Nat Hazards (2011) 57:245–266
DOI 10.1007/s11069-010-9610-x

ORIGINAL PAPER

Designing a long-term flood risk management plan for the Scheldt estuary using a risk-based approach

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Received: 1 December 2009 / Accepted: 25 August 2010 / Published online: 14 September 2010

Abstract The Scheldt is a tidal river that originates in France and flows through Belgium and the Netherlands. The tides create significant flood risks in both the Flemish region in Belgium and the Netherlands. Due to sea level rise and economic development, flood risks will increase during this century. This is the main reason for the Flemish government to update its flood risk management plan. For this purpose, the Flemish government requested a cost-benefit analysis of flood protection measures, considering long-term developments. Measures evaluated include a storm surge barrier, dyke heightening and additional floodplains with or without the development of wetlands. Some of these measures affect the flood risk in both countries. As policies concerning the limitation of flood risk differ significantly between the Netherlands and Flanders, distinctive methodologies were used to estimate the impacts of measures on flood risk. A risk-based approach was applied for Flanders by calculating the impacts of flood damage at different levels of recurrence, for the base year (2000) and in case of a sea level rise of 60 cm by 2100. Policy within the Netherlands stipulates a required minimal protection level along the Scheldt against storms with a recurrence period of 1 in 4,000 years. It was estimated how flood protection measures would delay further dyke heightening, which is foreseen as protection levels are presently decreasing due to rising sea levels. Impacts of measures (safety benefits) consist of delays in further dyke heightening. The results illustrate the importance of sea level rise. Flood risks increased fivefolds when a sea level rise of 60 cm was applied. Although more drastic measures such as a storm surge barrier near Antwerp offer more protection for very extreme storms, a combination of dykes and floodplains can offer higher benefits at lower costs.

Keywords Flood risk management · Cost-benefit analysis · Sea level rise · Floodplain restoration · Ecosystem services

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1 Introduction

The Scheldt River originates from France, crosses Belgium and the Netherlands and ends up in the North Sea. The river has a tidal influence reaching up to 155 km inland, covering an entire gradient from salt over brackish to fresh water areas (Cox et al. 2006). The tidal waves result in a flood risk in the Northern part of Belgium (Flanders region) and the Netherlands. Important flood damages occurred in the Netherlands in 1953 and in Belgium in 1976. In the Netherlands, no damages occurred in 1976 because the Deltaplan was almost completely finished. This gave rise to an accrued public awareness of the inundation risk along the tidal reach of the Scheldt in Flanders and the conception of a Flemish so-called Sigmaplan in the beginning of the 1980s. This Sigmaplan was composed of a tidal storm surge barrier downstream Antwerp, combined with a general heightening of the river-embankments and the construction of a number of controlled flood areas. A socio-economic analysis (Berlamont et al. 1982) showed that a storm surge barrier could not be economically justified and as a result the barrier was never constructed. However, due to sea level rise and economic developments, it is generally believed that flood risks will increase significantly during the 21st century. This is the main reason why the Flemish government required an update of its flood risk management plan.

The Flemish government wanted to reconsider the necessity of the Sigmaplan while considering several issues. First, besides a “fixed safety standard” approach also a risk-based approach had to be applied. The objective of this approach was not to avoid all floods but to limit flood damages at reasonable costs. Densely populated areas or areas with important industrial installations, where most flood damages might occur, have to be protected the most. On the contrary, agricultural and nature conservation areas, where less damage is expected, required less protection. There was a general belief that protecting the whole Scheldt River basin in the same degree, as is the case in the Dutch part of the Scheldt, would lead to disproportionate costs. Secondly, as mentioned, the impact of sea level rise had to be considered. As Berlamont et al. 1982 did not consider the long-term impacts of sea level rise and gradually increasing probabilities of extreme flood events, it was expected that the existing measures are insufficient. Thirdly, the effectiveness of floodplain restoration had to be examined considering the potential non-market benefits. It was expected that these benefits were an important distinction between floodplains and more technical approaches such as dyke heightening and storm surge barriers. Fourth, potential positive or negative impacts of flood protection measures in the Netherlands had to be included. A storm surge barrier, for instance, could have negative impacts in the Netherlands as no water can be stored further upstream when the barrier is closed during extreme events. The results of this study are also a step towards corresponding to the requirements of the EU Floods Directive (European Union 2007). The Directive requires Member States to assess if all water courses and coast lines are at risk from flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk.

