimates

This study largely focuses on cost estimates at the project and system level, whereas previous studies (e.g. IPCC CZMS, 1990; Hoozemans et al., 1993) provide global estimates. The project and system based estimates can be used as input for the cost estimates at higher levels. The coastal defence cost estimates in this study are derived from several studies conducted by the authors for the case study areas considered.

In addition to the three case studies for the Netherlands, New Orleans and Vietnam, another case study has been included in this research. M.A. Geldenhuys BSc studied the unit cost prices of coastal defence measures for Cape Town (South Africa) and this work was conducted as part of the COMEM MSc program at the Delft University of Technology. The results are included in appendix I of this report and the main results and unit cost prices are also included in the main report. This is an interesting comparison, as the three case studies (the Netherlands, New Orleans, Vietnam) are low-lying deltaic coasts, whereas the coast of Cape Town is more variable in terms of elevation, protection and coastal management strategies.

Structure of this report
This report is structured as follows. Section 2 provides a summary of relevant information for the three case studies. A summary of the coastal defence cost estimates is given in section 3. This section also includes a discussion of relevant aspects, such as the relationship between the sea level rise rate and the unit cost prices. Section 4 reviews various studies for the three case studies that give insight in the optimal standard of protection. The most important conclusions and recommendations are given in section 5.

2 Case study areas

This study focuses on three study areas: the Netherlands, the city of New Orleans (United States) and Vietnam (Figure 2-1). These three areas are all subjected to the risk of coastal flooding. The case study areas have a similar type of coast, a low-lying deltaic coast, and are all affected by sea-level rise.

This chapter gives a brief introduction of each case study area. The history, geography and coastal defence measures of the area concerned are described. Furthermore the studies as conducted by Delft University of Technology are introduced and the main relevant literature is discussed. For each case study area the cost information on coastal defence measures is provided and unit cost prices are derived.

Next to the overview of coastal defence measures and the main characteristics of the case study area, the background of the cost data is given. This provides insight in the background of the quantitative data and how to interpret these results.

Chapter 2.1 describes the Netherlands, in chapter 2.2 the New Orleans case study is described and chapter 2.3 concerns the case study of Vietnam.

Costs are provided in euro (€), where US$ were used in studies a conversion rate of 1€ = 1.35 US$ was applied.

Figure 2-1: World map with case study areas

2.1 The Netherlands

2.1.1 Background, history

The Netherlands, situated in the North-West of Europe, is a low-lying coastal zone of which the Southern coastline is largely formed by a delta of three European rivers; the

Rhine, Meuse and Scheldt. About one-forth of the country is below sea level and half of the country is situated below less than one meter above mean sea level. In the current situation 65% of the Netherlands is prone to flooding (this includes river-flooding).

The history, existence and the present day landscape of the Netherlands has been primarily influenced by water. Flooding events have shaped the Dutch landscape and efficient water management has shaped the country's organization: the water boards are the oldest democratic organization in the Netherlands (13th century). Through land reclamation by polders, a combination dikes and drainage, the Netherlands was shaped, continuously balancing natural processes and human needs. More in general, the polder concept as applied in the Netherlands can be considered a way to live in a delta; it is the result of a continuous optimization to live and cultivate the land on the one hand and sustain economic activities by controlling the water on the other.

In the current situation a flood defence system is in place to protect most of the Netherlands from flooding. This systems consists of several flood defence measures; dikes, storm surge barriers and several management systems such as dike rings and beach nourishments. Large well-known coastal defence structures in the Netherlands are the Afsluitdijk (direct translation: 'Closure dike') which closed off the tides of Zuiderzee (former sea, adjacent to the Wadden Sea) and the Deltaworks, an extensive system of dikes and storm surge barriers which protects the South-Western delta after the catastrophic flooding of 1953. The strategy to dam rivers and close off estuaries which shortens the coast line and the length of flood defences (Figure 2-2) has been regarded an effective coastal defence strategy. Nowadays the Dutch flood defences have safety standards up to 1/10000 years (Figure 2-3); e.g. these defence measures can withstand a flooding event with a 1/10000 year frequency.

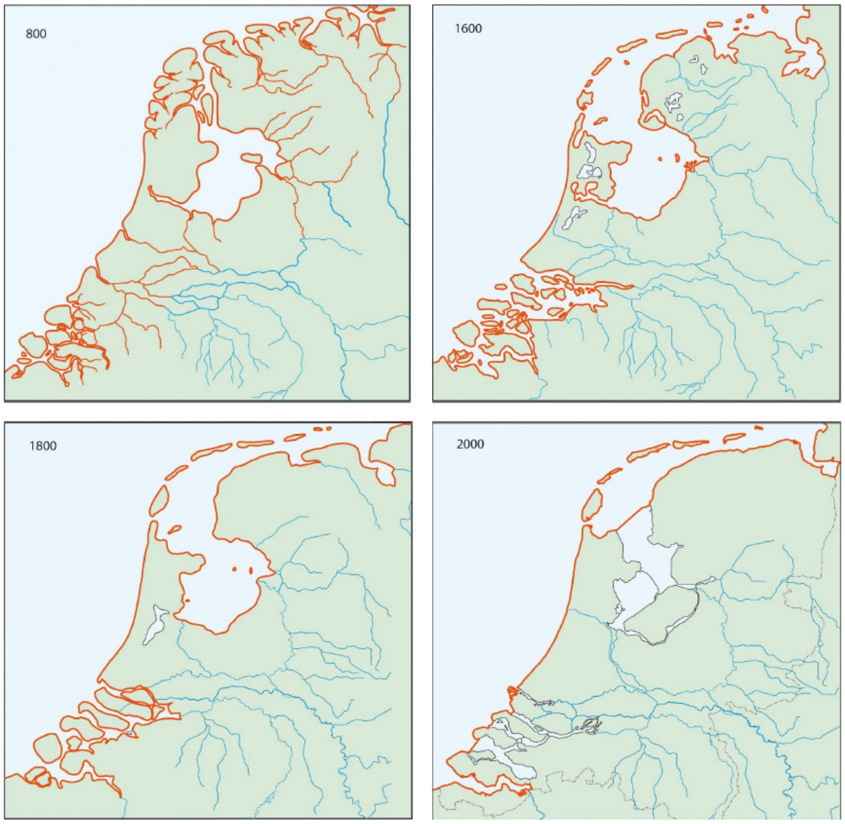


Figure 2-2: Shortening of the coastline of the Netherlands over time (Kok et al., 2008).

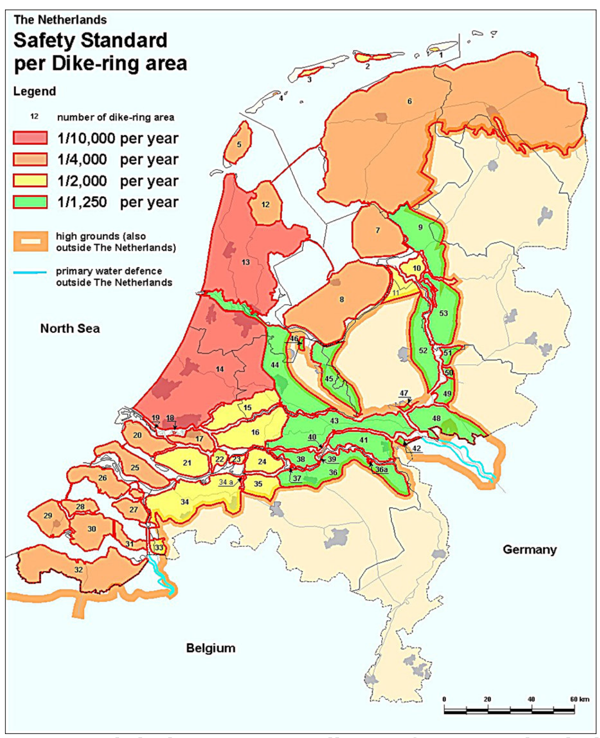


Figure 2-3: Dike-ring areas and their corresponding safety standards in the Netherlands

2.1.2 Coastal defence measures

As mentioned above, the coastal defence system of the Netherlands consists of several coastal defence measures. The dike ring areas along the coasts have two different safety standards (1/4000 and 1/10000) and are closed systems consisting of dunes, sea dikes and storm surge barriers on the sea side. In addition to these coastal defence measures, beach nourishments are applied along the Dutch coastline, which help to sustain the sandy beaches and dunes (Figure 2-6).

Figure 2-4: Examples of sea dikes in the Netherlands (photos: Royal Haskoning)

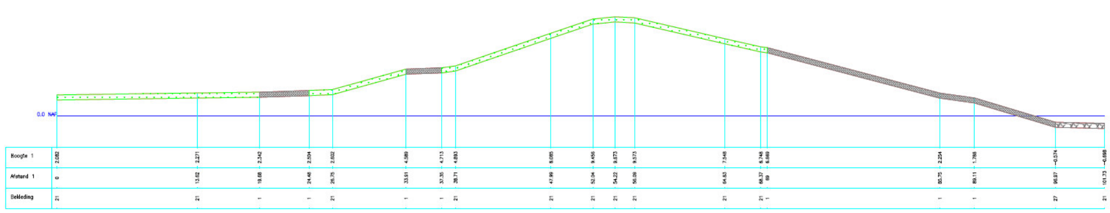


Figure 2-5: Cross-section of a typical sea dike


Figure 2-6: Beach nourishment in the Netherlands (www.rijkswaterstaat.nl)

2.1.3 Cost estimates

For the Deltacommittee Kok et al. (2008) investigated the sustainability and financial durability of the Dutch polder concept. The technical feasibility of the polder concept was investigated; e.g. is it possible to maintain the polder approach with climate change by keeping the current system of water defences in place? Also alternative strategies and other measures where researched: reduction of flooding impact, alternative enhancements of the flood defences and a different approach for the polder concept.

The costs to maintain the current safety standards with sea level rise and the costs to adopt higher safety standards with sea level rise up to 2200 were investigated for the primary water defences of the Netherlands. The costs mainly concern raising dikes, construction of new (or strengthening of) storm surge barriers and maintenance of the coastal defence measures.

Dikes

Kok et al. (2008) based their estimates on several studies conducted for the Rijkswaterstaat (Ministry of Public Works). These studies investigated the safety standards of dike ring areas. Arcadis and Fugro (2006) conducted such a study for three dike ring areas along the coast and the Central Planning Agency (CPB) of the Netherlands did investigate these standards in the same time period (Eijgenraam, 2005; 2006) for a larger number of dike rings, including river dikes.

The cost estimates to raise the sea dikes are presented in Table 2-1 (Arcadis and Fugro, 2006) and Table 2-2 (Eijgenraam, 2005). The cost estimates of Eijgenraam (2005) were found to be linear with the dike heightening (Figure 2-7).

Table 2-1: Cost estimates of three coastal dike-ring areas (Arcadis and Fugro, 2006)

Arcadis and Fugro (2006)			
Dike heightening	**North Sea dikes**	**Western Scheldt dikes**	**Averaged**
[m]	*[M€/km]*	*[M€/km]*	*[M€/km]*
0.8	4.36	4.46	4.41
1.6	5.82	6.37	6.095
2.4	7.3	8.28	7.79

Table 2-2: Cost estimates of coastal dike-ring areas (Eijgenraam, 2005)

CPB Cost estimates (Eijgenraam, 2005)		dike heightening 0.5	0.75	1
Dike ring number	*Name*	*[M€/km]*		
15	Lopiker- en Krimpenerwaard	6.8	8.9	11.1
16	Alblasserwaard en Vijfheerenlanden	8.5	11	13.3
22	Eiland van Dordrecht	6.6	8.4	10.2
23	Biesbosch (Noordwaard)	2.5	3.2	4.3
24	Land van Altena	3.5	4.7	6.1
35	Donge	4.7	6.4	7.9
	Average costs	5.4	7.1	8.8

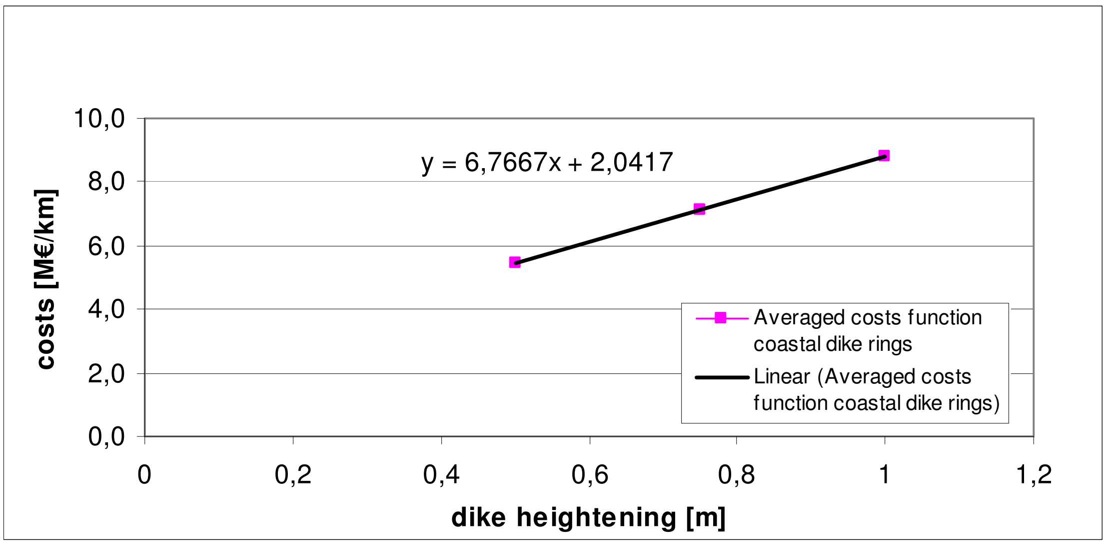


Figure 2-7: Averaged cost function of coastal dike-ring areas (Eijgenraam, 2005)

Nourishments

Due to the availability of nourishment material and the large amounts of beach nourishments in the Netherlands the costs of nourishments in the Netherlands used to be relatively low. Arcadis and Fugro (2006) estimated these costs to be 2.85 euro per m^3, where Kok et al. (2008) used a slightly higher number: 3 euro/ m^3.

However, both the Ministry of Transport, Public Works and Water Management (RWS, 2009) and the Algemene Rekenkamer (2009) ('court of audit') noted that the costs of nourishments in the Netherlands have increased rapidly over the last five years (Figure 2-8).

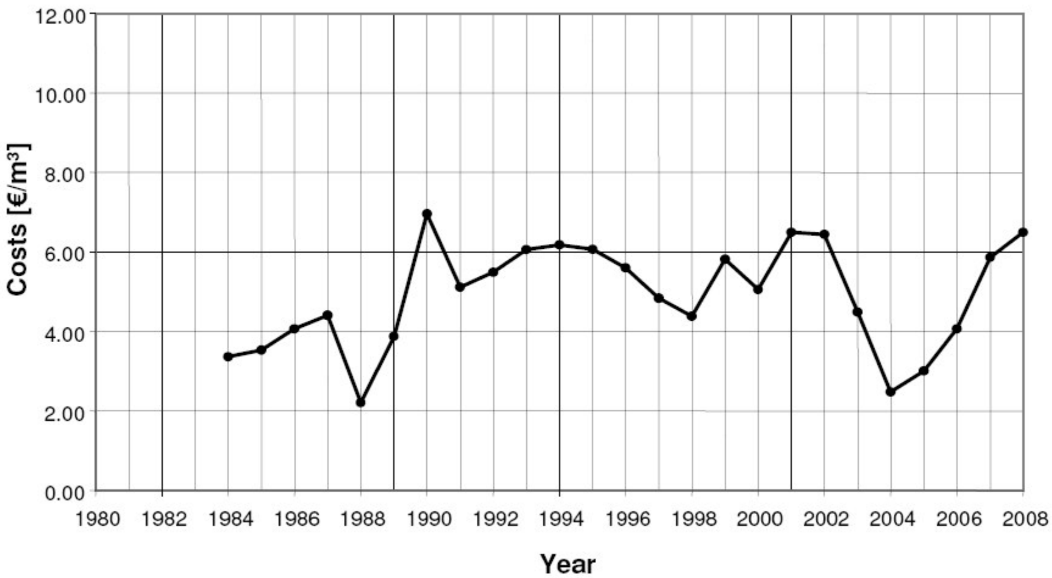


Figure 2-8: Price development nourishments in the Netherlands (RWS, 2009)

In the Netherlands more nourishments are required in the coming years and the Deltacommittee (2008) anticipates even larger amounts of sand are needed in the (near) future. Therefore, at the Ministry of Transport, Public Works and Water Management (RWS, 2009) there is a concern about the current price development of nourishments. Due to the current market situation; e.g. the limited number of large contractors available, the international market-prices and the large increase in demand the prices of nourishments have increased significantly. The Algemene Rekenkamer (2009) informed the Dutch parliament about this situation in a letter (Algemene Rekenkamer, 2009).

Structural increase in cost prices from 2004 till 2009 (in 2009 price level) as determined by RWS/ Ministry of Transport, Public Works and Water Management (2009):

- Foreshore nourishments: from €1.11 to €3.72 (Figure 2-9)
- Beach nourishments: from €2.54 to €7.55 (Figure 2-10)

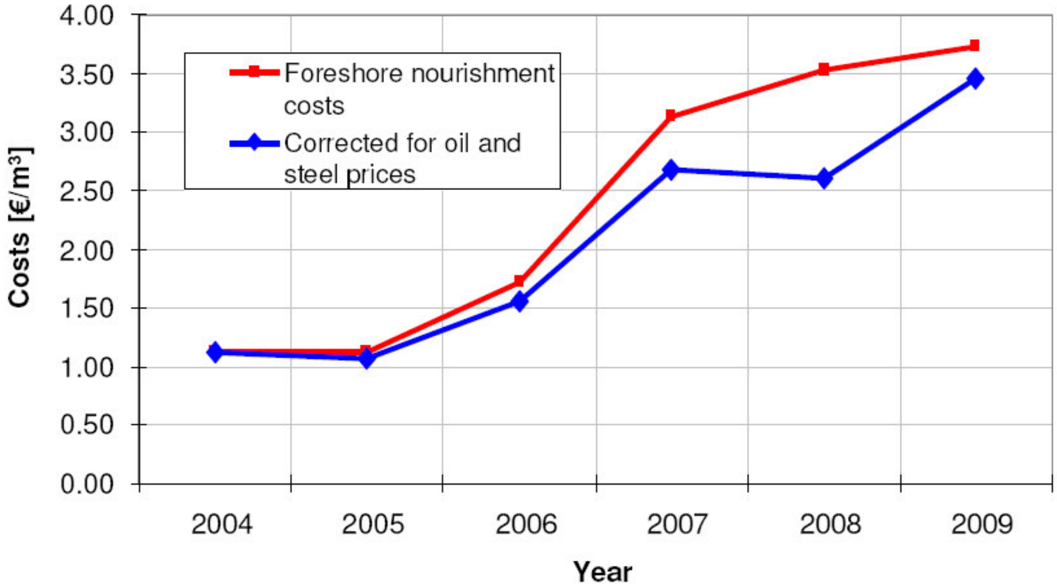


Figure 2-9: Price development foreshore nourishments in the Netherlands (RWS, 2009)

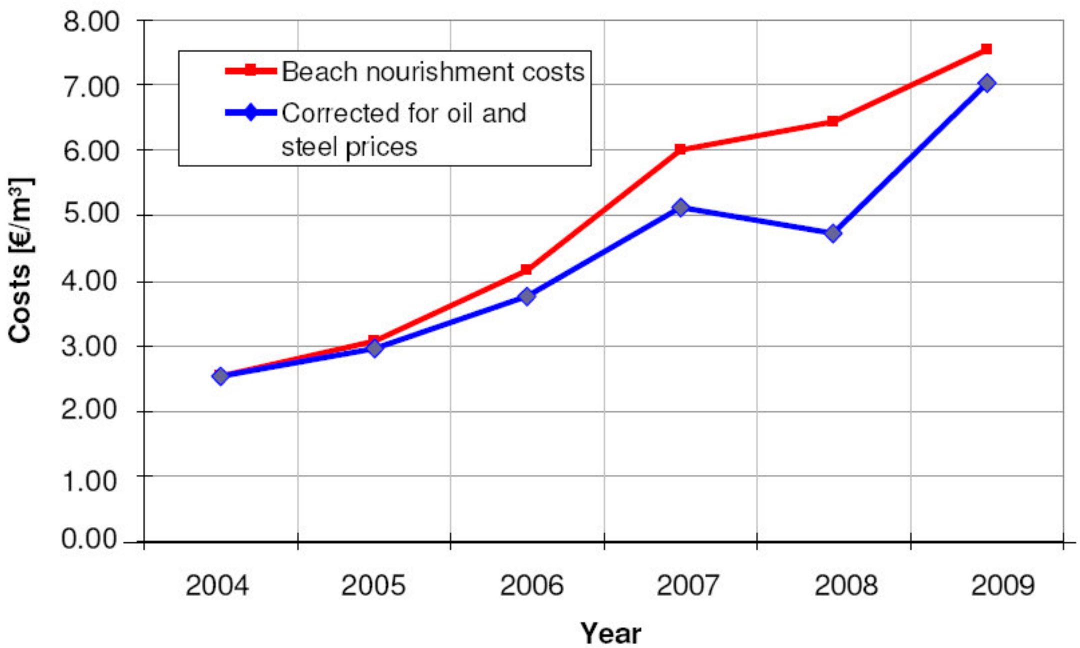


Figure 2-10: Price development beach nourishments in the Netherlands (RWS, 2009)

Maintenance

The yearly costs for management and maintenance for primary flood defences in the Netherlands is estimated to be approximately € 350 million per year (AFPM, 2006). With a total length of primary flood defences of about 3600 km the estimated costs for management and maintenance become € 100,000 per km flood defence per year.

Unit costs and relation to sea level rise (Kok et al., 2008)

Table 2-3 provides an overview of the unit cost prices as applied for the Netherlands.

Table 2-3: overview cost estimates the Netherlands

The Netherlands	
Dike (Millions € per km)	**Dike heightening (per m)** • 9 – 10.8 (rural) (Kok et al., 2008) • 18 – 21.6 (urban) (Kok et al., 2008) • 4 – 11 (rural) (Eijgenraam, 2006) • 6.9 (rural) (Fugro and Arcadis, 2006) • 13.8 (urban) (Arcadis and Fugro, 2006)
Beach Nourishment (€ per m^3 material)	• 2.3 – 6.7 (Stive, pers. comm., 2009) • 3 (Kok et al., 2008) • 2.85 (Arcadis and Fugro, 2006) • 3.72 (Foreshore nourishments) (RWS, 2009) • 7.55 (Beach nourishments) (RWS, 2009)
Maintenance	0.1 M€/km flood defence/year (AFPM, 2006)

Kok et al. (2008) applied these cost prices to determine the costs of sea level rise for the Netherlands. Therefore several factors need to be applied to the unit costs to determine the costs of the coastal defence system. These factors include the length of the coastal defences, the cost of storm surge barriers (section 2.4) and the costs of beach nourishments. Also the required height of the defence measures was determined based on its relation with sea level, by several conversion factors. As shown in Table 2-3 a different unit cost for rural and urban areas was applied. The results of this exercise are shown in Figure 2-11, depicting the contribution of several aspects of the coastal water system.