The use of a cost-benefit analysis framework to select flood protection measures has been applied frequently in the past within the study area. To support the decision-making processes in the implementation of the Dutch Deltaplan for instance, the socio-economic consequences were considered in Tinbergen 1959 and van Dantzig 1959. A cost-benefit analysis was also used to assess the original Sigmaplan (Berlamont et al. 1982). Since then, the available methodologies and tools to assess flood-related costs and benefits have evolved drastically. More recent efforts as in Brouwer and van Ek 2004, Andrews et al. 2006 and Turner et al. 2007 make use of hydrological models and land use data to estimate flood damage or ecological models and economic valuation tools to assess non-market impacts. The study presented in this paper uses similar methodologies. Most of these studies start from a fixed safety standard and compare alternative scenarios (usually dyke heightening vs. floodplain restoration). This paper presents a combination of both a fixed safety standard and a risk-based optimisation approach. Also the international context with an assessment of positive and negative impacts of different measures in both Belgium and the Netherlands makes this cost-benefit analysis an interesting case study.

The “fixed safety standard” approach, applied during a first phase, starts from a fixed protection level against flooding for the whole study area. The composed scenarios could theoretically offer safety against inundations caused by storm tides for return periods of 10,000, 4,000, 2,500 and 1,000 years in 2050, though not for all technical solutions all safety levels were studied (or even achievable). Since uniformly high safety levels throughout the basin were not achievable by means of storm barriers or flood control areas alone, the scenarios using those components were always supplemented by heightening of the dikes at the most vulnerable locations. The “risk optimisation” approach, applied during a second phase, targets to find an economically optimal combination of dike heightening and flood control areas in the basin. Considering the fact that flood risk was generated by downstream storm tides, eventually combined with high run-off discharges originating from the upstream tributaries, the basin was subdivided into five zones, each of them centred around “damage centres”. In a first step, the best combination of measures in downstream zone 1 was searched, by trial and error. The set of measures in zone 1 having the best result (costs vs. benefits) were kept for the next step. In a second step, the best solution for zone 1 was combined with various sets of possible protection measures in zone 2. Incremental costs and incremental benefits for the whole basin, compared to the cost and benefit realised with measures only in zone 1, were estimated. This resulted in a “best solution” for zone 1 and 2 together. This procedure was successively applied for zone 1, best of zone 1 + zone 2, best of zone (1 + 2) + zone 3, best of zone (1 + 2 + 3) + zone 4, etc.

2 Methodology

2.1 Possible measures

Depending on the predefined protection levels, alternative scenarios based on different combinations of technical measures were set up.

An overview of all possible measures is given in Figs. 1, 2. Measures which are considered can be grouped into a storm surge barrier, construction of the Overschelde, flood control areas and dyke heightening:

- The design of a possible storm surge barrier downstream from Antwerp is based on the existing Maeslant barrier near Rotterdam. The barrier consists of two giant, hollow, semicircular doors that can be closed in case of an anticipated high water level. The option of installing a much smaller barrier further upstream (Niel) was also examined. Contrary to the barrier in Antwerp, it only protects a part of the estuary.
- The Overschelde is a canal that connects the Western Scheldt with the Eastern Scheldt. The Eastern Scheldt is another tributary of the Scheldt already protected by a barrier. In case of high tides, the Overschelde can be used to store storm water from the Western Scheldt on the Eastern Scheldt.

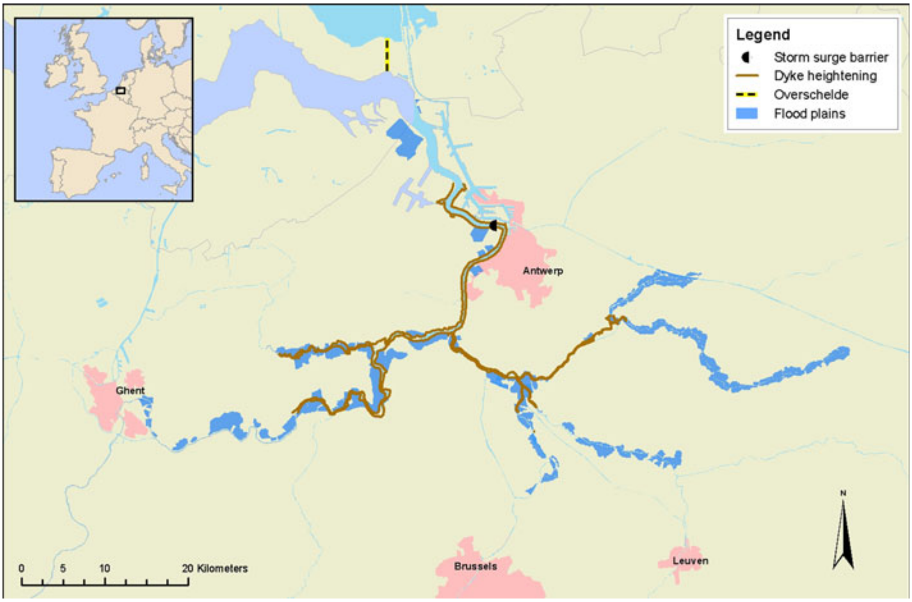

Fig. 1 Location of potential flood protection measures in the Scheldt estuary

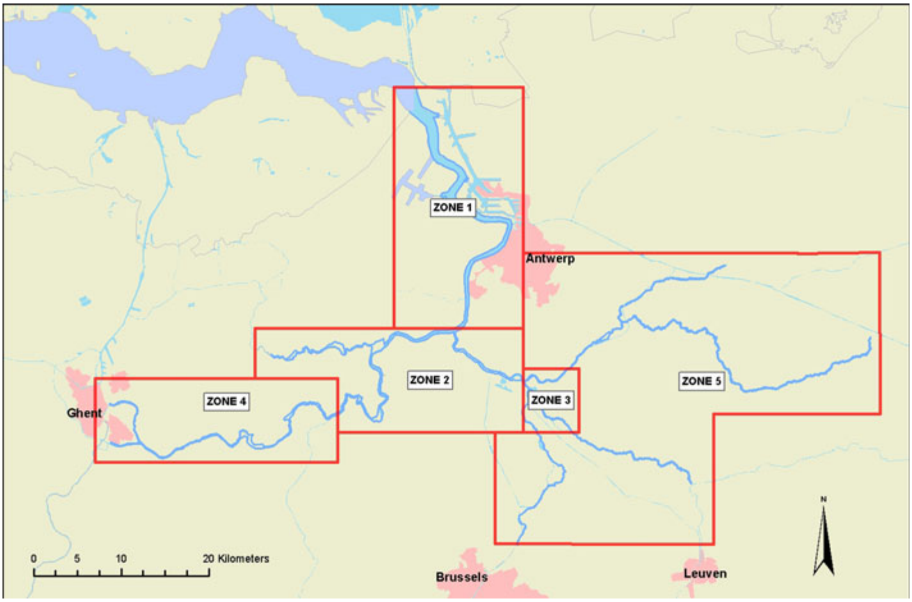

Fig. 2 Subdivision zones for bottom-up approach

- Flood control areas (FCA) are areas enclosed by a higher outer dike and a lower inner dike along the river. When during a storm surge, the water level rises above the inner dike, large amounts of water can temporally be stored in these areas. Usually, the frequencies of flooding for flood control areas vary between once every 10 years to twice a year. This means agricultural activities might still be possible.

- An alternative set-up is a flood control area with controlled reduced tide (CRT). In case of a CRT, the tidal regime is introduced. During normal tidal cycles, water flows in and out the area through well-designed culverts. This also means the area is used as a nature conservation area (Cox et al. 2006).
- Dyke heightening is the more classical way of increasing flood protection. Depending on the local circumstances, alternative designs are foreseen. For most of the cases, a standard design extending existing dykes on both land and river sides is possible. In case of space limitations, which is usually the case in urban areas, alternative designs are the construction of a small wall on top of existing dykes and a sheetpile wall. The quay walls in the city centre of Antwerp need to be reconstructed if increased protection levels are required.

2.2 Cost-benefit analysis

A cost-benefit analysis (CBA) was used to compare the economic efficiency of alternative combinations of measures. In CBA, costs and benefits of a project are compared over a fixed time horizon and subject to a discounting procedure. It is used to determine whether flood protection projects will achieve net gains in economic welfare for the society as a whole (Andrews et al. 2006).