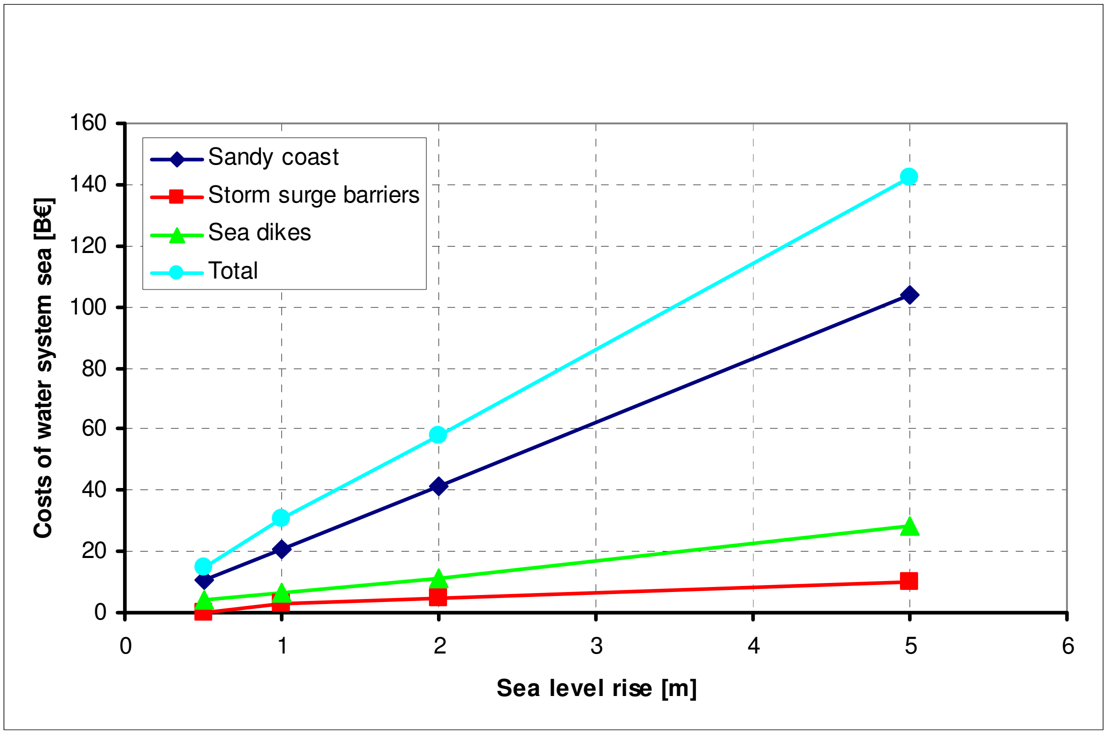


Figure 2-11: Cost function of coastal water system (Kok et al., 2008)

2.2 New Orleans (U.S.)

2.2.1 Background, history

New Orleans is situated in the delta of the Mississippi River (Figure 2-12). The city originated at the natural levees (higher grounds) along the Mississippi river. On the North side the city bounded by Lake Ponchartrain. Over time New Orleans gradually expanded into the marsh area in between the Mississippi river and Lake Ponchartrain and from the West Bank of the river further to the South.

Figure 2-12: Location of New Orleans in the state Louisiana of the United States (Wikipedia)

Currently, the city and its surrounding suburbs make up a metropolitan area that is partly below sea level and entirely surrounded by levees (American synonym for dikes). Since a large part of the city is below sea level (around 50%), with an average elevation between one and two feet (0.5 m) below sea level the area has a polder character and can be considered a bowl in between high waters (river and lake; see Figure 2-13).

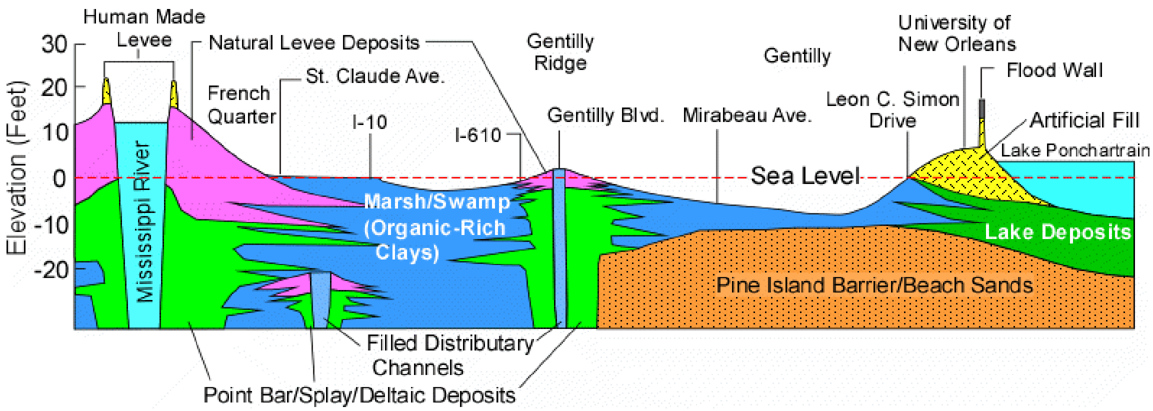


Figure 2-13: Geological cross-section of New Orleans (www.tulane.edu/~sanelson/Katrina/katrina_images.htm)

Because New Orleans is constructed on marsh area, large parts of the city continue to sink. The soft sand, silts and clay beneath the city settle over time because of natural consolidation but also groundwater pumping. The marsh area around the city also shows subsidence and due to the lack of sediment input from the river, this area deteriorates at a high rate.

As a consequence of its geographical situation, the area is vulnerable to flooding from hurricanes, high discharges of the Mississippi River and heavy rains. Large-scale pumping systems are installed for dewatering the city from rainfall and levees along the river, Lake Ponchartrain and the marsh areas of the Mississippi delta protect the city from storm surges. The vulnerability to flooding from hurricanes was tragically shown when 80% of the city flooded when it was hit by hurricane Katrina in 2005.

2.2.2 Coastal defence measures

The New Orleans area consists of three levee rings (Figure 2-14) and has a safety standard of a 1/100 year storm surge. These levee rings are constructed of Mississippi river levees along the Mississippi river (considered outside the scope of this study), hurricane levees along Lake Ponchartrain (Figure 2-15) and the marsh areas on the South and East and storm surge barriers (under construction). In the city levee ring (#1) several outfall canals are constructed which used to be in direct contact with the waters of Lake Ponchartrain. Along these canals floodwalls are constructed (see Figure 2-15).

New Orleans is situated in the Mississippi delta and the surrounding areas are marsh areas. These wetlands can be regarded as a natural storm surge defence system, since the marshes cause storm surge energy dissipation. The costs of these areas are hard to determine, however, marsh-creation and marsh-restoration costs can be estimated.

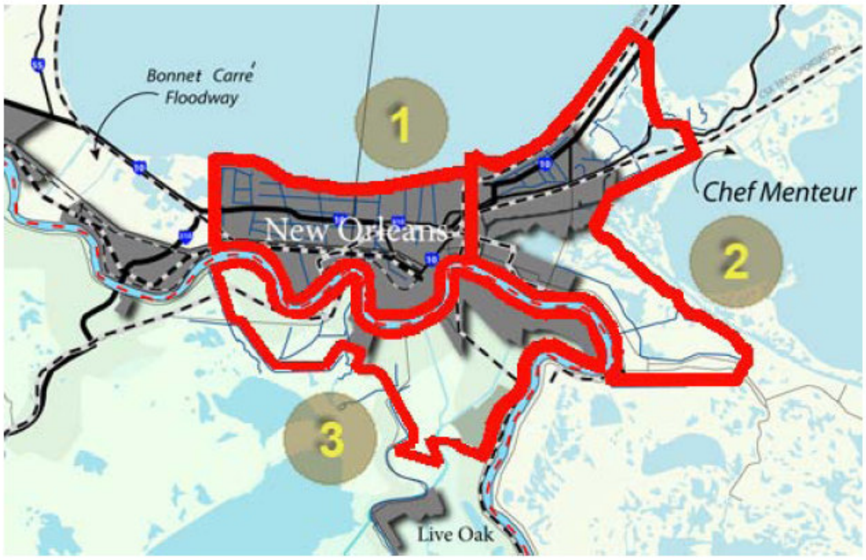


Figure 2-14: Levee rings New Orleans (Dijkman, 2007)

Figure 2-15: Lakeview levee and outfall canal floodwall (photo: Royal Haskoning)

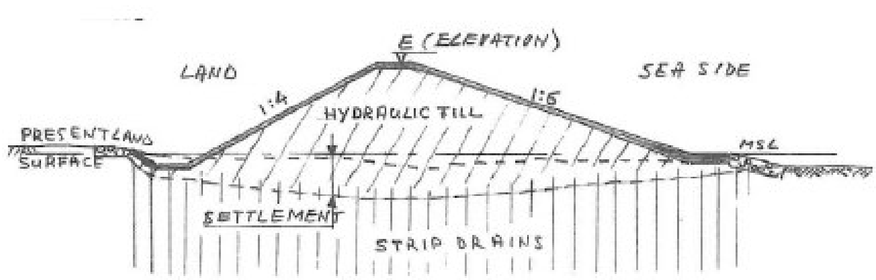
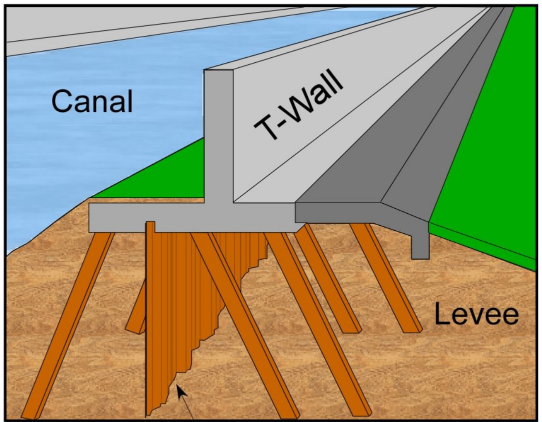


Figure 2-16: Schematic cross-section New Orleans levee (Dijkman, 2007)

2.2.3 Cost estimates

Floodwall

In New Orleans often concrete floodwalls are constructed on the top of levees to heighten the levee (Figure 2-17). After the flooding of hurricane Katrina in 2005 many floodwalls needed to be reconstructed. The data on the costs of these constructions varies due to different construction methods, but due to the reconstruction some construction cost data was available.



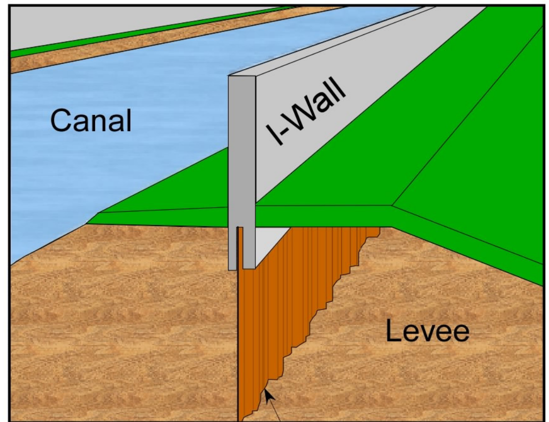


Figure 2-17: Two types of New Orleans floodwalls: T-Wall (left) and I-Wall (right) (Tulane, 2008)

Bos (2008) used costs of different types of concrete floodwalls to determine the optimal safety standard of the New Orleans East polder (Figure 2-14, #2). The costs were derived from historical construction costs. To determine the unit costs, the costs of floodwall per m heightening were derived in this study (Table 2-4).

Table 2-4: Overview of costs of different type of floodwalls (Bos, 2008)

Type of floodwall	$/Ft	€/m	M€/km	height (m)	costs in M€/km per m heightening
7-Foot High L-Wall with 6-Foot Wide Monoliths	3200	7874	7.87	2.13	3.7
8-Foot High T-Wall with 8-Foot Wide Monoliths	3400	8366	8.37	2.44	3.43
10-Foot High T-Wall with 8-Foot Wide Monoliths	4100	10089	10.09	3.05	3.31
12-Foot High T-Wall with 11-Foot Wide Monoliths	5100	12549	12.55	3.66	3.43
14-Foot High L-Wall with 11-Foot Wide Monoliths	6300	15502	15.50	4.27	3.63
16-Foot High L-Wall with 11-Foot Wide Monoliths	7000	17224	17.22	4.88	3.53
18-Foot High L-Wall with 13-Foot Wide Monoliths	8300	20423	20.42	5.49	3.72
20-Foot High T-Wall with 14-Foot Wide Monoliths	9900	24360	24.36	6.1	3.99
22-Foot High T-Wall with 16-Foot Wide Monoliths	10800	26575	26.58	6.71	3.96
24-Foot High T-Wall with 17-Foot Wide Monoliths	12200	30020	30.02	7.32	4.1
26-Foot High L-Wall with 6-Foot Wide Monoliths	14600	35925	35.93	7.92	4.54
28-Foot High L-Wall with 6-Foot Wide Monoliths	15500	38140	38.14	8.53	4.47
30-Foot High L-Wall with 6-Foot Wide Monoliths	16800	41339	41.34	9.14	4.52

Hurricane levees

The costs of sea dikes (hurricane levees) are based on the Dutch perspective on coastal Louisiana study (Dijkman, 2007), conducted by a team of experts from the Netherlands as part of the Louisiana Coastal Protection and Restoration planning and technical effort (LACPR).

The main design principle used 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. Redundancy in the design (applied as flexible asphalt protection) 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 strong and redundant structures, but also in relatively costly levees.

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 proposed levee construction principles for upgrading existing of Dijkman (2007) are identical to the principles applied for the design of new levees. Dijkman (2007) determined unit cost prices for New Orleans levees to be 5 to 8 million euro per kilometer for a meter dike heightening.

The focus in the Dutch perspective study is on so-called levee-rings (Figure 2-14). The levee rings, considered in the Dutch perspective on LACPR, consist of the following elements. Where openings are needed in such a ring (for shipping for example) a storm surge barrier is constructed.

- 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 of Mexico

The unit cost price of levee strengthening depends on the expected height of the levee and hence on the return period of the design water level (Figure 2-18). As mentioned above, the costs are considered relatively high, because the levees are constructed as unbreachable levees by the flexible asphalt protection. Table 2-5 provides an overview of the different levee upgrading costs and the costs for new alignment of hurricane levees for a range of return periods.

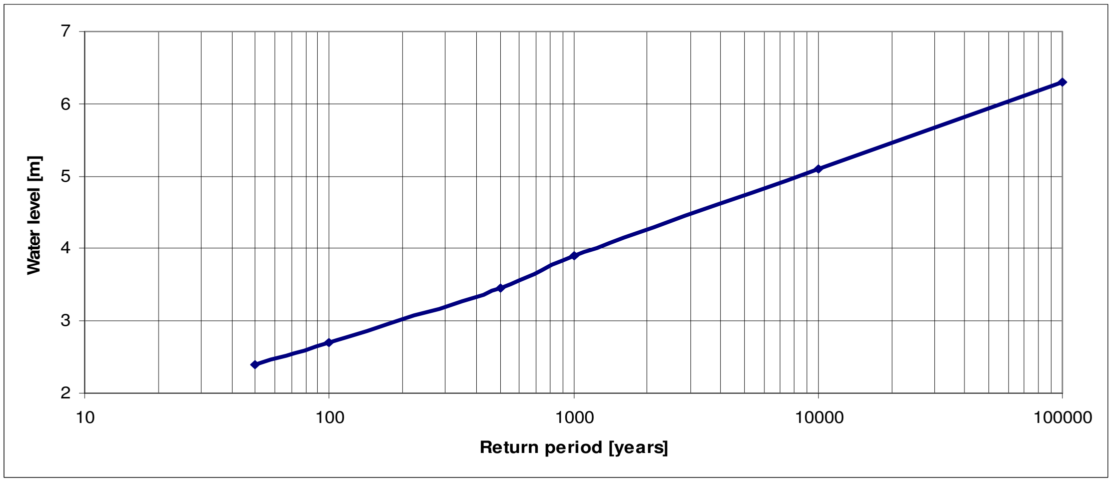


Figure 2-18: storm surge levels along Lake Ponchartrain (after Dijkman, 2007)

Table 2-5: Levee costs for return periods as determined by Dijkman (2007)

Price [M€/km]	**Return Period [years]**							
	50	***100***	***500***	***1000***	***5000***	***10000***	***100000***	***1E+06***
Upgrade existing levees	14.5	19.2	22.6	26.1	29.8	33.5	41.5	50
New alignment levee	35.7	37.8	44.4	46.7	51.4	56.1	66.1	76.7

Armoring

Personal communications with Ray Devlin (Haskoning Inc.) gave an overview of the costs of levee armoring (Table 2-6). These costs reflect the averaged cost prices quoted by armoring vendors of three types of armoring. Although they include labour-, plant-, and material costs, they are believed to not accurately reflect difficult site working conditions. Therefore, these numbers will probably increase once account has been taken of the large plant and restricted access required to work in very remote and inaccessible areas.

Table 2-6: costs of armoring for levees in New Orleans (Devlin, pers. comm. 2010)

	Installation costs including labour-, plant-, and material costs	
Type of armoring	*[$/SY]*	*[€/m^2]*
Fabrics and Filled Mat	16.4	14.51
Open Mat	33.4	19.56
Concrete systems/ACB	126.9	11.31

Marsh restoration

In Dijkman (2007) also ecological restoration is considered, there the restoration and stabilization of marsh areas around New Orleans was considered. It is expected that these marshes reduce the wave run-up and hence reduce the flood risk. By several measures (Figure 2-19) and via fresh water diversions the marsh areas are stabilized. For marsh restoration the following activities where expected:

- 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.

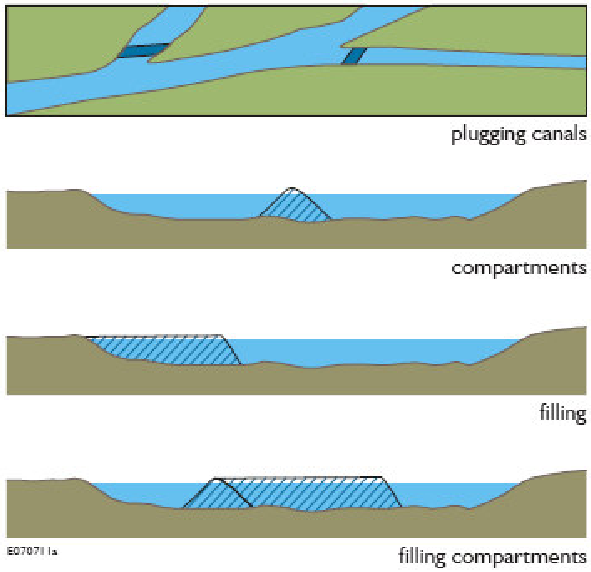


Figure 2-19: Measures undertaken for marsh stabilization (Dijkman, 2007)

Not the whole marsh restoration- and stabilization process is explained, but the costs to stabilize large marsh areas in Barataria Bay and around Lake Ponchartrain were provided. The unit costs are derived from these costs, taking into account the one-time investments for structures to enable marsh stabilization (Table 2-7).

Table 2-7: Unit costs of coastal defence measures in New Orleans

New Orleans	
Dike (Millions € per km)	**Dike heigthening per m:** 5 – 8 (Dijkman, 2007; Jonkman et al., 2009)
Concrete floodwall; L/T-wall type (M€ per km per floodwall height)	3.7 – 4.5 (Bos, 2008)
Marshland stabilization	**Marshland stabilization** • 1.4 €/m^2 (Dijkman, 2007) **Marshland creation** • 3 €/m^2 (Dijkman, 2007) **Freshwater diversion/culvert** • 10 M€ (Dijkman, 2007) **Marshland stabilization costs (€ per m^2 per year)** • 0.07 (Dijkman, 2007)
Closure dam (M€ per km per m height)	3.7 (in water) (Dijkman, 2007)
Levee armoring (€ per m2)	14.5 – 19.6 (Devlin, pers. comm. 2010)

2.3 Vietnam

2.3.1 Background, history

The Socialist Republic of Vietnam is with 88.6 million inhabitants a densely populated country in South East Asia (CIA World Factbook, 2009). From North to South the country is 1,650 kilometers in length and only 50 kilometers across in its narrowest point. Vietnam has two major river deltas, the Red River delta in the North and the Mekong delta in the South, and a relatively long coastline, which measures 3,260 kilometers. The coastal areas of Vietnam are subject to almost yearly flooding by typhoons formed in the South China Sea.

Many activities take place in the fertile, but also vulnerable coastal areas. The river deltas are the most densely populated areas of Vietnam and are prone to flooding from both the rivers and the sea. Although the river deltas are low-lying areas of land, all coastal land is above mean sea level. In the Northern and Southern part of Vietnam the coastal land is, from shoreline to approximately 20 kilometers inland, between 0.5 and 10 meters above mean sea level (Figure 2-20). In central Vietnam some higher areas are found.

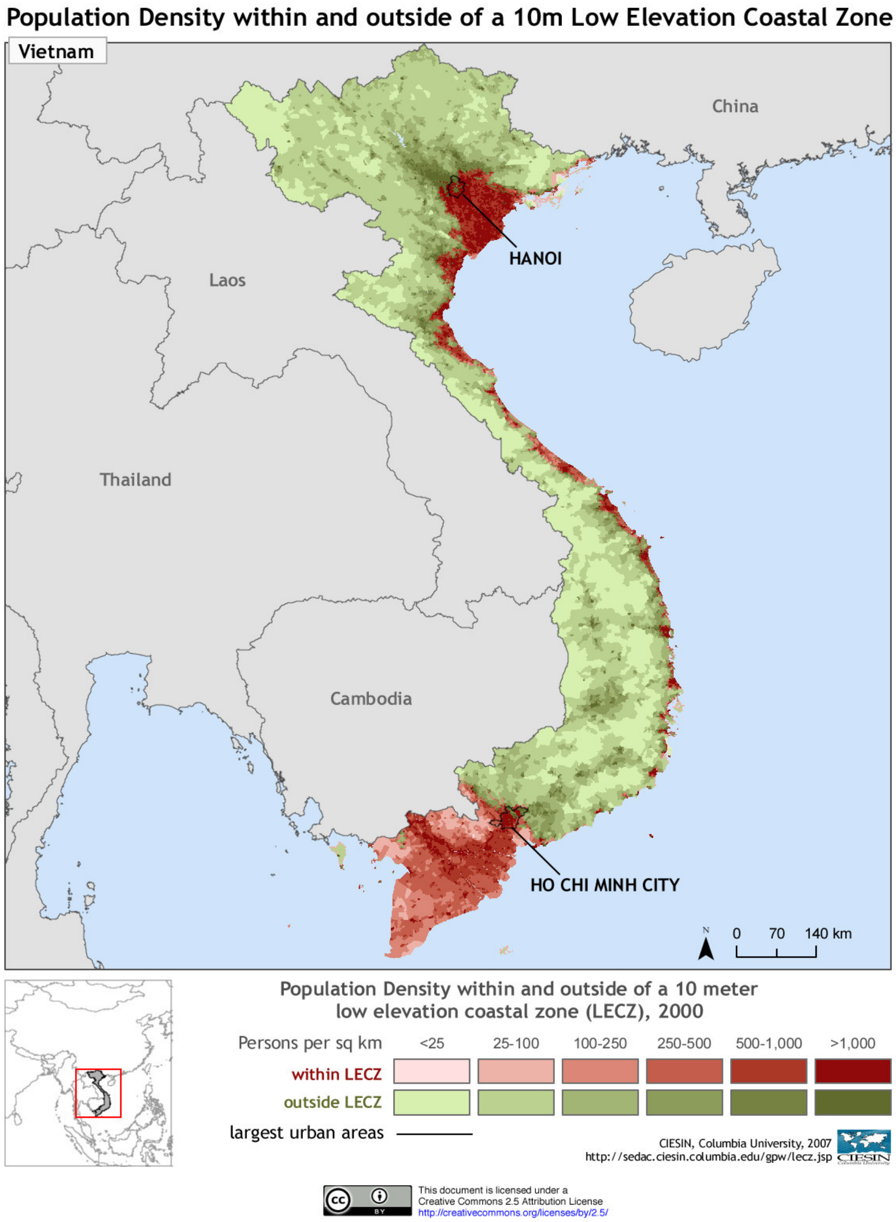


Figure 2-20: Population density within and outside 10m low elevation coastal zone; Vietnam (Columbia University; http://sedac.ciesin.columbia.edu/gpw/lecz.jsp)

The government of Vietnam wants to use the coastal zone to its fullest potential. This is illustrated by one of the objectives stated after the dike breaches in Nam Dinh province (Northern Vietnam) in 2005. The coastal defence strategies of Vietnam with respect to sea dikes, their construction and maintenance are the responsibility of a ministry and several dike departments. In total they maintain over 3,000 kilometers of coastal and estuarine dikes. A large sea dike project to review and upgrade the sea dikes of Vietnam and also formulate new guidelines for the construction of sea dikes was initiated in 2007. The current state of many of the sea dikes is far from optimal and many breaches of sea dikes in the Northern coastal provinces of Vietnam showed this vulnerability.

2.3.2 Coastal defence measures

For the Vietnam case study modern sea dikes have been investigated. In Vietnam there is no land area below sea level, dikes are constructed because of storm surges, river- and rainfall flooding and typhoon flooding.

Figure 2-21: New sea dikes in Vietnam (Nam Dinh province)

In some parts of Vietnam a tandem dike system is in place, however that system is not considered in this study. The cost estimates in this chapter are based on completely new sea dikes that have been and are constructed in Northern Vietnam in rural areas (Figure 2-21). These dikes consist of a sand/clay body and have revetments on the sea side of the dikes. The dikes have relatively steep slopes and are constructed up to heights of 8 m. A typical Vietnamese dike profile is shown in Figure 2-22.

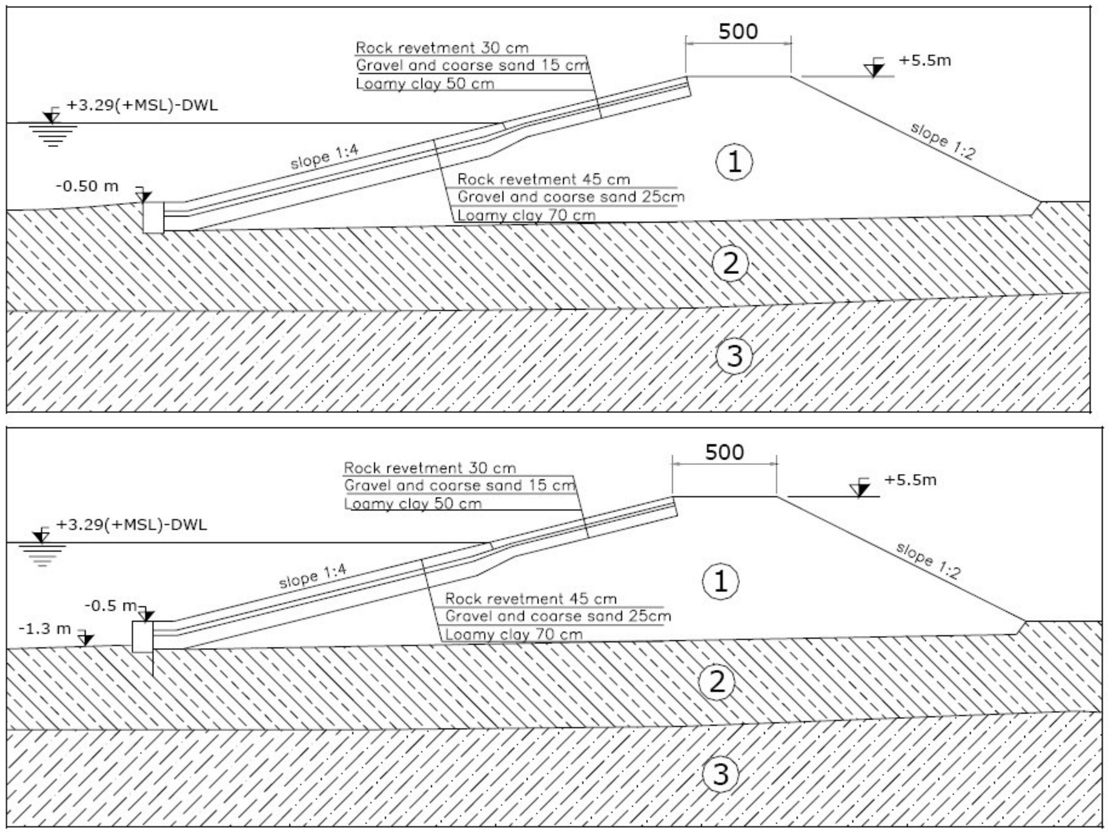


Figure 2-22: Representative cross sections of sea dikes in Nam Dinh province (Northern Vietnam) (adjusted from Mai, 2004)

2.3.3 Cost estimates

The costs of the Vietnam sea dikes were investigated to determine safety standards for the Northern provinces of Vietnam. Dike costs vary because of varying costs of material, land use and applied inner/outer protection or revetments. The costs of labour are highly variable, but relatively small and labour is often paid for by local departments – no clear insight into labour costs was obtained.

Hillen (2008) determined the costs of dike construction by data of local dike departments, cost data of stretches newly constructed sea dikes and interviews with dike departments, ministries and academic staff of the Hanoi Water Resources University. The dike costs as presented by Hillen (Figure 2-23) represent a new type of sea dike in the Northern provinces with only sea side revetment. This concerns dikes in rural areas where land-use costs are small. The dikes did not account for wave run-up and wave overtopping. Based on dike department and ministry budgets, the yearly dike maintenance costs for a 1 kilometer dike stretch were estimated to be 20,000 €/km.
In parts of the Northern provinces experiments with mangroves are conducted. The mangroves are re-introduced at some coastal areas as a natural barrier in front of sea dikes. Since the effects of these mangroves were not yet tested and only very young mangroves were placed in wetlands in front of the sea dikes, these costs are not taken into account in this study.

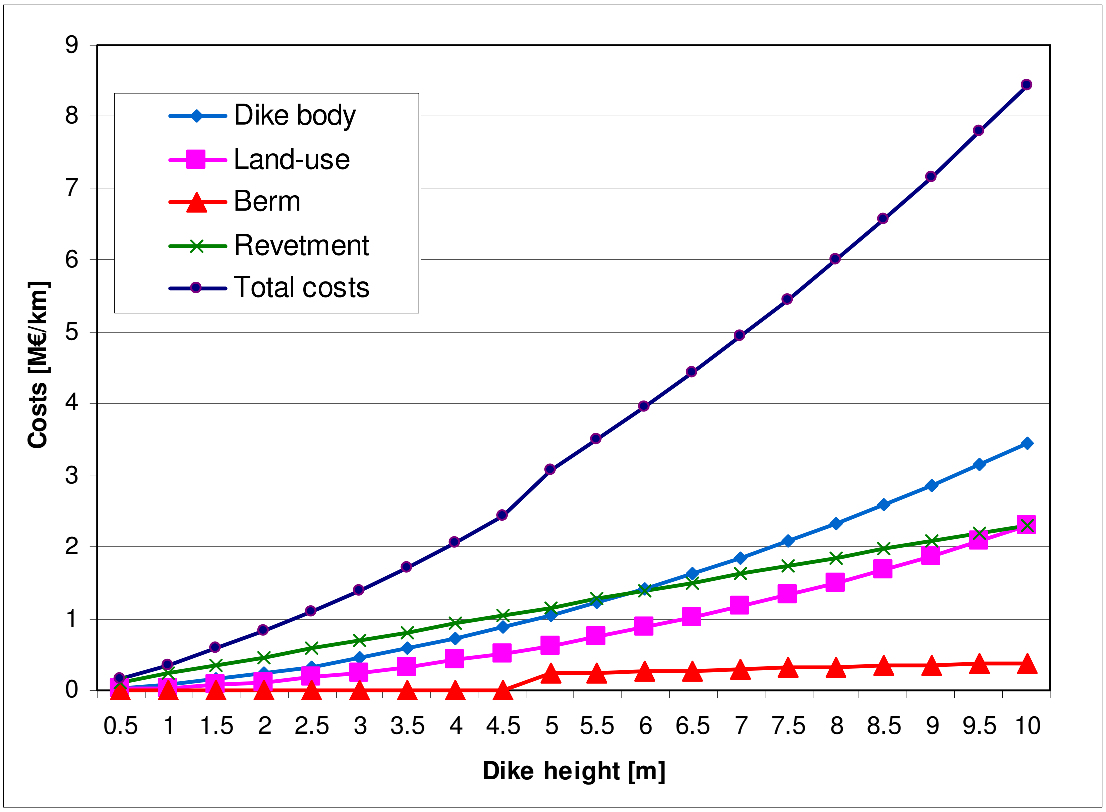


Figure 2-23: Costs of dikes as a function of dike height according to Hillen (2008)

Mai et al. (2008) determined costs of dike heightening in an effort to illustrate a comparable probabilistic approach to determine safety standards of Vietnam. Mai et al. determined the safety standards for the Nam Dinh province, so this concerns dikes in rural areas. The background of his cost data is unknown, but comparable safety standards to Hillen (2008) were found. The costs of dike heightening are also comparable to the costs as determined by Hillen. Mai et al. (2008) used both outer- and inner slope protection and included the costs of maintenance in his dike costs graphs (Figure 2-24) (Note that the costs in this figure are given in US$).

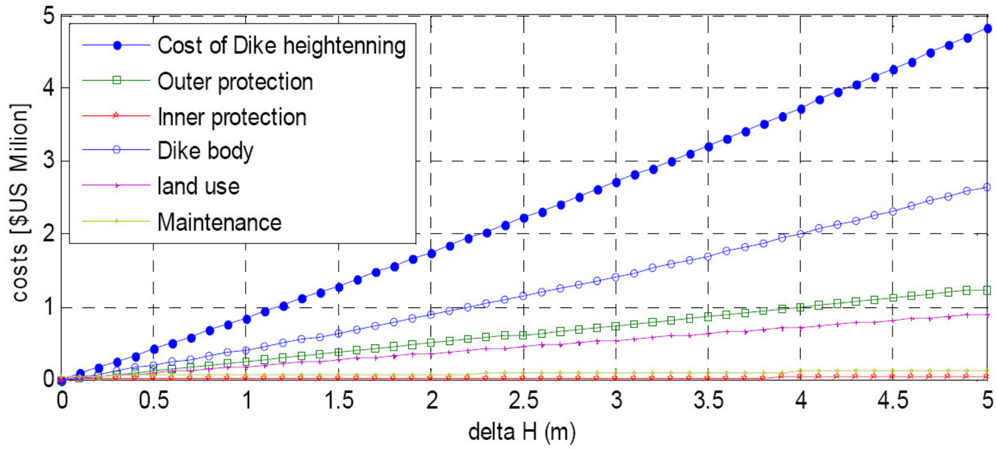


Figure 2-24: Dike heightening costs according to Mai et al. (2008)

The costs of the coastal defence for the Vietnam case study are based on the two previously mentioned studies. Relatively little data is available on sea dike construction in Vietnam and most of the data presented here is based on estimates, basic calculations and interviews.

Table 2-8: Unit cost estimates Vietnam

Vietnam (Northern provinces: Hai Phong, Nam Dinh)	
Dike heightening per meter for a kilometer stretch in Millions €	• 0.7 – 1.2 (Hillen, 2008) • 0.75 (Mai et al., 2008)
Maintenance	• 0.02 M€/km dike/year (Hillen, 2008) • 0.03 M€/km dike/year (Mai et al., 2008)

2.4 Storm surge barriers

In various locations around the world storm surge barriers have been constructed. Famous examples are the storm surge barriers in the Netherlands (Figure 2-26) in the Southwest of the country.

In New Orleans a storm surge barrier is being built after Katrina at the eastern side of New Orleans to protect the city from surges and reduce the length of the directly exposed system (see Figure 2-25). Storm surge barriers are often chosen as a preferred alternative to close of the estuaries and reduce the required dike strengthening behind the dams. Another important characteristic is that they are often partly opened during normal conditions and this will allow the tide and saltwater to enter the areas behind the barrier. An overview of the main characteristics of storm surge barriers around the world is given in Table 2-9.

Figure 2-25: Construction of the Inner Harbour Navigation Channel/St. Bernard storm surge barrier (photo Royal Haskoning)

Figure 2-26: Maeslant storm surge barrier (near Rotterdam) and the Eastern Scheldt barrier (South-Western delta)

Table 2-9: Overview storm surge barriers

Name barrier	*Type*	*Year*	*Width [m]*	*Height [m]*	*Head [m]*	*Construction costs [M€]*	*Construction costs 2009 price level [M€]*
				the Netherlands			
Measlant barrier (New Waterway, Rotterdam)	Floating sector gate	1991	360	22	5	450 *1)	656
Hartel barrier (Hartel channel)	Vertical lifting gates	1991	170	9.3	5.5	98 *2)	143
Eastern Scheldt Barrier	Vertical lifting gates	1986	2400	14	5	2500 *3)	4021
Ramspol (near IJssellake)	Bellow barrier	1996	240	8.2	4.4	100	132
				Europe			
Ems (Germany)	Sector gates	1998	360	8.5	3.8	290	368
Thames (Great-Britain)	Sector gates	1980	530	17	7.2	800	1449
Venice MOSE project (Italy)	Flap gates	2010	3200	15	3	4678	4678
				New Orleans			
Seabrook barrier (New Orleans)	Vertical lifting gates/sector gates	2010	130	8	4	114.7 *4)	115
IHNC barrier (New Orleans) - only gates (excl. floodwall)	Sector gates	2010	250	8	4	518 *5)	518

Remarks Table 2-9:
1) Maeslant barrier has a relatively low cost price due to heavy competition for the contract.
2) The Hartel barrier has one very large horizontal span which increased the cost price.
3) The Eastern Scheldt barrier is relatively inexpensive due to its repetitive character.
4) The Seabrook barrier (New Orleans) has two different types of gate in a small span.
5) From the IHNC/St. Bernard storm surge barrier only the parts containing the gates have been taken into account, the floodwall was excluded.

The costs of a storm surge barrier depend on many factors, such as the type of barrier/gates, the local soil characteristics, the desired height and hydraulic head over the barrier. A first attempt to provide an estimate of a unit cost price per unit width has been given below. The cost price per unit width has been deduced from the available data. This ranges between 0.5 M€ per meter width and 2.7 M€ per meter width.

As the hydraulic head will be an important determinant for the forces on the barrier and the required construction properties and costs, the relationship between the head and the unit cost prices has been plotted (Figure 2-27). It shows that there is a weak relationship between the head and the unit costs for storm surge barriers. It is recommended to further investigate which factors determine the unit costs for storm surge barriers.

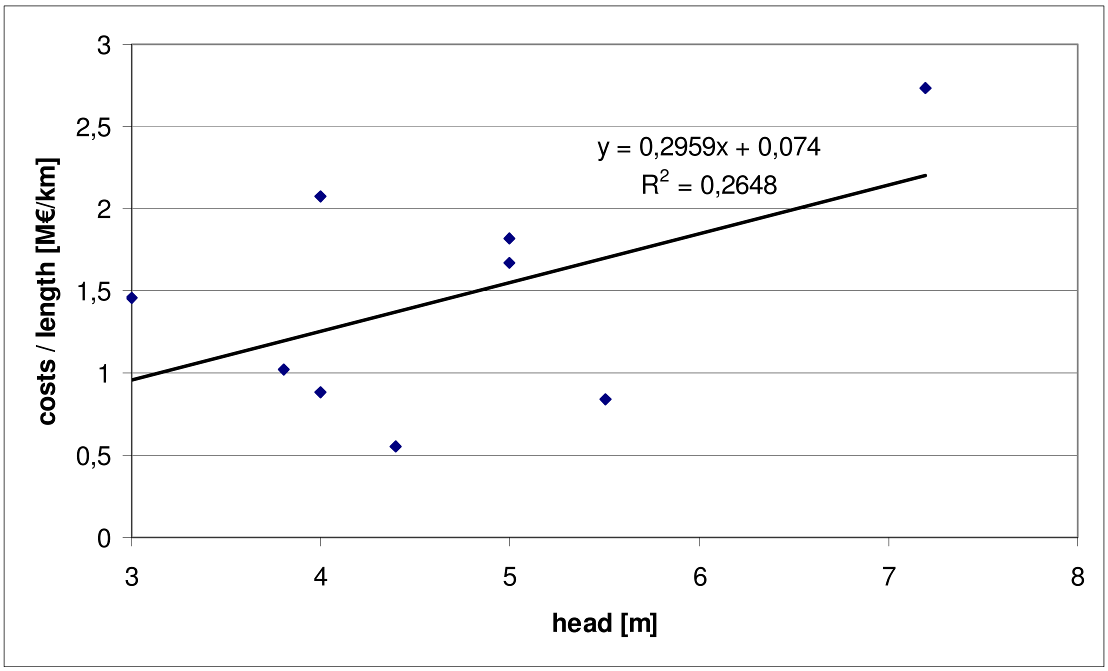


Figure 2-27: Storm surge barrier unit cost estimates; costs per unit length vs. the hydraulic head for the nine barriers shown in Table 2-9.

3 Coastal defense cost estimates and analysis

3.1 Unit cost prices for coastal defences

3.1.1 Overview

In this study we have analysed information on the costs of coastal defences for a number of different areas. Table 3-1 summarizes some of the main characteristics of these case studies areas. The results for Cape Town (SA) have been obtained from appendix I. Although all the case studies have different conditions and circumstances, it can be stated that the first three case studies are representative for a low-lying delta coast, whereas the Cape Town case is more representative for a coast that is more variable in terms of elevation and protection and coastal management strategies.

Table 3-1: Overview main characteristics case study areas

	Standard of protection [per year]	Main threat for coastal defences	Surge level for design conditions [m]	Wave height for design conditions [m]
Netherlands	1/4000 – 1/10000	Storm surge	6	8
New Orleans (LA, USA)	1/100	Hurricane	6 – 12	2
Vietnam	1/50 (expert judgement)	Typhoon	4 – 10	5
Cape Town (SA)	-	Storm surge	1.6	11*

* value for a 100 year return period (off-shore)

The unit cost data as provided in Table 3-2 is based on cost estimates as found on project level. These studies and projects were not intentionally set up to determine unit costs, but did include coastal defence cost estimates for a number of different reasons. The costs in Table 3-2 can be considered all in costs, which means they account for the total engineering process. However, the results of the different case studies show a large variability. Although for some estimates ranges are provided, it must be noted that cost estimates largely differ from project to project and can be considered location dependent. It can be stated that the unit cost of Table 3-2 largely reflect the Dutch perspective on coastal defence costs, since most of the data was determined by Dutch projects.

As mentioned, the available information on unit cost estimates for the case studies has been summarized in Table 3-2. These numbers provide a first indication based on studies for the four cases. There are several issues and uncertainties associated with the interpretation of these unit numbers and their use in the context of national or global studies on adaptation of the coastal defences to sea level rise. These issues are discussed in section 3.2 to 3.4.

Table 3-2: Unit costs of coastal defence measures, converted to 2009 price levels

<table>
<tr><th></th><th colspan="5">Unit Cost (2009 price levels)</th></tr>
<tr><th>Country and locality if appropriate</th><th>Vertical Seawall (Million € per km length)</th><th>Dike (Millions € per km)</th><th>Beach Nourishment (€ per m^3 material)</th><th>Storm surge barriers</th><th>Other Measures</th></tr>
<tr><td>NETHERLANDS
National</td><td>-</td><td>Dike heightening (per m)
• 9 – 10.8 (rural) (Kok et al., 2008)
• 18 – 21.6 (urban) (Kok et al., 2008)
• 4 – 11 (rural) (Eijgenraam, 2006)
• 6.9 (rural) (Fugro and Arcadis, 2006)
• 13.8 (urban) (Arcadis and Fugro, 2006)</td><td>• 2.3 – 6.7 (Stive, pers. comm., 2009)
• 3 (Kok et al., 2008)
• 2.85 (Arcadis and Fugro, 2006)
• 3.72 (Foreshore nourishments) (RWS, 2009)
• 7.55 (Beach nourishments) (RWS, 2009)</td><td rowspan="2">Costs per unit width (m) of a storm surge barrier
0.5 – 2.5 M€ (this study)
Unit costs related to hydraulic head over barrier (m).</td><td>Maintenance
0.1 M€/km flood defence/year (AFPM, 2006)</td></tr>
<tr><td>UNITED STATES
New Orleans</td><td>Concrete floodwall construction; T-wall type (per m floodwall height)
• 3.7 – 4.5 (Bos, 2008)</td><td>Dike heightening (per m):
• 5 – 8 (Dijkman, 2007; Jonkman et al., 2009)</td><td>-</td><td>Marshland stabilization
• 1.4 €/m^2 (Dijkman, 2007)
Marshland creation
• 3 €/m^2 (Dijkman, 2007)
Freshwater diversion/culvert
• 10 M€ (Dijkman, 2007)
Marshland stabilization costs (€ per m^2 per year)
• 0.07 (Dijkman, 2007)
Closure dam (M€ per km per m height)
• 3.7 (in water) (Dijkman, 2007)
Levee armoring (€/m^2)
• 14.5 – 19.6 (Devlin, pers. comm. 2010)</td></tr>
</table>

	Unit Cost (2009 price levels)				
Country and locality if appropriate	**Vertical Seawall (Million € per km length)**	**Dike (Millions € per km)**	**Beach Nourishment (€ per m^3 material)**	**Storm surge barriers**	**Other Measures**
VIETNAM Hai Phong/Nam Dinh	-	**Dike heightening (per m)** • 0.7 – 1.2 (Hillen, 2008) • 0.75 (Mai et al., 2008)	**-**	-	**Maintenance** • 0.02 M€/km dike/year (Hillen, 2008) • 0.03 M€/km dike/year (Mai et al., 2008)
SOUTH AFRICA Cape Town (Geldenhuys, 2010; appendix I of this study)	0.3 – 3.96	**-**	• 1.2 – 1.5 M€ per km beach (*note: different unit than other nourishment indicators*)* • 14.3 (Mather, 2009)	-	**Managed retreat** • € 180 - € 290 per m^2 surface

* The actual amount of nourishment material per beach was not available for this study; this number was included to give a rough indication. This indicates that the nourishment costs for the non-generic South-African coastline are much higher than for the Netherlands situation.

3.1.2 Comparison with IPCC CZMS (1990)

In the past, unit cost prices of coastal defence measures have been determined by IPCC CZMS (1990) and later adjusted by Hoozemans et al. (1993). In the IPCC CZMS (1990) effort the costs of a number of typical coastal defence measures were calculated based on assumed standard dimensions of these measures. With material costs and assumptions based on construction 'all-in' costs for several coastal defence measures were determined.

Table 3-3: Comparison unit costs IPCC CZMS (1990) with findings of this study

Type of coastal defence measure	Unit Cost IPCC CZMS (1990); 2009 price level	This study (the Netherlands); 2009 price level
New 1 m high sea dike	0.41 M€/km	Not included, no real project data available
New 1 m high sea dike with regular maintenance	0.62 M€/km	Maintenance costs: 0.1 M€/km flood defence/year
Raising low sea dikes by 1 m in rural areas	0.52 M€/km	Only existing (high) dikes taken into account
Raising high sea dikes by 1 m in rural areas	1.04 M€/km	4 - 10.8 M€/km
Raising sea dikes by 1 m in urban areas	10.39 M€/km	13.8 - 21.6 M€/km
Beach nourishment	3.12 - 6.24 €/m^3	2.3 - 7.6 €/m^3

Table 3-3 shows a comparison of the coastal defence measures found both in IPCC CZMS (1990) and this study. In the table the dike construction costs are compared. The method as applied by IPCC CZMS (1990) gives the costs for an ideal situation, the dike heightening costs for the Netherlands as found in this study are therefore higher (both for rural and urban conditions) than the estimated costs of IPCC CZMS (1990). This can be attributed to the difference between an idealized dike of standard dimensions (as applied by IPCC CZMS) and the actual construction costs, because in practice projects often encounter more complex problems which cause an increase in costs. Hillen (2008) determined the costs of the Vietnam sea dikes in a similar way as by IPCC CZMS (1990) and these costs can be considered comparable.

The fact that coastal defence costs on project level are higher compared to idealized dikes was also found in a study to include the costs of dike construction in a flood damage computer model (Royal Haskoning, 2007). In that study it was concluded that to determine the costs of flood defence measures in the Netherlands (both river-, lake- and sea dikes) one could not rely on calculations based on a idealized dike cross-section and unit costs of materials. In the report it is stated that 'due to the large number of variables, no cost calculation with unit costs is applied (…) instead expert judgement is used to provide dike construction cost estimates including ranges.' There is a large difference between theory and practice. The increase in costs between IPCC CZMS

(1990) and Hoozemans et al. (1993) may also be attributed to this effect, as Hoozemans et al. (1993) focused on the construction of a type of dike section.

The coastal defence unit cost estimates of this study are intended to contribute to the global effort to determine unit costs (Linham et al. 2010). Compared to the numbers found by Linham et al. (2010) especially the dike (heightening) costs of this study are much larger. This accounts especially for the dike construction costs. It is recommended that the dike construction costs are based on dike heightening and actual project data. This gives comparable data and accounts for the additional costs that are always included in large engineering projects.

3.2 Overview of factors that determine the unit cost price

General costs factors
In order to assess the cost of flood defences, a distinction can be made between five different categories of factors that determine the costs (see below).

1. Planning and engineering costs
2. Material costs
3. Labour costs
4. Costs for implementation in the environment (urban or rural)
5. Costs for management and maintenance

Ad 1: Planning and engineering costs: This concerns the dike design and planning of the flood defence. In case of large uniform sections in rural areas, the unit costs may be low, while in residential areas with non-uniform conditions, the unit cost are relatively high.

Ad 2: Material costs: The cost of materials is very site dependent. In deltaic regions, there is sometimes scarcity of construction material (e.g. clay in New Orleans; stones for revetments in the Netherlands). This highly influences the unit price and method of construction.

Ad 3. Labour costs: the cost of labour is varying a lot between countries. However, when the cost of labour is low, labour is more intensely used, while in the case of expensive labour, mechanized equipment is more widely applied.

Ad 4. Costs for implementation in its environment.
An important factor concerns the implementation of the flood defence in its environment. Two main factors are:

- Land use by flood defences. The required width of a flood defence usually increases with its height. The required amount of land has to be obtained, which could be financially and legally and challenging and thus a costly and time consuming task. However, in a rural environment, less challenges are expected.
- Rural or urban implementation. In an urban environment, space is usually scarce and space-saving solutions are needed for the implementation of flood defence projects. The solutions needed in urban environment (e.g. sheet piles) are usually more expensive than the relatively cheap rural purchases of land.

Figure 3-1 gives an illustrative example that concerns the strengthening of a flood defence. The first “round” of heightening does not lead to conflicts with the urban environment. However, the second round would require alternative solutions or removal of parts of the urban environment.

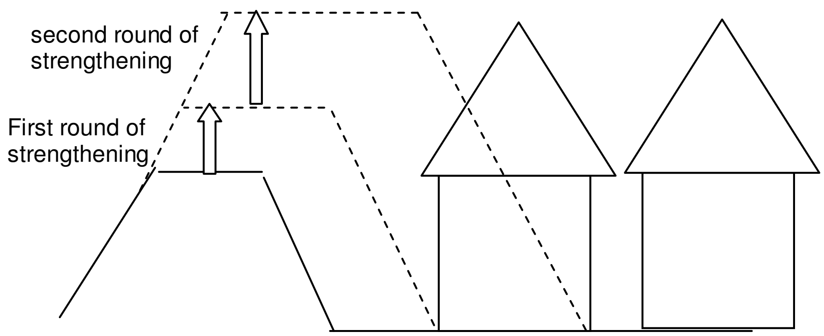


Figure 3-1: Example of strengthening of a flood defence and possible conflicts with the existing urban environment.

Ad 5) Costs of management and maintenance
An organization is needed for the management and maintenance of flood defences. This will result in an additional percentage of cost on the total expenses. The management and maintenance in the Netherlands is carried out by so-called Water Boards. In other countries there are usually also (semi-) governmental bodies for management and maintenance.

To give an indication: The yearly costs for management and maintenance for primary flood defences in the Netherlands is estimated to be approximately € 350 million per year (AFPM, 2006). With a total length of primary flood defences of about 3600 km the estimated costs for management and maintenance become € 100,000 per km flood defence per year.

Discussion: Comparison of costs between countries
As mentioned above, the different unit costs vary per country and per location. The differences between locations in a region will be largely determined by the exact design and the implementation.

Country specific factors will be related to the local economic situation. The contribution of the categories to the unit price is likely different is for each country. The costs for material and labour will also affect the selected design, the materials used and the construction method. In countries with low labour cost, and high material cost, another choice is made for e.g. dike revetments than in countries with low material and high labour cost.

The relative contributions may be compared. Though in case of comparison per country, the development (GDP, specific education etc) needs to be taken into account. This is be illustrated by comparing the derived average unit cost prices for dikes the three countries (see section 3.1) to the GDP per capita (source: CIA World factbook; assumed exchange rate 1 Euro = 1.34 US $). This shows that the estimated unit cost prices for Vietnam are relatively high in comparison with the GDP per capita.

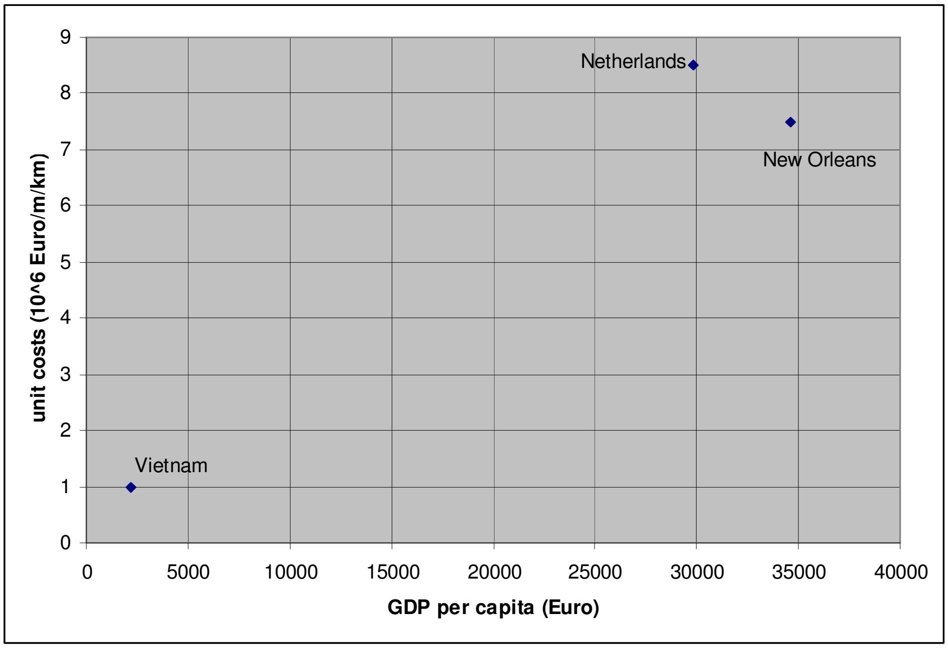


Figure 3-2: comparison between the average unit cost prices for dikes and the relationship with the GDP per capita

3.3 Cost estimates at a system level

The unit cost of flood defences on a project level were discussed in the previous section. In this section, we discuss some main factors and issues that determine the cost estimates at a system level.

Main factors that determine the costs at a system level
The transition from unit cost prices to system level cost estimates are influenced by three main factors:

1. Measures and solutions chosen for individual reaches
2. The system length
3. Modifications in the system's alignment

Ad 1: the cost factors for individual projects have been discussed in section 3.2

Ad 2: system length: the total cost for (adaptation) of a flood defence system is determined by the length of the flood defences in the system. The total costs are found by integrating the unit costs prices for invidual reaches over the total system length.

Obviously, the costs will be high for a system with a large length. A good example concerns the protected areas that are found in the so-called Plaquemines area in Louisiana, south East of New Orleans. These are wide scarcely populated areas along the Mississippi that are protected by levees / dikes from river and hurricane flooding. Due to the large system length protecting the values in this area will be relatively costly. This also has a relationship with the cost benefit analysis and optimal protection level that would be found for such an area (see also section 4). An area with a relatively low economic value but high systems adaptation costs, will have a lower optimal protection level (or “demand for safety”) than an area with a high concentration of values and a relatively small systems length.

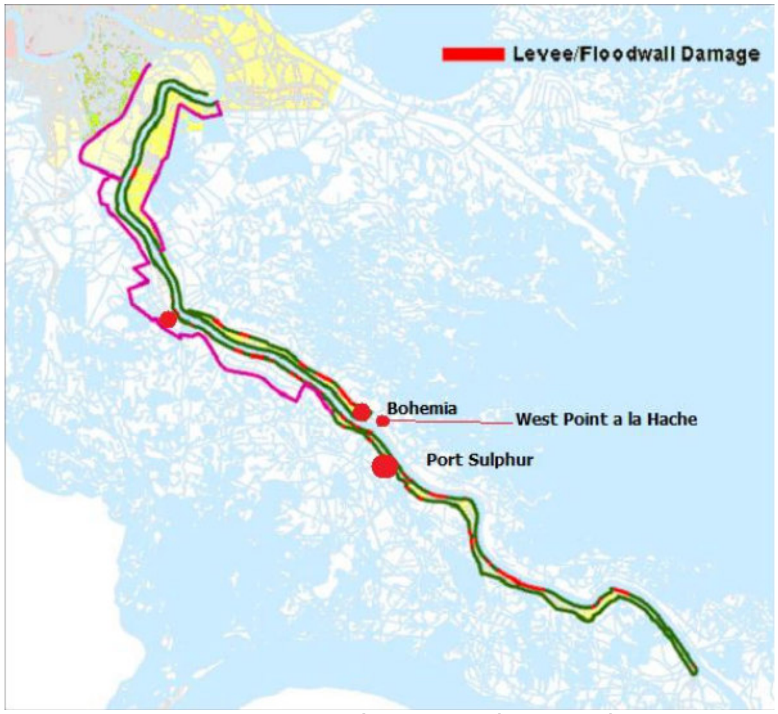


Figure 3-3: Plaquemines area in Louisana, SE of New Orleans. Green and purple lines indicate the current levees. North to South is app. 120km.

Ad 3 Modifications in the system’s alignment: The length of a coastal flood defence system may be shortened by closing off estuaries. This could bring additional advantages for for example navigation and agriculture (availability of fresh water), but could also have negative effects on the ecological system. Such an adaptation is usually done when the benefits (e.g. less costs due to a smaller system length and reduction of the risk) outweigh the costs of such a modification (e.g. additional dams or storm surge barriers). Examples of such projects are:

- Netherlands: construction of storm surge barriers, such as the Eastern Scheldt and Maeslant barriers, to close of the estuaries and reduce the required dike strengthening behind the dams and barriers (see Figure 3-4 for an overview of some of the dams in the Dutch delta plan that was constructed after the 1953 storm surge disaster)
- New Orleans: A storm surge barrier is being built after Katrina at the eastern side of New orleans to protect the city from surges and reduce the length of the directly exposed system. In addition, gates were built in the outfall canals in the north of the central city to prevent that the levees along these canals could be directly exposed during surges (see Figure 3-5 for an overview – new gates and barriers in red).

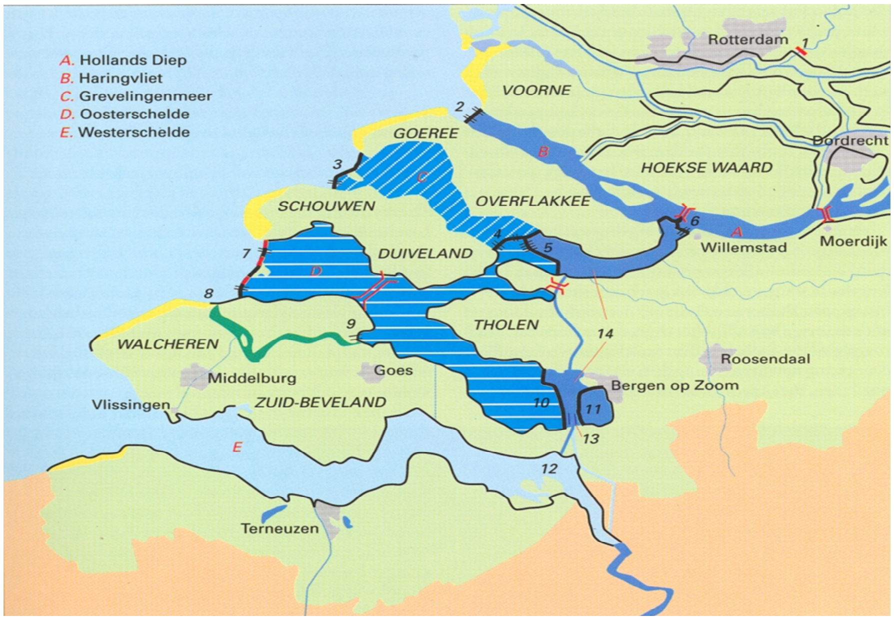


Figure 3-4: Overview of dams (indicated with numbers) that were constructed after the 1953 storm surge disaster in the Netherlands.

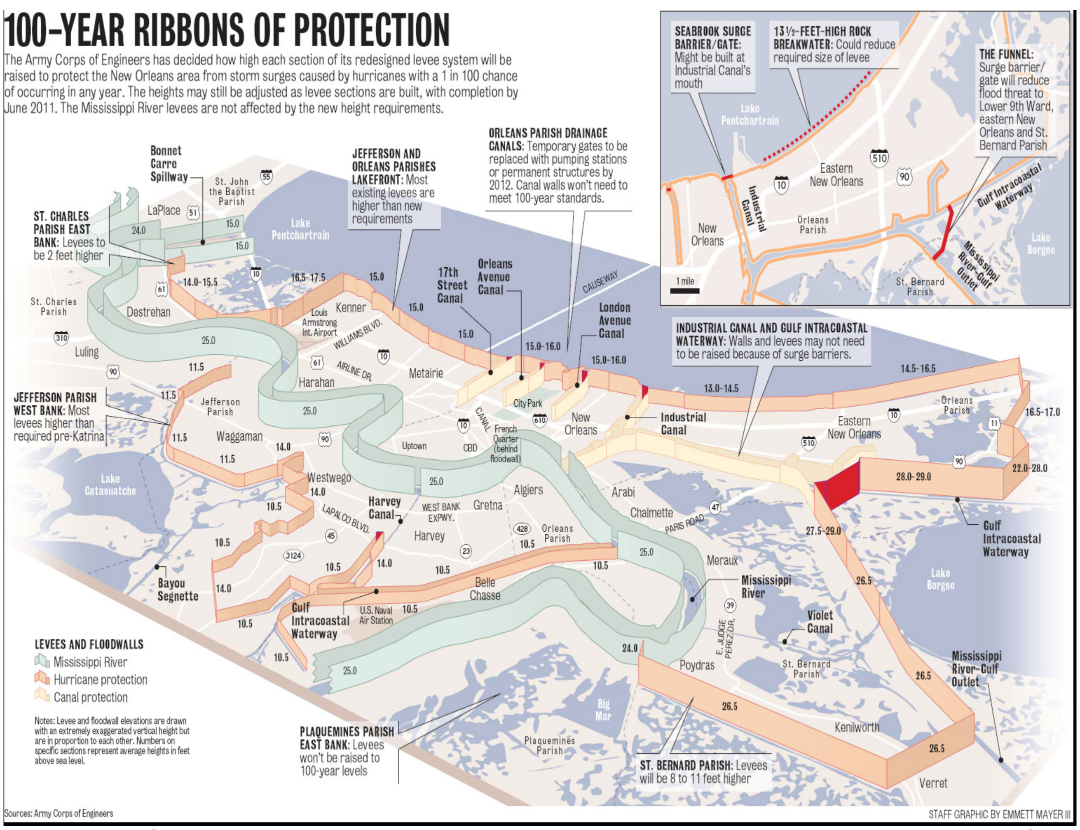


Figure 3-5: Overview of new dams and gates (in red) that were constructed in New Orleans after hurricane Katrina (source: Times Picayune newspaper).

Costs made for other functions
The costs of a project will depend on the exact solution or measure that is chosen. A measure or project will never be solely based on the flood defence requirements. The flood defence function (and its cost) is in this case will only form a part of the total project. Other functions (recreation, infrastructure, ecological quality etc.) will influence the design as well. Multifunctional and integrated approaches become more and more common and the total costs of these solutions would be generally higher than would only be the case for the flood defence function. Examples of recent projects where this played a role are given below.

- Room for Rivers in the Netherlands: Instead of heightening the river dikes, the room for rivers strategy has been adopted. This strategy is more expensive than strengthening the dikes. Ecological and landscape issues were were important factors in the choice for this strategy.
- The ‘Sand engine’, which is a single sand nourishment that is large enough to replace many years of future nourishments. While obviously involving a large safety aspect, additional costs have to be made as more sand is needed for merely ecological values.
- The plans for the multi-functional Afsluitdijk (closure dam) in the Netherlands: the proposed multifunctional solutions have much higher costs than a basic strengthening of the Afsluitdijk.

Figure 3-6: One of the proposed designs for the Afsluitdijk / closure dam in the Netherlands, with several additional functions, such as nature development and tidal energy generation.

- Multifunctional defence types and concepts:
    - Delta dikes, super levees that integrate wide dikes with spatial development
    - Comcoast project: wide coastal zones that integrate coastal zones with nature development.

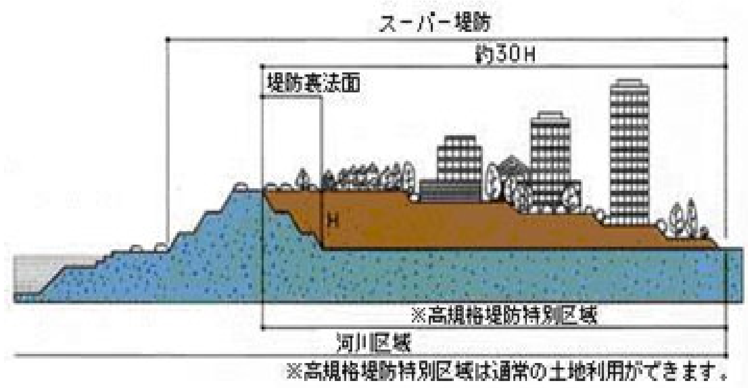


Figure 3-7: Example of a multifunctional super levee in Japan that combines a flood defence with urban development.

Figure 3-8: Example from the Comcoast project of a coastal development zone that combines flood protection and nature development.

3.4 Relationship between sea level rise and coastal defence costs

General

In this section we discuss the possible extrapolations of these coastal defence costs into future expenses to adapt to sea level rise. One must carefully distinguish two relationships:

1. The development of the hydraulic loads over time (largely determined by the sea level rise rate) and the required adaptation of flood defences
2. The relationship between the adaptation of the flood defence and the the associated costs

The combination of these two relationships determines the eventual the development of costs of adaptation over time. If both relationships are linear, the costs will shows a linear increase over time (see Figure 3-9). If one of the two relationships is non-linear, the eventual development of costs over time will be non-linear as well. The underlying factors are briefly discussed below.

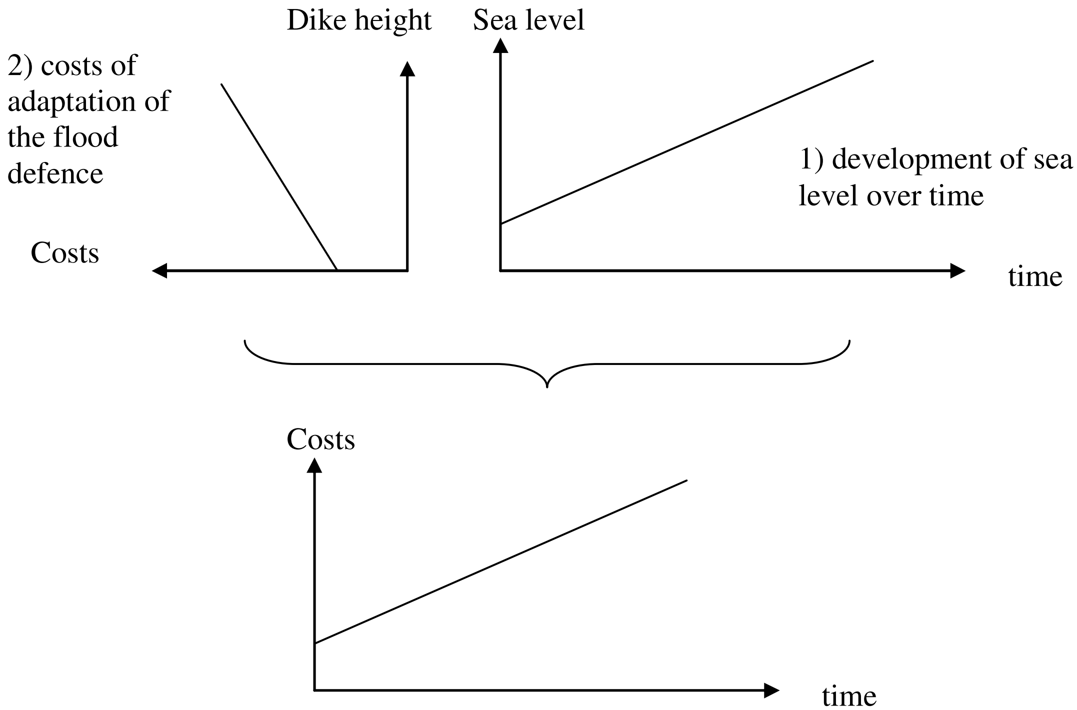


Figure 3-9: Conceptual scheme that shows how the development of adaptation costs over time depends on the development of sea level rise and the relationship between costs and sea level.

Adaptation of existing flood defence structures to sea level rise
It is noted that the required adaptation of flood defences will be based on the local value of the relative sea level rise rate[1]. The combination of sea level rise and subsidence is usually referred to as relative sea level rise. In New Orleans, it appeared that the crest elevation of many of the levees and floodwalls around New Orleans was substantially lower during hurricane Katrina than at the moment of design and construction due to the effects of subsidence.

Regarding the adaptation of existing flood defence systems, one should consider different design parameters and how they change with sea level rise. Parameters that increase linearly with a constant SRL rate are:

- The required nourishment volumes
- Dike height

[1] This means that subsidence of the land has to be considered in addition to the effect of sea level rise. Subsidence can have several causes: Inclination of organic materials (which is usually the case in delta), extraction of natural resources (oil, gas, water) and tectonic movement (e.g. post-glacial rebound of Scandinavia causes subsidence in the Netherlands).

- Footprint of the dike and required purchases of land

Parameters that will increase not-linearly with a constant SLR rate are:
- the dike volume and thus the required amount of soil.
- Expected costs of implementation. The wider the footprint of the dike, the higher the probability that houses or other buildings or objects have to be removed, or that specific and costly measures have to be implemented to prevent this.

It depends on local circumstances which parameters are dominant, and thus it depends on local circumstances whether the costs develop linear or non-linear.

Effects of the sea level rise rate
The future sea level rise (SLR) rate will determine required dike strengthening and investments. In case of an existing dike system, this results in:
- Linear SLR rate: same strengthening every interval. Note that with a higher, yet constant SLR rate, the costs will go up, but linearly.
- Non-linear (concave) SLR rate: the required strengthening becomes larger in time.

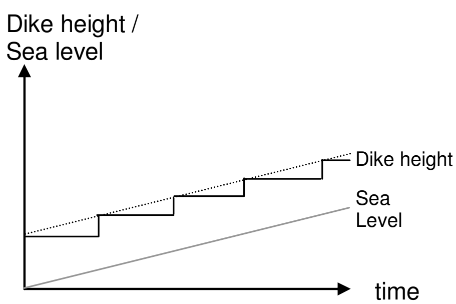
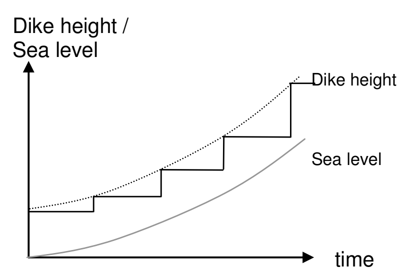
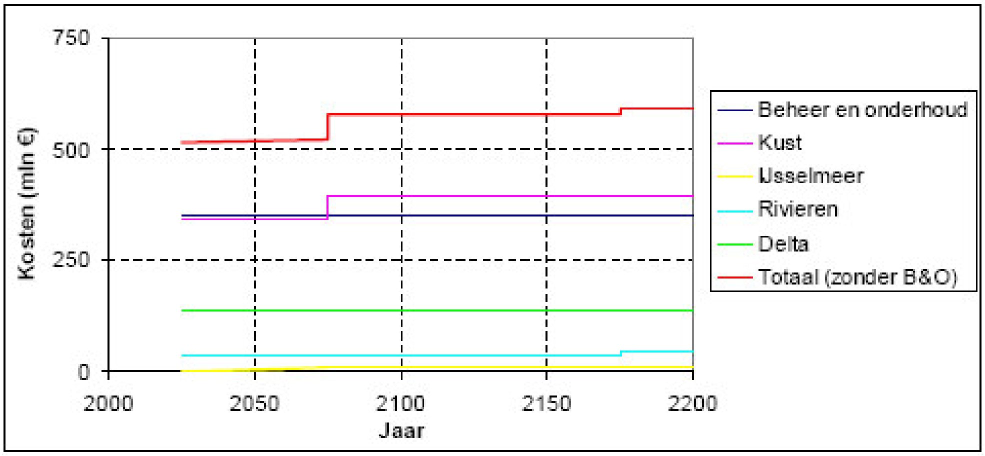
Linear SLR: the heightening steps remain constant.	Exponential SLR: The heightening steps increase in time.
	

Figure 3-10: The effects of the sea level rise rate on the dike heightening steps

It must be noted that for instance for sea dikes, the required dike height goes up faster that the SLR rate, as one has to incorporate the effect of increased wave height on the dike design. However, the relationship will still be linear.

Findings for the Netherlands (Kok et al., 2008)
For the Netherlands a prediction of the development of the future costs of flood defences has been made (Kok et al., 2008) as part of the investigation of the Deltacommittee. A sea level rise scenario was assumed that concerned a sea level rise of 0.85m in 2100 and a total sea level rise of 2.0m in the year 2200. The development of costs for different subsystems has been predicted. The figure shows the (average) yearly costs.
In general, a linear relationship between the costs of adaptation and the sea level rise was found. The most important design and cost parameters (height, width, land use) of the flood defences showed a linear increase over time. An important reason was that a constant sea level rise rate was assumed. However, replacement of existing major flood defence structures, such as storm surge barriers, was expected to lead to small “jumps” in the cost function, see example below.



Figuur 5-1: Kostenontwikkeling bij het middenscenario van het KNMI bij vasthouden huidige normen.

Figure 3-11: Development of yearly costs for flood defence in the Netherlands over time (Kok et al., 2008).

Other considerations and factors
Several (other) factors will affect the development of coastal defence costs over time and some of those have been discussed in the previous sections. A specific issue is the prediction of cost estimates for future expenses. Several developments could to changes in the unit cost price levels:

- uncertainty in development of costs and market prices (e.g. oil price)
- new innovative techniques with different price levels

Possible strengthening of the primary flood defence system could affect the internal water management system, e.g. drainage and pumping systems, especially in low-lying delta areas. For example if the sea level rises pumps with higher capacity are needed to drain these areas.

An important driver for changes in coastal protection could be the economic and population growth. This results in an higher need for safety and thus in the improvement of flood defences. This effect is discussed in chapter 4. This could lead to the decision to raise the level of protection. With that it could also be decided to adapt the alignment of the system.

Linear or non-linear development of the costs of coastal protection over time?
In summary, it is not easy to determine whether the costs of flood defences and coastal management will develop linearly or non-linearly over time. This will determine on local factors that have been described above. Some important factors that would contribute to a linear of non-linear development are summarized below:

Linear development (unit cost prices remain constant over time)

- Constant (relative) sea level rise rate
- Same measures can be used for higher design water levels
- Most design parameter increase linearly with a linear SLR rate
- Relative costs levels for labour and material remain constant over time
- No increase of the costs of purchasing land for additional widening and strengthening
- Level of protection remains constant over time

Non-linear development (unit cost prices increase over time)

- sea level rise rate increases
- System modifications required (e.g. storm surge barrier replacements)
- Important design parameter increase non-linearly with sea level
- Construction of new flood defences required
- Relative costs levels for labour and material increase over time
- Adaptation of the defences requires measures in “difficult” areas, e.g. urban areas
- Level of protection increases over time

There are factors that could contribute to a decrease of the unit costs over time. When material or labour costs decrease or when new cheaper techniques and constructions are invented the marginal costs of adaptation could decrease. The relationship between sea level rise and costs will be determined by a combination of the above factors.

4 Optimal protection levels

This section focuses on the determination of optimal protection levels in a so-called economic optimization or cost benefit analysis. The unit cost prices that have been discussed in the previous sections will be important input, but not the only input, in determining the optimal protection levels. The general approach and theory is presented in section 4.1. Findings for the three case studies are included in section 4.2. Section 4.3 compares the results of the case studies with the demand for safety that follows from the DIVA model.

4.1 Background and general approach

After the 1953 flood disaster a Delta Committee was installed to investigate the possibilities for a new approach towards flood defence. The committee proposed to reduce the vulnerability by shortening the coastline and closing off the estuaries in the Southwest of the country. In addition, safety standards for flood defences were proposed. In an econometric analysis the optimal safety level was determined for the largest flood prone area, South Holland (van Dantzig, 1956). In this economic optimization the incremental investments in more safety are balanced with the reduction of the risk. The investments consist of the costs to strengthen and raise the dikes. In the simple approach it was assumed that flooding could only occur due to overtopping of the flood defences. Thereby each dike height corresponds to a certain probability of flooding (the higher the dikes the smaller the probability of flooding). Dike 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 safety 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 safety level was determined for the largest flood prone area, South Holland.

The equation for the optimal protection level is as follows:

$$P_{opt} = \frac{I' rB}{D}$$

Where:

- P_{opt} – optimal protection level [1/year];
- I' – costs per unit of heightening / strengthening of the flood defence;
- r' – nett discount rate (economic growth minus inflation);
- B – constant related to the statistical distribution of the water levels [-];
- D – potential damage in case of flooding [Euro]

This shows that the marginal costs of improvement of the safety and the potential damage will be important factors that determine the optimal protection level. The other two factors (B, r') are generally constant and do not depend on regional or local characteristics of the area under study. The economic optimization is often also referred to as cost benefit analysis.

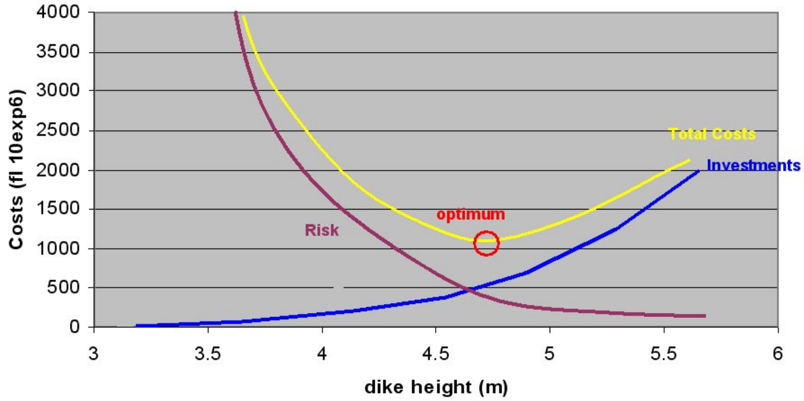


Figure 4.1: Principle of the Economic optimization approach by the Delta Committee.

In recent work (Eijgenraam, 2006) some modifications of the approach have been proposed. In essence, the difference is that van Dantzig assumes one major improvement at the current moment, while Eijgenraam considers the periodical character of the improvement of the flood defence system under changing conditions such as economic growth, sea level rise etc.. As a result the optimal flooding probability will change over time, e.g. due to economic growth (see figure 4.2). Comparison of both these methods for some practical case studies for the Netherlands and New Orleans shows that they give similar results for the first decades of the considered time period.

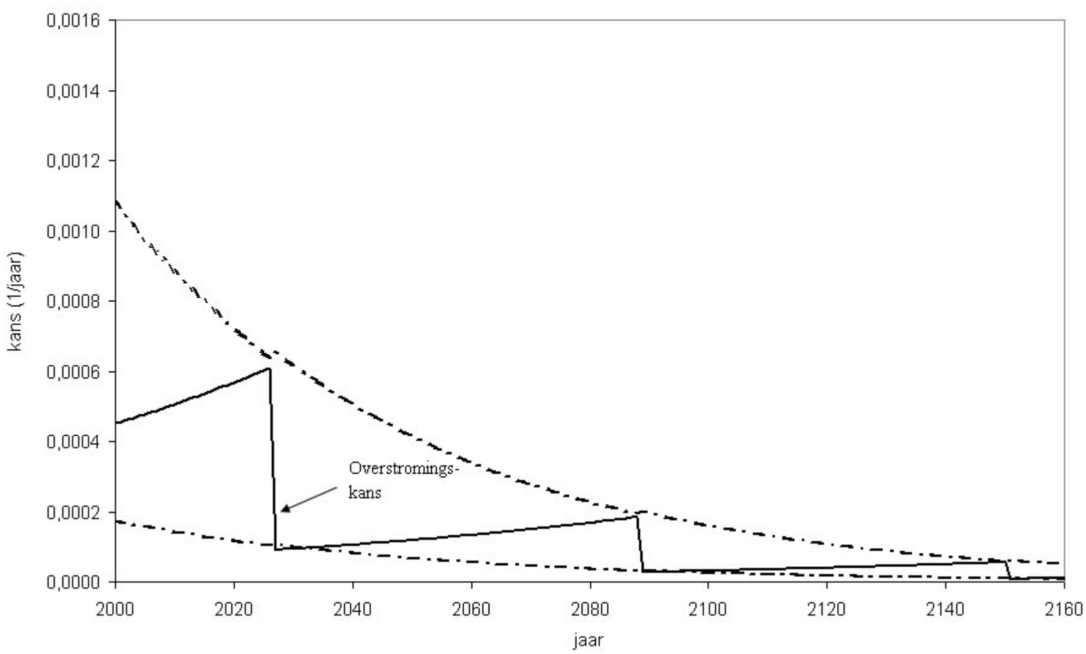


Figure 4.2: Development of the optimal flooding probability over time (Kind et al., 2008)

4.2 Case studies

This section briefly presents the results for three case studies for which the method of economic optimization was applied. Further background is given in the publications that are referred to.

4.2.1 Netherlands

Background

After the 1953 disaster a delta committee was installed. The analysis of the Delta Committee laid the foundations for the new safety approach, in which dikes are dimensioned based on a design water level with a certain probability of exceedance. The current design criteria and the process for safety evaluation of the flood defences 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 dike ring areas, i.e. areas protected against floods by a system of water defences (dikes, dunes, hydraulic structures) and high grounds. The safety standards for the various dike depend 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 1/4000 per year and 1/10,000 per year. For the Dutch river area the safety standards were set at 1/1250 per year and 1/2000 per year. Some smaller dike ring areas bordering the river Meuse in the south of the country have a safety standard of 1/250 per year.

Recent economic optimization

More recently, the cost benefit analysis / economic optimization, has been applied to all major dike rings in the Netherlands. This was done by applying the “dynamic” model proposed by Eijgenraam (2006). A first indication of the results was presented in (Kind, 2008). The results are shown in figure 4-3. These are the so-called “middle” optimal safety levels. This means that these are the middle probabilities in the bandwidth shown in figure 4-2. When these results are compared with the current safety standards it is found that especially in the dike rings in the river system in the east of the country would need to receive a higher protection level than the current level. It is noted that the results below are a first indication, as further extensive studies are ongoing. Final results will be used for a possible update of the existing safety standards.

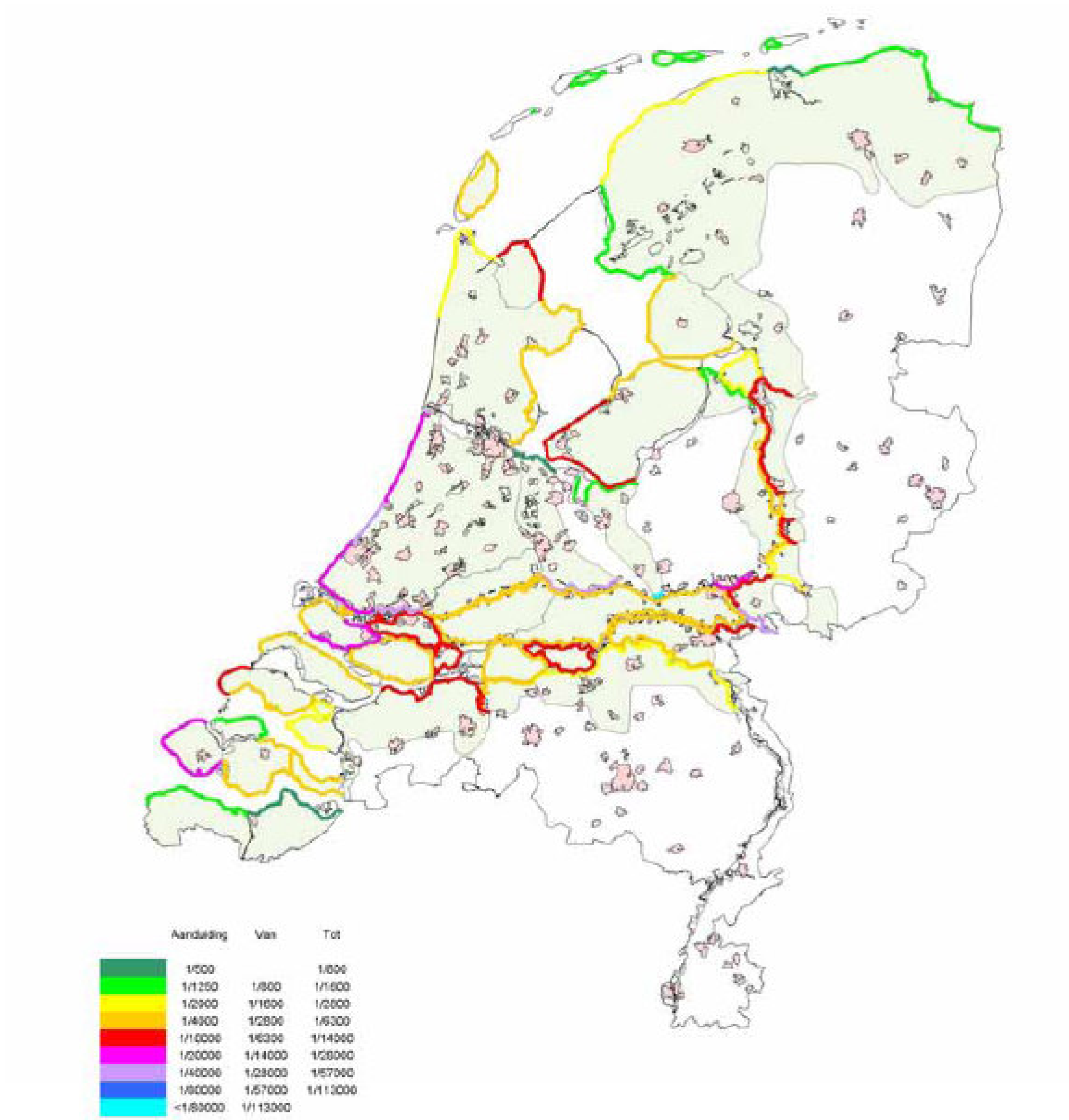


Figure 4.3: Optimal safety levels for dike rings in the Netherlands.

4.2.2 New Orleans

The economic optimization has been applied to New Orleans. As part of the broader "Dutch perspective study" (Dijkman, 2007) the optimal safety levels for the three polders that are shown in Figure 4.4 have been determined. Table 4.1 and Figure 4.4 give the results for the central part of New Orleans (dike ring 1). As part of the approach design surge levels and their return periods were determined. The costs have been based on the unit cost estimates that have been presented in section 3. Damage estimates have been used based on various studies that were published after hurricane Katrina.

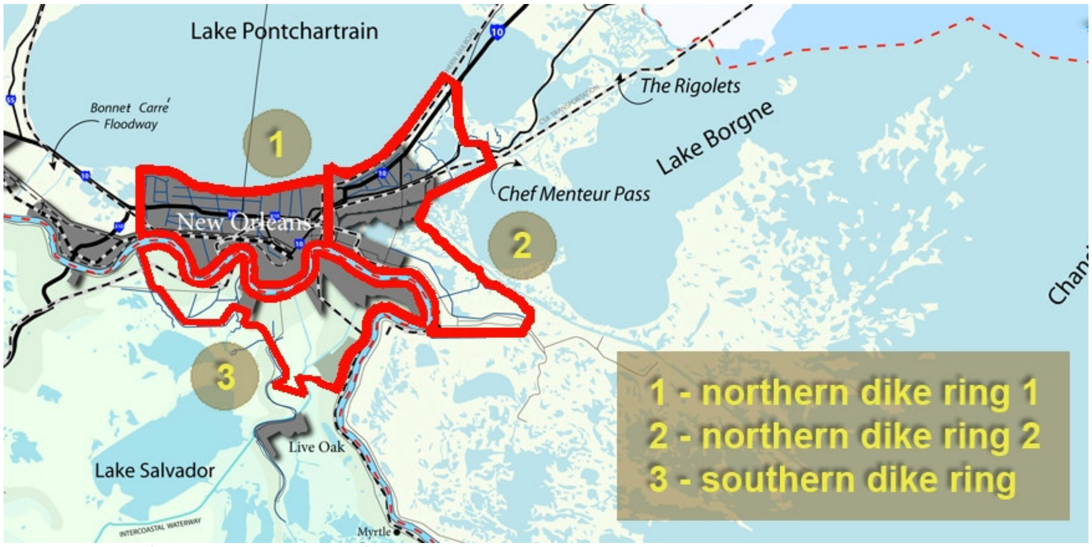


Figure 4.4: Overview of New Orleans metropolitan area and proposed flood protection systems in de Dutch perspective: (1) Northern dike ring 1 (central part of New Orleans); 2) Northern dike ring 2 (East Orleans and St Bernard); (3) Southern levee ring (West bank).

Table 4-1: Economic optimization for Northern dike 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
Design surge level Lake Pontchartrain (ft)	9	11	13	15	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

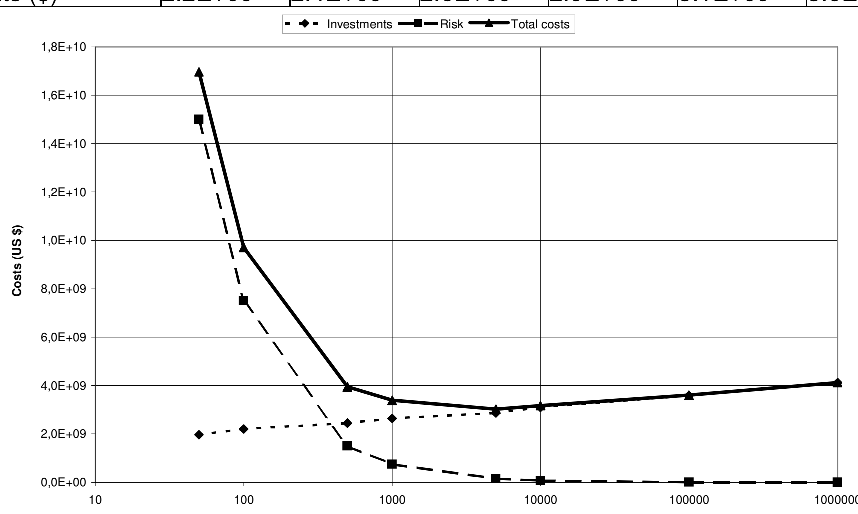


Figure 5: Results of economic optimization for the Northern dike ring, central part of New Orleans

For the central area (northern dike ring 1) an optimal safety level of about 1/5000 per year has been found. For the other two polders optimal safety levels of around 1/1000 per year were obtained. Given the preliminary character and the uncertainties in the assumptions (See Jonkman et al., 2009 for discussion) the presented outcomes can be regarded as a first indication.

4.2.3 Vietnam

In a number of publications the approach has been applied to Vietnamese sea dikes, (Hillen, 2008; Mai et al., 2008; Mai, 2010). A case study has been done for the Nam Dinh province, in the northern part of the country. This was also the area that was seriously flooded after typhoon Damrey in the year 2005. This event caused about US $ 500 million of damage. Based on cost estimates for the sea defences (see section 3), information on typhoon induced surges and their return periods, and assessments of damage in coastal areas the economic optimal level of protection was determined. Figure 4.5 shows the results for Nam Dinh province for the current level of economic development. This leads to an optimal protection level of about 1/50 per year. Vietnam has a fast growing economy. If future economic development is taken into account, leading to a growth of the potential damage, a higher protection level is found of about 1/90 per year.

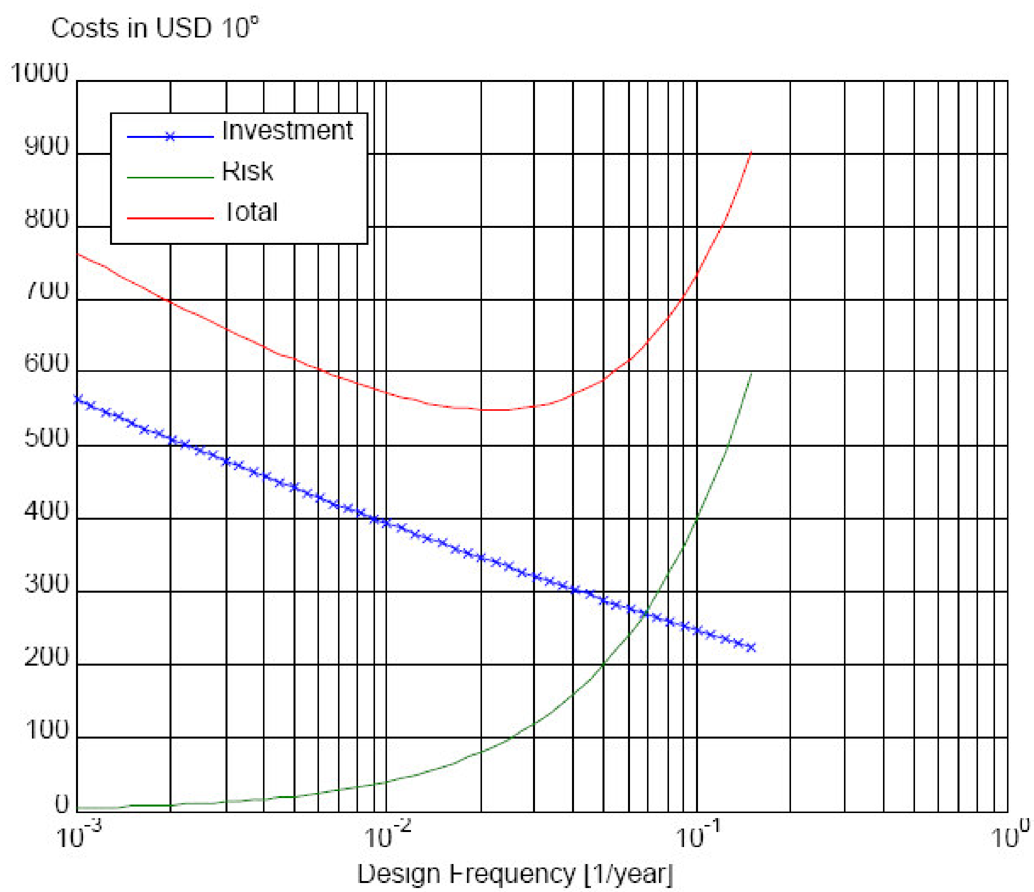


Figure 4.5: Economic optimization for Nam Dinh province for the current economic situation (Mai, 2010).

4.3 Discussion and comparison with the DIVA model

The results for the three case studies have been compared with the "demand for safety" that resulted from the DIVA model (personal communications with Linham, 2010), see table 4.2. It is clear that both approaches given different results.

Table 4-2: Comparison between the optimal protection level determined with the economic optimization and the demand for safety that resulted from the DIVA model

Location	Demand for safety according to DIVA (return period [yr])	Optimal protection level (return period [yr])
Netherlands	1739 (Amsterdam) 1396 (Rotterdam)	20,000 (Rotterdam area) 4000 (Amsterdam area) (Kind et al., 2008)
New Orleans (USA)	1385	1000 – 5000 (Jonkman et al., 2009)
Vietnam	14 (Hai Phong) 1 (Ho Chi Minh City)	50 (Nam Dinh, current situation) 90 (Nam Dinh, incl. economic growth) (Mai Van, 2010)

A further general comparison of similarities and differences between the two approaches is given. Table 4-3 compares the factors that are included in the DIVA approach (Anon, 2010) and the factors that are included in the economic optimization.

Table 4-3: comparison between the factors included in DIVA and the economic optimization

DIVA	Economic optimization
• GDP • Coastal population density • Storm surge regime Higher GDP and coastal populations generate greater demand for safety	• Damage in case of flooding • Marginal cost of improving the level of protection (determined by system length and costs of measures) • Nett discount rate • Return periods of hydraulic load levels

Generally speaking one can see that DIVA includes more general factors whereas the economic optimization focuses on more specific factors that relate to the system's characteristics. This is not surprising as DIVA as used for global assessments, whereas the economic optimization is more used as a design supporting approach for flood defence systems.

Two important factors in the economic optimization are the potential damage and the marginal costs of improving the level of protection. The information on the GDP and coastal population density in DIVA are related to the damage potential. One additional factor that is not included in DIVA but is important for the damage potential is the amount of flood prone / low-lying areas in the considered region.

In the DIVA model the (marginal) costs of improving the level of protection are not directly included. One important factor that will determine these costs will be the length of the defence system. The longer the alignment, the more expensive raising the level of protection will be. That the system's length is an important factor was also found in the economic optimization (Eijgenraam, 2006). For dike rings in the Netherlands it was found the the optimal level of protection was directly related to the ratio of the number of inhabitants and the system's length (see figure 4.6). The number of inhabitants will be proportional to the damage, and the system's length will influence the costs of improving the level of safety. These two factors (damage and marginal costs) are the most important determinants of the optimal protection level (see also the formula in section 4.1). Following this approach a smaller system with a high concentration of people and values will receive a higher optimal level of protection than a very long system with a low population density.

Figure 4.1 Middle optimal safety and the number of inhabitant per kilometre dike (logarithmic)

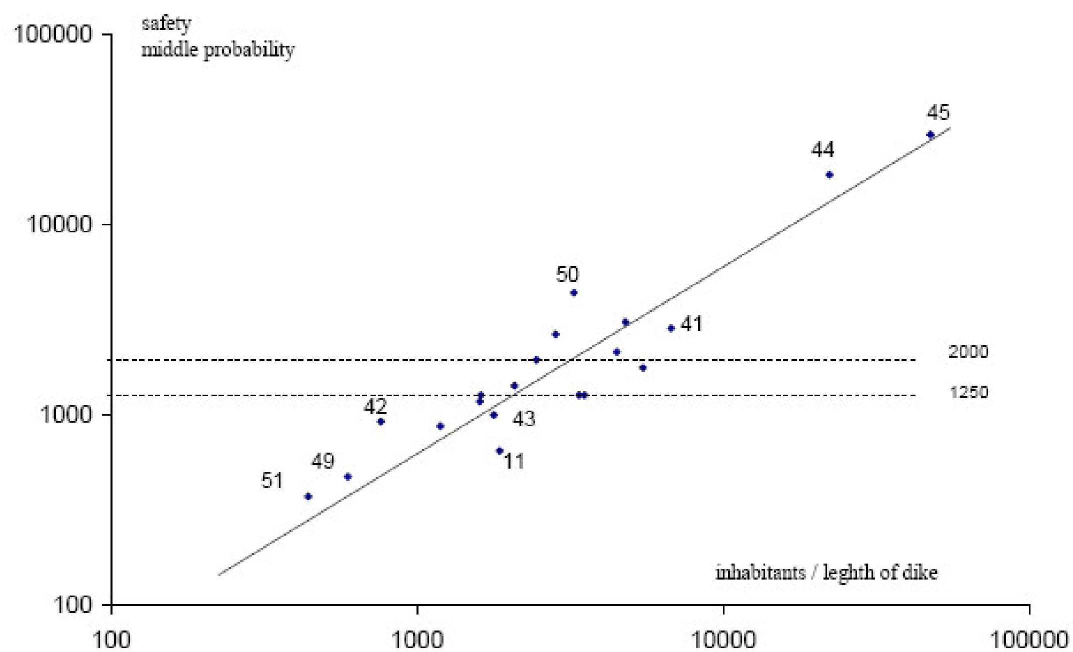


Figure 4.6: Optimal safety level (return period) versus the number of inhabitants per unit dike length (Eijgenraam, 2006).

The above shows that the number of inhabitants per unit of the length of the defence is a good approximate measure for the optimal protection level. It is recommended to use this measure as a representative for the optimal standard of protection, and to investigate if and how the length of the defence system can be added to the approach implemented in DIVA. More overall, it is recommended to compare the approach of the economic optimization and the DIVA method for determining the "demand for safety" at a methodological level and for a number of selected case studies.

5 Main findings and recommendations

Information on the costs of coastal defences has been investigated for the full range of hard and soft engineering measures, such as dikes/levees, nourishments and storm surge barriers. Information and cost estimates from previous studies have been used to derive unit cost estimates for the Netherlands, Vietnam, New Orleans (LA, USA) and Cape Town (South Africa)

An overview of the resulting unit cost estimates is given in table 3-1. Some main findings are summarized below:

- **Dikes**: for the Netherlands the unit costs for strengthening of dikes range between 4 and 11 M€ per km per m heightening for rural areas and between 14 and 22 M€ per km per m heightening for urban areas (2009 price levels). The cost estimates for dike and floodwall heightening for New Orleans are between 4 and 8 M€ per km per m heightening.
- **Storm surge barriers**: the cost price per unit width has been deduced from the available global data. This ranges between 0.50 M€ per meter width and 2.7 M€ per m width
- **Beach nourishment**: for beach nourishment in the Netherlands the available literature sources indicate a unit cost price of about € 3-4 per m^3 material for foreshore nourishment and € 7-8 per m^3 material for beach nourishment. A somewhat higher unit cost € 11 per m^3 material for beach nourishment has been obtained for South Africa.

- The unit cost prices will depend on the measure selected and consequently on the costs for planning and engineering, labour, equipment, materials. There are two important factors:
    1. **Local economic factors**: The average unit costs for dike strengthening in Netherlands and New Orleans are about eight times higher than those for Vietnam. It is necessary to use different cost estimates for regions with different economic development levels.
    2. **Implementation in urban or rural areas**: Additional costs have to be made if measures are implemented in urban or ecologically sensitive environments. For the Netherlands the unit cost price for strengthening dikes in urban environments is about two times higher than the unit cost price for rural areas

- The costs estimates at the level of a coastal protection system will depend on the unit cost prices, the system's length, the chosen alignment and costs made for other functions than coastal flood protection (e.g. recreation, ecology). All these factors have to be taken into account when predicting the costs of adaptation to sea level rise.
- A comparison between the unit cost estimate from IPCC CZMS and the findings of this study shows the following. The unit costs in the IPCC study are lower, likely because the IPCC numbers are based on dike construction or strengthening in an idealized situation, whereas the numbers from this study are based on actual project data.
- It has been investigated whether there is a linear or non-linear relationship between the sea level and the costs for adaptation of flood defences. Current

studies for the Netherlands (Kok et al., 2008) suggest a linear relationship. A number of factors have been identified that would affect this relationship. Important factors are the sea level rise rate, future changes in price levels (labour, materials), the need for modification of the system's alignment and the need for adaptation of large structures, such as storm surge barriers.
- Given all these factors, the derived unit costs estimates should be considered as indicative and they can only be applied with a considerable bandwidth / uncertainty margin.
- The optimal levels of protection that have been found by applying the economic optimization / cost benefit analysis to three case studies differs from the "demand for safety" that is found with the DIVA model. One important difference is that the economic optimization takes into account the potential damage and the actual length and improvement costs of the flood defence system, whereas the DIVA model is based on more global indicators, such as the population density, GDP and storm surge regime.

Recommendations

- For consideration of the costs of measures at a system or higher level (country or regional) it is essential to specify which measures are implemented. This means that studies on the costs of adaptation to sea level rise would also require specification of the (assumed) measures, the system alignment and the strategies that are implemented.
- Given the uncertainties and / or lack of knowledge of underlying factors it is recommended to express unit cost estimate by means of bandwidths.
- Further analysis of existing cost information for storm surge barriers is recommended. It can be investigated whether a relationship between various barrier characteristics (width, height, hydraulic head, barrier type) and the barrier costs could be found. A general formula could be derived to give a first indicative prediction of the costs of storm surge barriers.
- In new Orleans approximately US $ 15 billion has been invested in recent years to repair and improve the safety of the hurricane protection system. Although a lot of cost information is confidential, analysis of public information on levee projects could improve the empirical basis of the cost estimates for this region. It is recommended to set up a specific investigation for this system.
- It is recommended to review and update the county factors that are used in the IPCC CZMS study based on more actual data from costs of coastal defence projects and regional economic indicators.
- In an economic optimization an optimal level of protection can be determined based on the required investments in providing a higher safety level and the benefits in terms of reduction of the economic risk. The investments will be highly dependent on the design of the flood defence system for the system and possible changes in the alignment and the implemented defence measures. A good approximate measure for the optimal protection level is the number of inhabitants per unit of the length of the defence. It is recommended to use this measure as representative for the optimal standard of protection, and to investigate if and how the length of the defence system can be added to the approach implemented in DIVA.

- More overall, it is recommended to compare the approach of the economic optimization and the DIVA method for determining the “demand for safety” at a methodological level and for a number of selected case studies.

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Appendix I – Coastal defence cost estimates Cape Town (South Africa)

M.A. Geldenhuys BSc

Coastal Adaptation to Climate Change: Measures and Costs

A Cape Town Case Study

M.A. Geldenhuys BSc (TU Delft – CoMEM program)

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1 Introduction

Much of the world's population is living along the coast. Climate change, along with the corresponding rising sea levels, and population growth is putting much pressure on existing coastal defences and could cause significant damage to unprotected coastlines.

There is a need to quantify the potential adaption measures and costs in terms of climate adaption worldwide. Research is currently done about the impact of climate change on 136 port cities around the world (Linham et al 2010); this project is coordinated by Robert Nicholls from Southampton University. Delft University of Technology, in cooperation with Royal Haskoning, has been approached to research coastal defense unit costs in more detail; with real costs from case studies relating to The Netherlands, Vietnam and New Orleans projects. This report is an additional case study provided as an annexure to this abovementioned coastal defence cost project report. It should be noted that this report only gives an indication of costs related to coastal protection in Cape Town due to the limited scope and timeframe that was available for this project.

The City of Cape Town Municipality (hereafter referred to as the City of Cape Town) has experienced increasing coastal damage relating to more frequent and bigger storms and is vulnerable to rising sea levels. The most significant hazards to the Cape Town coastline are erosion and wave run-up during storm events. This leads to large economic risk and damage, for both the City of Cape Town and private property owners, to infrastructure and assets in proximity to the coast. This study is a brief review of relevant literature to give indicative costs for climate change adaption in Cape Town. Information relating to the damage caused by a recent storm, which took place in 2008, is provided along with an estimate about economic risk to the City of Cape Town in event of a design storm.

Figure 1-1 gives the location of Cape Town on the Southern tip of Africa.

Figure 1-1: Location of Cape Town on the world map

2 Description of the Local Situation

2.1 General

The City of Cape Town Municipality administers approximately 307 km of coastline; which is arguably its single greatest economic and social asset (Cartwright et al, 2008 – Phase 1). Cape Town is the second most populous city in South Africa, with an estimated population of approximately 3.5 million inhabitants (Statistics SA, 2007); and with an area of 2,450 km^2, which is the largest city area in South Africa. Figure 2.1 shows the 8 district municipalities managed by the City of Cape Town.

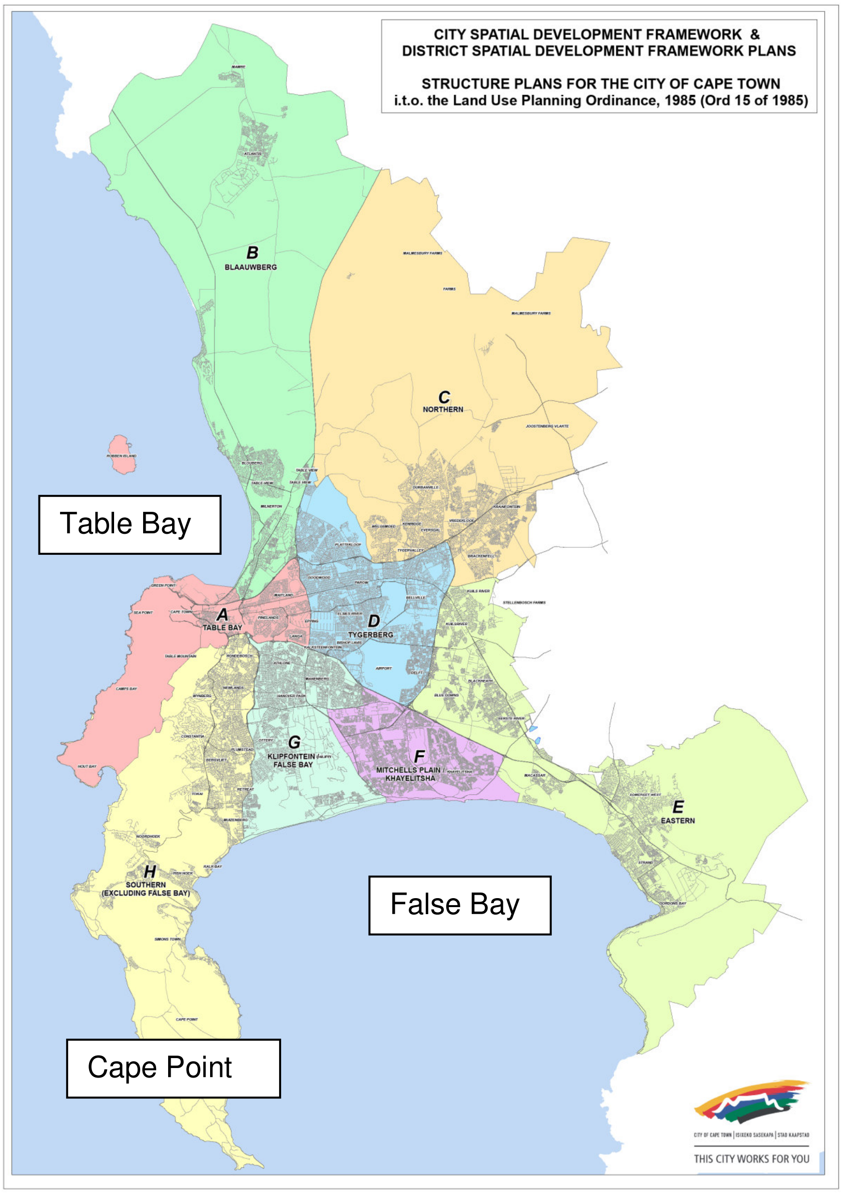

Figure 2-1: Cape Town districts

Cape Town has a Mediterranean climate, with cold wet winters and dry hot summers, with an annual ambient air temperature of 19℃ (Wikipedia).

Cape Town is arguably the most popular tourist destination in South Africa; in 2006 foreign tourist expenditure in the Western Cape totaled R19.80 billion (US$2.64 billion), while domestic tourism receipts were R1.50 billion (US$200 million). The forecast for 2008 for total tourism revenue is R24 billion (US$3.2 billion) (Cartwright et al, 2008 - Phase 3). According to the five year plan, Cape Town currently generates about 78% of the Gross Geographic Product (GGP) of the Western Cape and some 12% of South Africa's Gross Domestic Product (GDP) (City of Cape Town Annual Report, 2009). The 2008 GGP for the City of Cape Town was R165 billion (Based on 2006 figures of R123.6 billion) (Cartwright et al, 2008 - Phase 3). An exchange rate of R7.5 for $1 is used throughout the study.

2.2 Topography

Cape Town is a city interspersed with mountains, most notable Table Mountain and the Cape Point mountain range. The topography is therefore very variable with some low lying sandy areas, such as the Cape Flats (Figure 2-2), as well as maximum elevations in excess of + 1,500 m MSL (Figure 2-3). The Cape Town coastline is extremely variable and differs between mountain cliffs, rocky outcrops and pocket beaches as found along Cape Point to gentle beaches with dunes behind them as found along False Bay and Table Bay (refer to Figure 2-1 for locations). Generally it can be said that most of the Cape Town area is high enough not to be prone to inundation after the breach of coastal defences, but rather that it is vulnerable to erosion during storms (a situation which is exacerbated by the variation between rocky and sandy coastline and occurrence of pocket beaches).

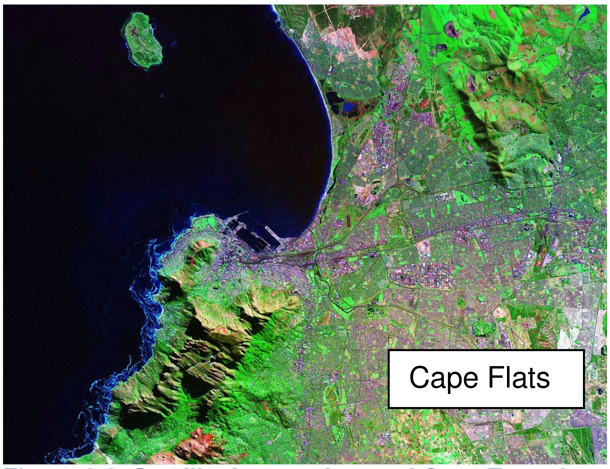

Figure 2-2: Satellite Image of central Cape Town (www.Geology.com)

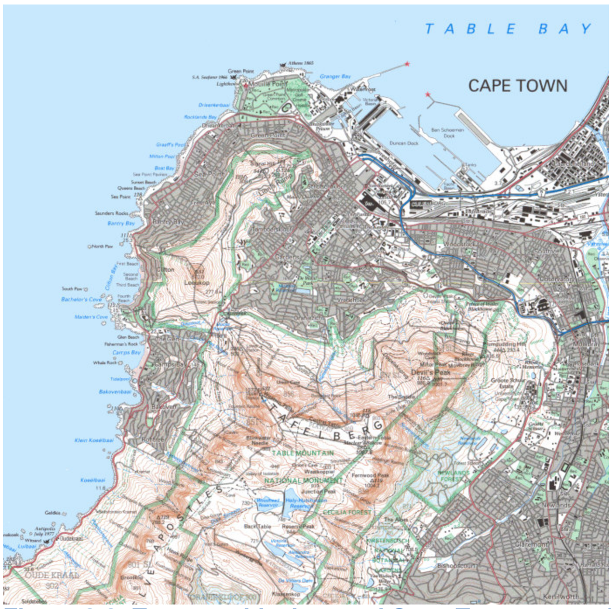

Figure 2-3: Topographical map of Cape Town centre (www.mapstudio.co.za)

2.3 Bathymetry

The bathymetry of the ocean surrounding Cape Town is also highly variable, the general trend is however that most of the exposed coastline has steep gradients as shown in Figure 2-4, which allows big waves to propagate close to the shore. Other areas are sheltered, such as False Bay, and have shallower gradients. The gradient of the zone just offshore of Sea Point can be approximated from Figure 2-4 as 20 meters divided by 600 meters, which gives a slope of 1:30. This is a relatively steep slope; deep water can be found close to the shore on many locations along the Cape Town coast.

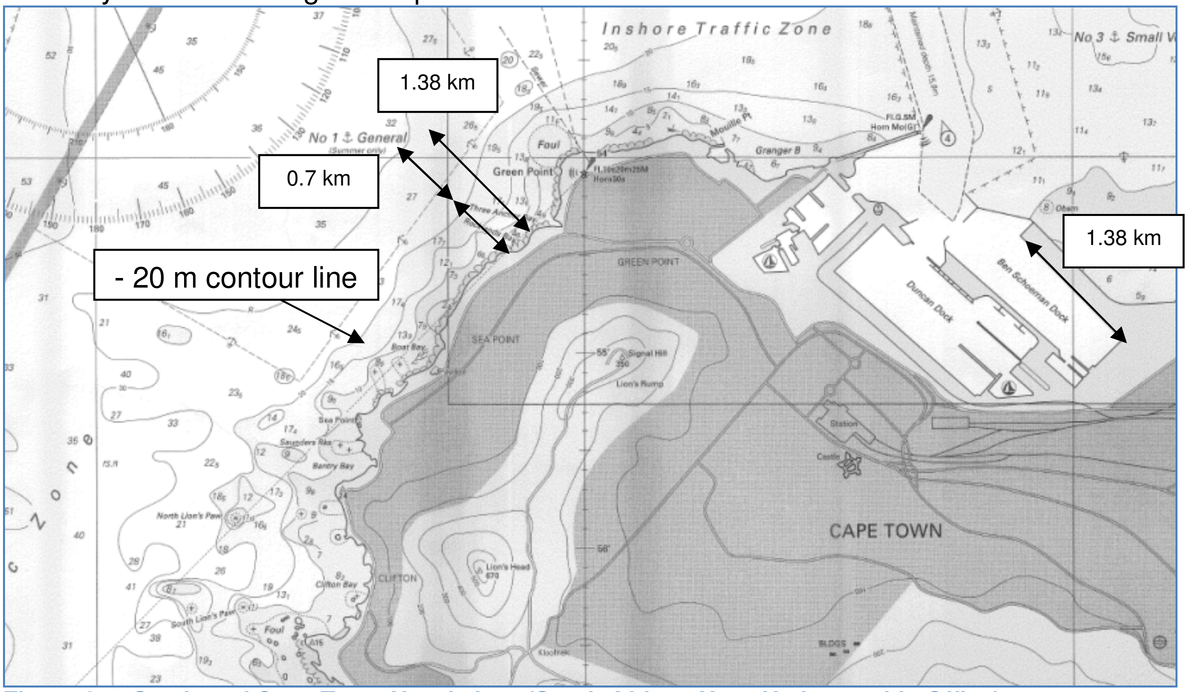

Figure 2-4: Section of Cape Town Naval chart (South African Navy Hydrographic Office)

2.4 Tides

The maximum tidal variation between Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT) is approximately 2 meters. The offset of Chart Datum (CD) relative to Land Levelling Datum (LLD) is -0.843 metres at Simon's Town Naval Harbour in False Bay (www.satides.co.za), HAT is equal to LLD + 1.24 metres.

2.5 Sea Level Rise and Surge

According to the IPCC report on sea level rise in South Africa (Goschen et al, 2009) the greatest hazards to the South African coastline is that of short term events caused by extreme storms and floods. The abovementioned report indicated relative sea-level trends for Cape Town provided in Table 2-1.

Table 2-1: Relative sea-level trends for Cape Town. Stations are from the Permanent Service for Mean Sea Level (PSMSL) data holdings (Mather et al., 2009) (adapted from Goschen et al, 2009)

Tide station	Period of Record	Years of record	Completeness of record (%)	Observed annual sea-level trend using monthly data (mm yr^{-1})	Observed annual sea-level trend using annual data (mm yr^{-1})
Table Bay	1957-1972	16	Insufficient data		
Simons Town	1957-2007	51	78	$+1.6 \pm 0.2$	$+1.2 \pm 0.5$

The maximum still water effects as recommended by Theron and Rossouw (2008) are given in Table 2-2, it should be noted that the values in this table are mean values for the whole South African coastline.

Table 2-2: Parameters and estimated maximum effects on still-water levels for the South African coast (Theron and Rossouw, 2008) (adapted from Goschen et al, 2009)

Parameters and effects	Elevations (m to mean sea level) and setup (+ m)
Mean high water spring tide	1.0
Highest Astronomical Tide (HAT)	1.4
Severe wind set-up	+0.5
Maximum hydrostatic set-up	+0.4
Wave set-up	+1.0
100 year sea-level rise	+0.2 to +0.6 (say 0.4)

This can be compared with the overall monthly maximum deviation in sea level (without tidal impact), in a recorded period of 30 years, which was recommended to be +0.4 metres in the City of Cape Town Sea-Level Rise Risk Assessment (Cartwright et al, 2008 – Phase 1) and is much smaller than the potential combined set-up of 0.9 metres recommended in Table 2-2. The sea levels of LLD +1.54 m at a return period of 100 years and LLD + 1.63 m for a return period of 500 years are extrapolations used in further studies by the City of Cape Town (Cartwright et al, 2008 - Phase 1).

2.6 Waves

A summary of the wave climatology for Cape Town as described in Phase 5 of the Sea Level Rise risk assessment report (Brundrit et al, 2009) is given:

- A deep water wave recording site, Slangkop, situated 14 kilometres offshore in 170 metres deep water provided records for 12 years (1976-1988) (11424 records at 6 hourly intervals = 63% coverage).
- A median peak period of 12.4 seconds was measured for the wave date in Table 2-3.

Table 2-3: Significant Wave Height Statistics from Slangkop 1976-1988 (adapted from Brundrit, 2009 – Phase 5A)

Significant wave height H_S	Metres
Median value	2.6
Value at a return period of 1 year	7.6
Value at a return period of 10 year	9.4
Value at a return period of 100 year	11.1

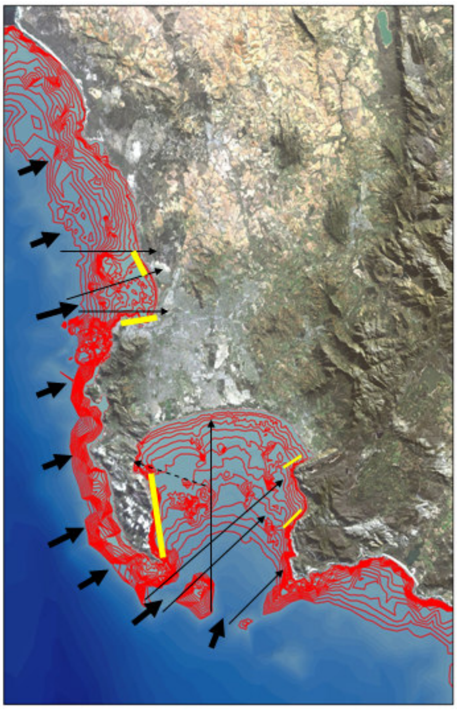

Figure 2-5 Bathymetry around the Cape Peninsula down to a depth of 70m at 5m intervals. (Brundrit et al, 2009 - Phase 5A)

The coastline is more exposed to extreme events from the South West as shown in to Figure 2-5. Wave information is summarized below (Cartwright et al, 2008):

- A big wave event is defined as one which has a significant wave height exceeding 6.5 metres for at least 6 hours (Van der Borsch, 2004).
- Thirty two big wave events were identified at Slangkop over the 21 year measurement period (1983 to 2003).
- It should be noted that the distribution of these events are grouped and seem to correspond to years that had persistently warmer sea surface temperatures.
- The average significant wave height within these 32 big wave events is 7.7 metres, with standard deviation 1.0 metres, which can be compared with the value of the significant wave height at a return period of one year of 7.6 metres, as given in Table 2-3.
- The average of the maximum individual wave heights within each big wave event is 12.7 metres, with a standard deviation of 1.8 metres, so that the events can certainly be classed as big wave events.
- The overall maximum individual wave within these 32 big wave events reached 17.1 metres.
- There is a restricted directional spread, with 95% of the records taken within the big wave events being from the south-west between 200 and 260 degrees.
- Big waves also occur from the South-East, but at somewhat lower chances of occurrence.

The following scenario is assumed to by the present day worst case scenario for Cape Town; the maximum sea levels that can be expected taking into consideration storm setup, wave height and tides (rounded up to the 0.5 metres to fit the GIS system).

- a 2.5 metre increase in sheltered environments
- a 4.5 metre increase in exposed environments
- a 6.5 metre increase in very exposed environments

This scenario would see 25.1 km^2 covered by the sea (1 percent of the Cape Metro's total area of 2,499 km^2), albeit for a short time (Cartwright et al, 2008 - Phase 1), as can be seen in Figure 2-5. The analysis was also done for two other future scenarios, but would not be considered in this report. It is assumed that Scenario 1 has a 95% chance of occurring in the next 25 years (Cartwright et al, 2008 - Phase 3). Figure 2-6 gives an indication of the elevation of vulnerable coastal areas. The areas in blue will be flooded in event of a total storm surge of +2.5 metres (this includes wave and tidal impact); in red in event of a +4.5 metres storm surge (as could be expected in exposed environments according to Scenario 1) and orange the flooding in event of a storm surge of +6.5 metres all above LLD.

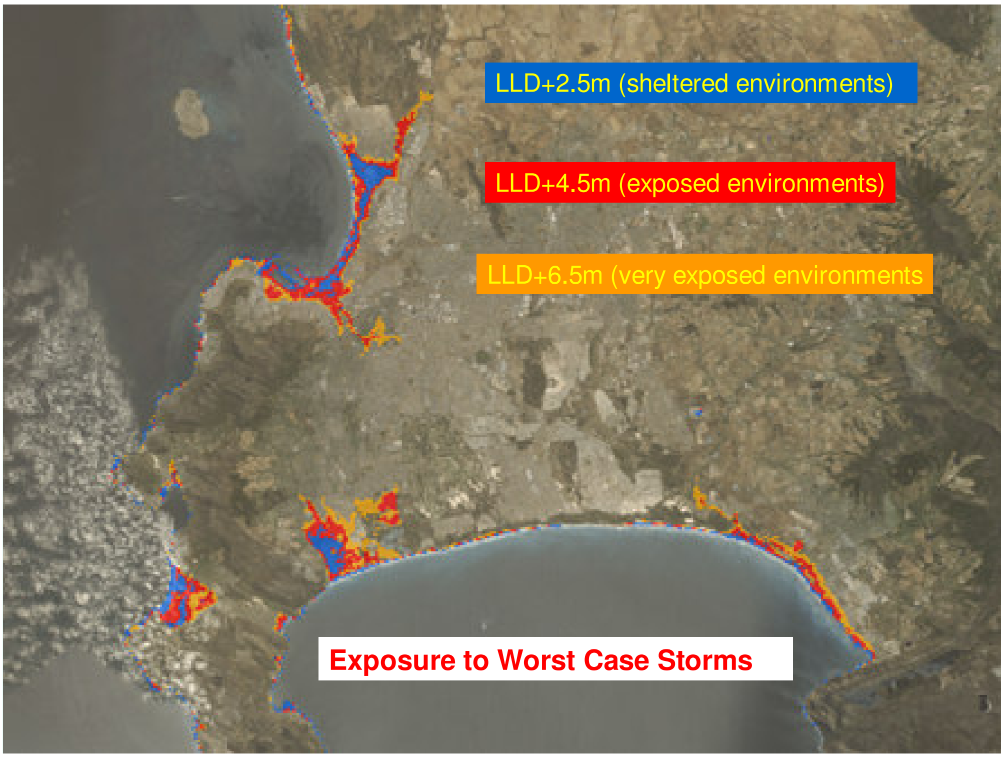

Figure 2-6: The exposure of the City of Cape Town to the worst case storms to be expected (Brundrit, 2009 - Phase 5)

These vulnerable areas are mostly built-up (with the exception of two estuaries) and are of high economic value. It includes parts of the central business district of Cape Town and also much of the most expensive housing in the city (such as housing along Clifton beach as shown in Figure 2-7).

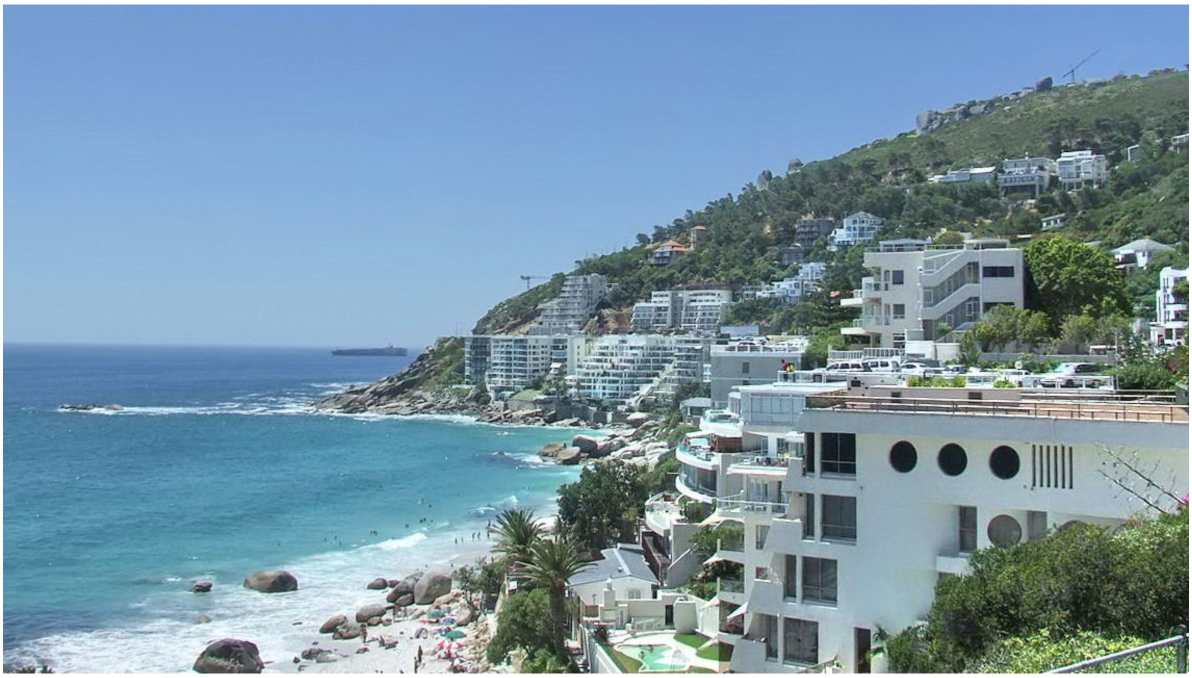

Figure 2-7: Expensive real estate along Clifton beach (www.about.com)

Figure 2-7 also gives an indication of the vulnerability of some of these developments that are situated directly along the beach against the steeply inclined slope of Lion's Head Mountain.

3 Current Coastal Protection and Management Strategy

The City of Cape Town does not currently have generic coastal defence solutions implemented along shore, but rather tailored solutions (where necessary) to accommodate the variations of the coastline. Most of the coastline is not, in essence, protected by artificially designed solutions, but rocky cliffs (such as along Chapman's Peak and Cape Point) and coastal dunes (e.g. along False Bay and Table Bay) provide natural protection. In many instances the natural dune protection has however deteriorated due to encroaching development and would need maintenance and potentially have to be expanded in future.

There are parts of the coast protected by sea walls such as the reclaimed area Sea Point (which is also an old landfill site). The Port of Cape Town and V&A Waterfront leisure development is protected by breakwaters. A wide variety of protection measure is needed for Cape Town's constantly changing coastline. Figure 3-1 shows the differing types of coastal protection around the central part of the city. It again highlights the variability of the coastline and the associated need for different protection measures.

Figure 3-1: Broad protection types along coast

A Coastal Act was passed in 2009 (Government Gazette), which aims to establish integrated coastal and estuarine management by means of a legislative basis. It provides the base for creating coastal 'buffer zones', in an attempt to stop inappropriate development (Government Gazette, 2009). The current protection level for the coastline is estimated to range between 1:20 and 1:200, but is not freely available or known for all areas.

It is apparent that the current coastal protection measures need to be studied in more detail to provide integrated solutions for the whole coastline. To reach the abovementioned goal the City of Cape Town has been proactive in developing its own Coastal Zone Strategy (2003). This Coastal Zone Management Strategy was adopted, by the City of Cape Town, with the intention to manage and safeguard the coast. Previously this coastal zone was managed in a fragmented way by three different governmental agencies (Cartwright et al, 2008 - Phase 1) and was mainly reactive.

According to the Coastal Zone Management Strategy it offers a unique opportunity to introduce a paradigm shift in coastal management practises (Coastal Zone Strategy, 2003):

- *'A coordinated and integrated approach to coastal zone management from a citywide perspective*
- *Recognition of the coastal zone as a distinct and unique management area*
- *Recognition of the coastal asset in terms of economic and social development*
- *The establishment of a multi-disciplinary coordinating coastal management team*
- *Responsibility, accountability and action*
- *Centralised planning and budgeting around coastal issues*
- *Equitable access to our coast and its associated economic and social opportunities*
- *Participative, open and transparent approaches to coastal zone management*
- *Creative, dynamic and new approaches to coastal zone management'*

The City of Cape Town sees climate change and rising sea levels as an important part of its future coastal zone management and has therefore embarked upon a thorough study of the impacts of this on Cape Town titled 'Global Climate Change and Adaption – A Sea-Level Rise Risk Assessment' . The study involves different phases of which the following has been completed:

- Phase 1: Sea Level Rise Model (Brundrit, 2008)
- Phase 2: Risk and Impact Identification (Fairhurst, 2008)
- Phase 3: A Sea-Level Rise Risk Assessment for the City of Cape Town (Cartwright, 2008)
- Phase 4: Sea-Level Rise Adaption and Risk Mitigation (Cartwright et al, 2008)
- Phase 5A: Full investigation of alongshore features of vulnerability on the City of Cape Town coastline, and their incorporation into the City of Cape Town Geographic Information System (GIS) (Brundrit, 2009)
- Phase 5B: Sea-level rise vulnerability assessment and adaption options (Cartwright, 2009)

The aim of the Sea-Level Rise Risk Assessment Project (according to Phase 1 - 5) is to:

- Model the predicted sea-level changes in a range of scenario's
- Model the form that those changes will take
- Understand the associated impacts on existing coastal systems, infrastructure and property
- Provide guidance and implications to future coastal development (to be included in the City's Coastal Development Guidelines)
- Identify high risk areas
- Develop long-term mitigation measures

The primary objective of this study is therefore (according to Phase 1 - 5):

- To model and understand the ramifications of predicted sea-level rise and increased storm events for the City of Cape Town, thereby providing information that may be used for future planning, preparedness and risk mitigation.

The Sea-Level Risk Assessment Project identified vulnerable parts of the coastline. As much economic activity is located along the coast the financial losses and risks in event of flooding and storm damage would be very significant. Figure 3-1 shows the proposed impact a Scenario 1 event could have on Cape Town's central business district (CBD) and port.

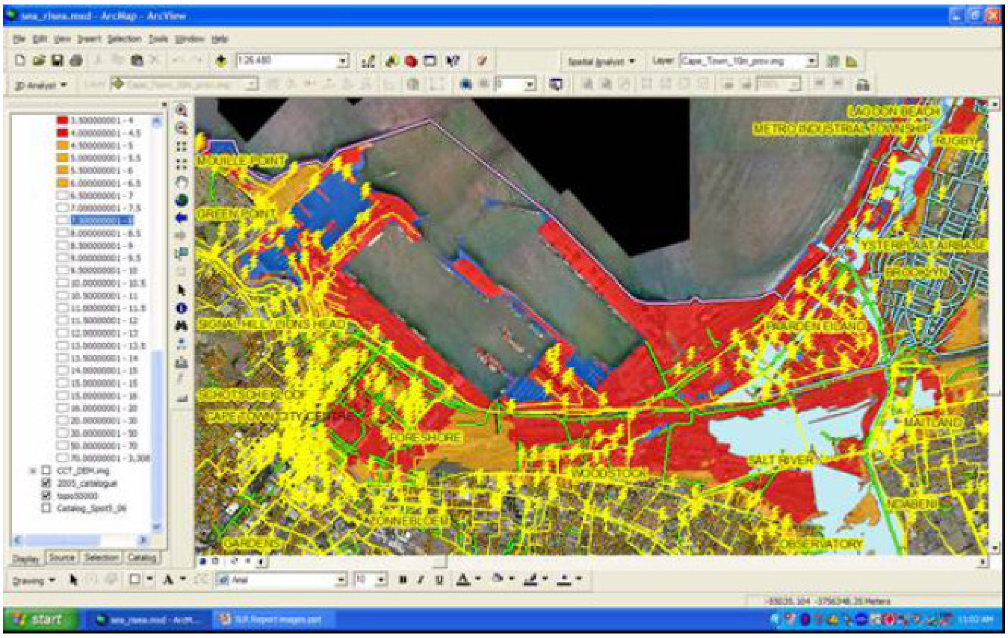

Fig. 2 A snap shot image (1:26,480) of Cape Town City centre, the docks and some of the surrounding suburbs depicting the three inundation levels used in the GIS inundation model (Scenarios 1 and 2) used to identify areas under threat to sea level rise.

Figure 3-2: Cape Town Centre flooding (Cartwright et al, 2008 – Phase 3)

The rise in water level is not necessarily such a big risk to the Port of Cape Town, but the increase in storminess would most likely lead to increased downtime in port operations which is linked to significant loss of potential income for the port. Figure 3-3 shows the low-lying and generally unprotected Strand coast; which is situated on the eastern end of False Bay. The sea wall along the beach road is insufficient protection against bigger storms. The area is urban and contains housing and commercial facilities.

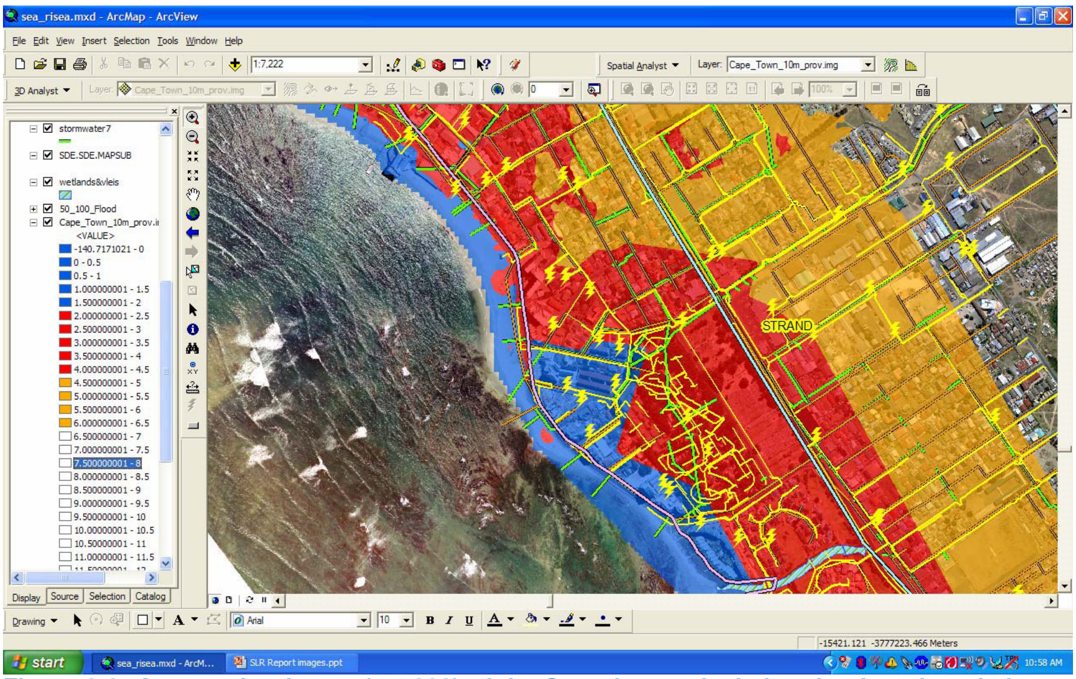

Figure 3-3: A snap shot image (1:7,222) of the Strand area, depicting the three inundation areas used in the GIS inundation model (Brundrit et al, 2009 – Phase 5A)

Figure 3-4 shows a proposed upmarket development site situated on False Bay coast; the narrow dunes protecting this region and the corresponding exposure to sea level rise should be noted. In some areas development has taken place almost up against the beach; the road along the coast is a main transport hub and it is noticeably vulnerable to sea level rise.

Figure 3-4: Photograph of a proposed upmarket development site on False Bay coast (Cartwright, 2008 - Phase 3 report)

The Cape Town coastline is very vulnerable to coastal erosion during storm events and many of the climate adaption options are focused on this aspect. Selected climate adaption options advised for the proactive coastal management of the Cape Town coastline (Cartwright, 2008 - Phase 4) are shown in Figure 3-5.

First resort – no regrets options	Second resort – "additional" institutional measures	Third resort – additional biological measures	Last resort – additional physical measures
▪ No further land reclamation from the sea ▪ No further wetland and estuary degradation ▪ No further dune degradation and development ▪ Maintain storm water infrastructure ▪ Integrate sea-level rise into spatial planning ▪ Incorporate with disaster risk management ▪ Decentralise strategic economic infrastructure and services	▪ Enforce coastal buffer zone – blue line ▪ Early warning system ▪ Correct insurance market failures and under-pricing of sea-level rise risk ▪ Managed retreat where necessary ▪ Social and geographical vulnerability mapping ▪ Risk communication ▪ Apply the requisite legislation ▪ Prevent sand mining of coastal dunes ▪ Additional research into rates of change and causes	▪ Dune stabilisation and planting ▪ Proactive estuary and wetland rehabilitation ▪ Kelp bed protection and ensuring kelp remains on exposed beaches at key times	▪ Beach and dune replenishment ▪ Sea walls ▪ Barrages and barriers ▪ Raising infrastructure ▪ Revetments, dolosse, rock armour ▪ Beach drainage ▪ Off-shore reefs

Figure 7: Stylised sequencing sea-level rise options available to the City of Cape Town in terms of preference and order in which they should be considered.

Figure 3-5: Climate adaption options for Cape Town (Cartwright et al, 2008 - Phase 4)

It has become apparent to the City of Cape Town municipality that the current level of coastal protection is not in all instances sufficient to handle the larger and more frequent storms influenced by rising sea levels. Figure 3-6 and 3-7 were taken in August 2008 when the biggest storm in 7 years hit Cape Town. Figure 3-6 shows the Sea Point sea wall which is currently being restored; it is visible that the wall is not designed to withstand these bigger storms.

Figure 3-6: Waves breaking on prime property at Glen Beach (lesterhein.blogspot.com)

Figure 3-7: Waves overtopping the Sea Point Sea Wall (lesterhein.blogspot.com)

4 Overview of existing cost estimate information

Relevant literature relating to climate adaption cost estimates, potential damage costs and actual damage costs for Cape Town are recapitulated in this section. All tabulated costs are given in terms of 2008 values in South African Rand (ZAR) and United States Dollar (US$).

4.1 General

In Phase 3 and 4 of the City of Cape Town Sea-Level Rise Risk Assessment report (Cartwright et al, 2008) an attempt is made to quantify the opportunity costs in event of environmental damage. The following paragraphs briefly highlight some of the findings in abovementioned reports for a Scenario 1 event.

Cape Town is associated with its beautiful beaches and a Scenario 1 Sea-Level event would presumably lead to foregone tourism revenue (it is assumed that tourism will decrease by 3 percent during the year of the event). This is related to the erosion of beaches such as Camps Bay, Clifton and Llundudno which would decrease their aesthetic appeal as was illustrated in the tourism losses experienced after an extreme storm took place during 2007 in Durban on South Africa's east coast (Cartwright et al – Phase 3; Mather et al, 2007b).

The cost of replacing public infrastructure (which falls under the City of Cape Town's authority – this excludes the Port of Cape Town which is the responsibility of national government) is a financial risk to the municipality. Storm water and electrical distribution infrastructure and municipal transport lines are assumed to be some of the most affected services. It is assumed that 1.5 percent of the city's storm water infrastructure would need to be repaired in a Scenario 1 event. The estimated cost of road replacement is R900 million and should be compared to the annual road maintenance budget for the City of Cape Town, which is approximately R200 million (Cartwright et al, 2008 - Phase 3). The estimation is that 1 percent if the above surface energy infrastructure will need repair or replacement. A cumulative risk cost is estimated for the City of Cape Town using the occurrence probabilities for the event during the next 25 years, it should be noted that this is an extreme value as the assumption is made that flooding occurs all along the coastline whereas it is generally more localized. The values therefore represent the cumulative risk and coasts over a 25 year period. The cost of damage according to Phase 3 (Cartwright et al, 2008) is summarized in Table 4-1.

Table 4-1: Cost of Damage in a Scenario 1 sea-level rise event (2008 values) (Cartwright, 2008 – Phase 3)

Item	Value in ZAR	Value in US$
Real Estate	R 3 255 000 000	$434 000 000
Tourism	R 720 000 000	$96 000 000
Stormwater	R 167 000 000	$22 266 667
Roads	R 900 000 000	$120 000 000
Electricity	R 94 800 000	$12 640 000
Probability of occurrence in next 25 years	0.95	0.95
Total potential cost to city	R 5 136 800 000	$684 906 667
Value of risk to city	R 4 879 960 000	$650 661 333

The Sea Point seawall is currently being repaired. According to Phase 3 (Cartwright et al, 2008) provisional estimates given to the city indicate that at least R 12.6 million (US$ 1.68 million) will be required for immediate repair and an additional R250 000 (US$ 33 300) per annum should be budgeted for maintenance. The Sea Point sea wall dimensions can be approximated as a length of 4.8 kilometres and a height of 6 metres above the mainly rocky shore.

The different adaption options presented in section 3 above (Figure 3-5) were also compared in terms of their relative implementation cost and the suitability of their implementation. Table 4-2 gives a summary of the available cost information about climate adaption.

Table 4-2: Indicative costs for different climate adaption options (Cartwright et al, 2008 – Phase 4)

Option	Cost (2008 values)		
	Description	Value ZAR	Value US$
Managed retreat	Weighted average property prices for City's coastline given	R 1 800 – 2 900 /m^2	240 - 390 / m^2
Sea walls	High and ongoing maintenance costs	R 3 000 - R 30 000 /m	400 – 4 000 /m
Beach and dune replenishment	Moderate, but ongoing cost	R12 000 - R15 000 /m beach*	1 600 – 2 000 /m*
Rock armour and gabions	Depends on availability of rock		
Barrages and barriers	Very expensive		
Raising infrastructure	Expensive		
Wetland and estuary rehabiltation	Could be low cost		

*A value per cubic metre of US$14.3 is given in Linham et al (2010) (sourced A Mather, pers. comm.)

It should be noted that the cost given for managed retreat in this instance only includes the weighted average cost of the property which will be lost; the real cost will be higher and include compensation to property owners, lost public infrastructure and loss of real estate. The unit cost for sea walls are dependent upon the height of the wall, the design of the cross section and the materials used; however the unit cost provided in Table 4-2 was not defined in terms of height or other factors in Sea Level Rise Risk Assessment (Cartwright et al, 2008 – Phase 4) and therefore is given as a wide range of possible values with a potential difference of a factor 10 as could easily be the case in practice. Two costs for beach nourishment are given; one is sourced from the Sea Level Rise Risk Assessment (Cartwright et al, 2008) for Cape Town and is in cost per meter, whereas the other is from Linham et al (2010) and in cubic metres. Due to the variability of beach profiles, widths and lengths in Cape Town it is not really feasible to estimate a generic nourishment volume in cubic metres per metre and the value provided in Linham et al (2010) is favored as a unit cost. As seen in Table 4-2 cost information is not freely available and it is difficult to source accurate unit cost values for local projects. This makes it difficult to budget for future adaption. In this instance the tendering process for government projects is very competitive and consultants are therefore not eager to provide costing information. It is recommended that the City of Cape Town should build up a costing database relating to coastal protection projects (if it does not already exist).

4.2 Estimated damage cost for specific storm event

4.2.1 Details of Storm

Cape Town was affected by a 'super storm' over the weekend of the 30th – 31st of August 2008. This storm was associated with the passage of an intense mid-latitude cold front. Violent North-Westerly winds of 50 km/h were experienced, with gusts of 80 km/h, which caused a storm surge by piling up the water against the coast. These factors contributed to an increase in mean sea level of over 5 metres; which had a damaging impact on the coastline. Sea swell and waves in excess of 10 metres were experienced as shown in Figure 4-1; this caused major damage to property and altered the beach profiles. Heavy rainfall was experienced during the storm. (Beckman, 2008)

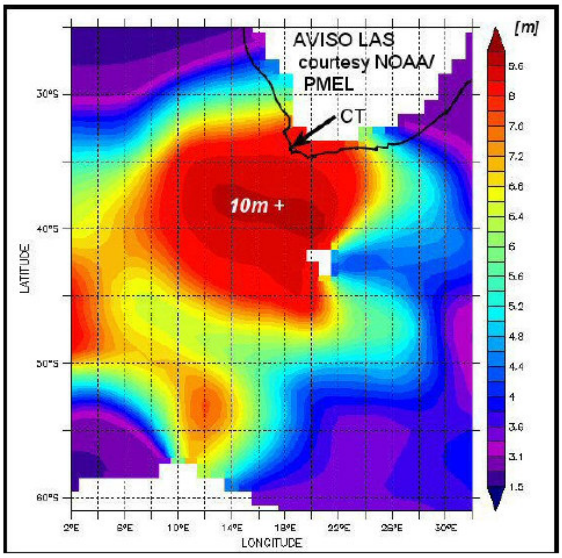

FIGURE 15: Significant wave height between 25°S / 60°S and 2°E / 32° E

Image courtesy of SAWS

This figure shows the significant wave height around the coasts of southern Africa as measured by a satellite radar altimeter. Wave heights associated with the intense mid-latitude cyclone that made landfall on the 30th August were in excess of 10 meters. The massive swells and huge waves caused great damage to property along the south Atlantic seaboard; countless photos of which were to be commonly found in the media at the time (Picture 1 to 3).

Figure 4-1: Significant Wave Height during storm (Beckman, 2008)

4.2.2 Recorded losses and damage

It is estimated that most of the damage that occurred during the storm was to formalized private and commercial property and referred to insurers. Unfortunately this information is confidential and has not been made available by insurance companies. Much infrastructural damage transpired along the coastline; including damage to retaining walls, buildings, transport and parking areas etc. The total estimated damage to coastal facilities and structures is valued at roughly R4 937 500 (US$ 655 300). This could be compared to an approximate damage estimate to municipal infrastructure at eThekweni Municipality (Durban) of R100 million (US$13.4 million) during a low pressure storm system, which coincided with the 18.6 year highest tide, on 19 and 20 March 2007 (Mather, 2007b) (This cost is given in 2007 values). Table 4–3 gives a summary of the estimated damage cost of the August 2008 storm in Cape Town to the municipality.

Table 4-3: Cost of damage to municipal property during storm event (RADAR, 2008)

Facility/Feature	Damage Description	Estimated cost (2008)	
		ZAR	US$
Bikini Beach Ablutions	Seawater-flooded ablutions	50 000	6 667
Bikini Beach Nodal	Sand and rocks on beach to be removed	15 000	2 000
Kogel Bay Resort	The sand next to the wall of the tidal pool was removed by the sea	25 000	3 333
Strand Beach	Excessive damage and flooding of building	100 000	13 333
Glencairn Walkway (close to subway)	Due to severe storm damage - the retaining wall was badly damaged.	2 500 000	333 333
Soetwater Resort	Damaged stonewall, walkway paving, poles, roof at Busses Parking area.	100 000	13 333
Fish Hoek Beach	Refuse and cottage access gates broken	180 000	24 000
Simonstown Country Club	Wooden and glass doors damaged	10 000	1 333
Fish Hoek Beach	Damages to the pumps under subway	12 000	1 600
Fish Hoek Beach	Pathway and retaining wall badly damaged	75 000	10 000
Fish Hoek Beach	Steps and railings dislodged	60 000	8 000
Seaforth Beach	Railing on pathway to changing cubicles were damaged, and railing on main steps were washed away.	80 000	10 667
Fish Hoek Beach	Access steps and wheel chair access point were damaged	60 000	8 000
Fish Hoek Beach - Jaggers Walk	Jaggers Walk and retaining wall badly damaged	1 500 000	200 000
Muizenberg Pavilion	Stormwater pipes blocked with sand, doors damaged.	12 000	1 600
Surfers Corner Beach Road	Footpath paving damaged, wooden rail handrail broken, outlet pipes blocked.	15 000	2 000
Sonwabi – Baden Powel Drive	Parking lot tarmac and kerbing damaged. Toilet doors & windows broken.	60 000	8 000
St. James Public Toilets	External shower damaged. Paving slabs around bathing boxes washed away.	3 500	467
Silwerstroom resort	Slipway damages (extensive)	80 000	10 667
Total		4 937 500	658 333

The cost of storm damage is potentially very significant in Cape Town as seen in Table 4-3. This indicates that future coastal zone management should focus on protecting the coast and minimizing the damage during storm events; which is also a goal of the City of Cape Town municipality. The extreme storm experienced in KwaZulu-Natal (in South Africa) during March 2007 showed that areas which were either only sandy or only rocky were generally more resilient to the storm, whereas mixed coastlines of rock and sand (such as much of the Cape Town coastline), especially pocket beaches, were severely impacted (Mather, 2007a; Goschen et al, 2009). Extensive damage was incurred during the extreme storm in KwaZulu-Natal and the statement above indicates that Cape Town could be potentially be even more vulnerable due to the variable nature of the coastline.

5 Discussion and conclusions

5.1 Challenges in terms of protection and coastal management

Cape Town has a long and variable coastline. Much of the coastline has also been encroached with development; unwisely so in some instances. This means that adaption will be difficult and a diverse mix of solutions would be needed. A generic solution for coastal protection cannot in this instance be formulated for the whole coastline. This makes the adaption process much more expensive and time consuming.

Currently there is no specified protection level or recommended hydraulic boundary conditions for building along the coast. There has however been much work done by local and national government in terms of coastal policies and the protection of the coast. It can be said that the City of Cape Town municipality is taking the risk of climate change very seriously and that they are proactively looking at the issue.

5.2 Comparison between Dutch and Cape coasts

To illustrate the variability of the impact of climate change on coastlines around the world a brief comparison is made between the Dutch and Cape Town coasts. As introduction it can be said that more than one-fifth of the Netherlands is situated below sea level and is therefore much more vulnerable to the sea than Cape Town is; coastal defence is therefore a case of national safety and taken much more seriously in The Netherlands than in Cape Town. The main risk in The Netherlands is that a breach of the coastal defences could lead to flooding of the hinterland, whereas the main risk in Cape Town is that of erosion and short term flooding during storm events.

The Dutch coast is a low-lying deltaic coast (Hillen et al, 2010) and generally sandy. It can be separated in three generic sections; Zeeland in the south consists of islands, river mouths and estuaries; the Holland coast in the middle; and the Wadden Sea coast with a big tidal basin and barrier islands in the north. The coastline is sandy throughout and is in most instances protected by dunes, with the exception of some sections sea dike. The estuaries and tidal basin require more intervention and this led to the building of storm surge barriers such as the Oosterscheldt and Maestlandkering. The generic nature of the Dutch coast makes it simpler to develop standard design solutions such as dune protection, which can be used along most of the coast with only slight adaption's necessary for the specific location. Coastal protection costs would therefore also be easier to estimate.

In comparison the Cape Town coastline is extremely variable. Some areas such as False Bay have gentle sandy beaches and dune protection solutions similar to that used in the Netherlands is suitable here. However large parts of the Cape Town coastline are rocky and mountainous. Figure 5-1 of Cape Point shows rocky outcrops with a narrow pocket beach in between. Other areas are protected by sea walls, revetments or breakwaters as described in Section 3.

Figure 5-1: Cape Point (www.capepoint.co.za)

The Cape Town coast is also very rich in ecological and marine biodiversity. It is one of only three cities in the world classified as urban biodiversity hotspots. It is also one of the smallest of the 25 biodiversity hotspots in the world, which means that it is one of the places in the world with the richest and most threatened plant and animal life (Green Map of Cape Town, 2009). The warm Agulhas current that sweeps down the east coast and the cold Agulhas that flows north along the west coast meet at Cape Town, which leads to rich biodiversity in marine life (Beaches: A diversity of coastal treasures, 2009) . There are various marine and land based nature reserves in the city limits (where no development is allowed) and all new development in the coastal zone now requires an Environmental Impact Assessment (this would also be required for coastal protection work). Figure 5-2 (Green map of Cape Town, 2009) and 5-3 (City of Cape Town Beaches: A diversity of coastal treasures, 2009) shows the land and marine nature reserves within the city limits.

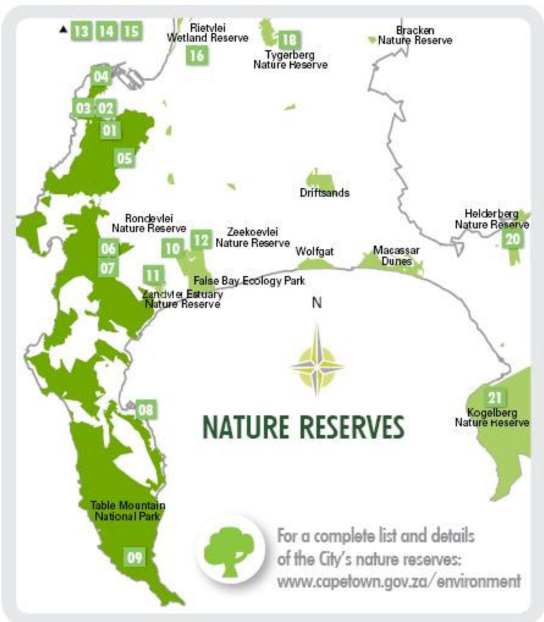

Figure 5-2: Land based nature reserves

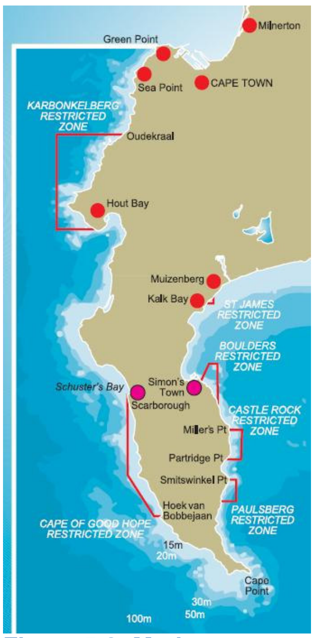

Figure 5-3: Marine protected areas

The diversity in terrain and ecosystem along the Cape Town coast complicate the development and implementation of coastal protection solutions, it is generally necessary to develop a new design solution for each part of the coast. It is also difficult to determine unit costs for coastal protection in Cape Town due to a big range in solutions and costs (as well as the fact that the available information is limited).

In Cape Town much of the coastline is a focus for economic activity. This is not traditionally the case in the Netherlands where the economic hotspots were generally situated more inland (although connected to the coast by rivers, estuaries and channels e.g. Rotterdam and Amsterdam). Population growth and economic expansion in The Netherlands have however led to development encroaching upon the coast, although the coastal protection legislation of the Netherlands still limits the development. Main highways in the Holland region are generally not situated along the coast as can be seen in many coastal cities, including Cape Town. In Cape Town development started along the coast (as a Dutch colony) and expanded inland, the harbour was one of the first areas developed and businesses and industry was developed around it.

Cape Town's Central Business District (CBD) is situated in close proximity to the sea and the coast is a hotspot of economic activity and investment as Figure 5-3 illustrates. The World Cup stadium cost R4.4 billion (or approximately US $600 million) to build and was completed in 2010 (Wikipedia). The V&A Waterfront shopping mall and entertainment area is arguably the most visited tourist destination in South Africa; Sol Kerzner's One and Only Hotel was completed in 2009 and cost approximately R1 billion (US$134 million) to build (The Property Magazine) . The Port of Cape Town handled 774000 TEU's in the 2008/2009 financial year (Transnet). In Figure 5-4 and 5-2 it is also visible that space for further development of the city centre is restricted by the sea and Port of Cape Town, as well as by the surrounding Table Mountain nature reserve.

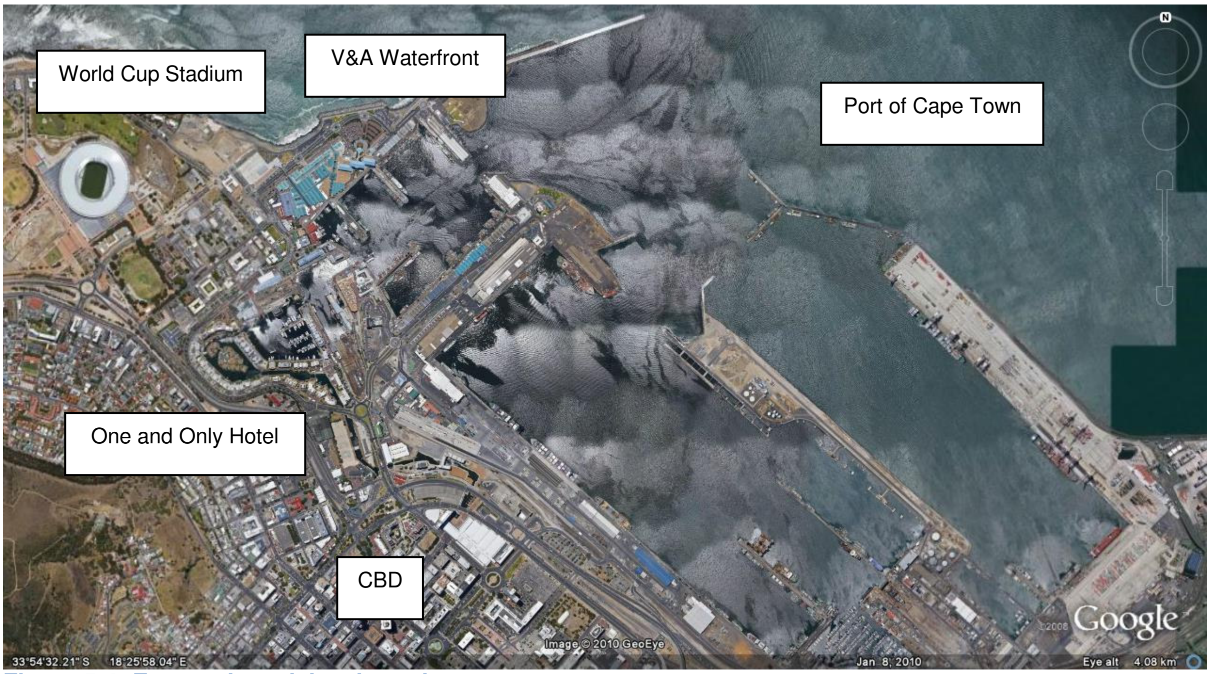

Figure 5-4: Economic activity along the coast

The Cape Town coast is a very valuable tourist attraction and many businesses are catering for the foreign tourist market. It is famous for its beautiful beaches (such as Clifton shown in Figure 5-5) and nature reserves. If the beaches are damaged and eroded due to a big storm it could affect their attractiveness to tourists. Tourism in the Netherlands is dominated by visitors to Amsterdam, Keukenhof and cultural locations (such as dikes and windmills); beaches are not such an important attraction.


Figure 5-5: Clifton beach (www.southafrica.to)

In The Netherlands the geography and shallow water depths of the North Sea basin leads to very high storm surge, the design storm surge level is therefore 6 meters, whereas in Cape Town the design surge is lower than a meter. Cape Town can however experience bigger waves due to the deep water close to shore and thus wave penetration are not as restricted by water depth as in the Netherlands.

A very common protection measure in The Netherlands is beach nourishment. This is a relatively uncomplicated exercise in The Netherlands due to the availability of dredgers and also potential for offshore sand mining close to site. This solution is much more difficult in Cape Town, where offshore sand mining is much more expensive and environmentally damaging.

The level of available information about shoreline movement and hydraulic records (wave, wind, water level etc) is very high and of a long duration in The Netherlands. Most information is freely available and hydraulic design conditions have been established by a governmental organization for the whole Dutch coastline. In Cape Town there is a significant lack of freely available information about coastal protection, hydraulic records and shoreline movement.

To conclude it is apparent that the Dutch and the Cape coasts are very different and that this also necessitates different protection measures. Adapting coastlines around the world would also require site specific solutions and the cost of solutions would be influenced by local conditions such as the cost of labour.

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