The costs included in the analysis are the investment and maintenance costs of measures and the opportunity costs from the loss of economic value of the former land use in flood control areas. Flood protection benefits are estimated both for Flanders and for the Netherlands. Other impacts are the expected ecosystem benefits of floodplains, economic damage for shipping during construction and testing of the large storm surge barrier near Antwerp and visual intrusion due to the construction of new dykes near houses.

Starting date of construction was assumed to be 2010. The construction period depended strongly on the measure, varying between 10 years in case of the storm surge barrier and 4 years in case of construction of floodplains. Safety benefits are achieved after the completion of the measures.

The parameters that were used to evaluate alternative measures were net present value and the discounted payback period. Both statistics were calculated, as the lifespan of these kinds of projects is difficult to determine. A fixed discount rate of 4% was applied. Economic growth was based on scenarios developed in CPB 1996 and further updated in Saitua 2004. The standard growth rate was estimated at 2.4% until 2020 and 1.8% after 2020. Costs and benefits were estimated until the year 2100.

2.3 Investment and maintenance costs of measures

Costs included the investment costs, maintenance and operation costs of flood protection measures and necessary expropriation costs for houses, industry and agriculture. An overview of the average costs per category is shown in Table 1. The costs of dyke heightening and flood control areas were estimated for each area specifically. Depending on the size and structure of the existing dykes, the required heightening and the available space available, the construction techniques, the required materials and hence the costs differ significantly. The numbers in the tables are average estimates.

Table 1 Average investment and maintenance costs measures (Resource Analysis 2004)

Item	Cost (€ 2002)
Storm surge barrier Antwerp (mln €)	560
Overschelde (mln €)	1,570
Storm surge barrier Niel (mln €)	55
Dyke heightening (€/m)	
Standard	300–2,000
Wall on top	800–2,500
Sheet pile wall	3,500–5,000
Quay wall (Antwerp)	16,100
Flood control area	
Inner dike adaptation (€/m)	770
Outer dike construction (€/m)	840
Outlet sluices (€/ha)	19,000
Inlet sluices CRT (€/ha)	4,000
Engineering cost	10% investment cost
Other cost	5% investment cost
Annual maintenance cost	0.5–1.5% investment cost
Dispropriation cost grounds (€/ha)	
Residential area	700,000
Industrial area	24,046
Recreational area	12,200
Dispropriation cost buildings (€/building)	
Houses	100,000
Farms	250,000
Companies	250,000
Destruction cost	30,000

2.4 Opportunity costs for agriculture

The cost estimates of creating additional flood control areas on existing agricultural area was based on the opportunity costs or the cost of lost earnings from current to future agricultural activities (Dierckx 2004). Agriculture could be maintained within a flood control area. However, it was expected that high-value crops such as vegetables, sugar beets and orchards will be moved into other areas and replaced by low-value crops as corn or pasture for livestock. In this case, adaptation costs for relocating these high-value crops to other areas were included. The relocation costs include costs for replanting, soil improvement, drainage and sprinklers and were assumed to be 10,000 €/ha for sugar beat, potato, vegetables, orchards and tree nurseries. Additionally, a 10% loss of production is assumed for all crops during the first 10 years after relocation. Other costs are the consequences of flood events inside the flood control area. This comprises loss of crops (100% loss in case of floods), administrative costs (250 €/ha) and clean-up costs (150 €/ha).

When agriculture cannot be maintained within the area (reduced tidal area), the relocation costs for high-value crops are still considered. Other costs are the loss of added value of low-value crops (288 €/ha), a loss of manure deposition capacity (270 €/ha) and the loss of labour (924 €/ha).

The total cost per ha of crop situated inside flood control areas is given in Table 2.

2.5 Benefits of reducing flood risks

2.5.1 Hydrodynamical modelling

A hydrodynamic branched 1-dimensional model was created of the Scheldt River and its most important tributaries using the MIKE11 software package from DHI. The model started at the mouth of the Scheldt in the North Sea and covered the entire tidal reach of the river (in total about 362 km of river). The floodplains along the rivers were included as separate branches, which are dry under normal circumstances. The dikes between the river and the floodplains were included in the model as so-called link-channel units. Overtopping of dikes occurs when the simulated water level exceeds the topography of the dike.

The 1D model uses several boundary conditions: time series of water levels and wind speed at the downstream boundary and discharges at the upstream boundaries. To calculate the flood risk, boundary conditions were used for 12 different return periods, ranging from 1 to 10,000 years. The methodology used for deriving these boundary conditions was based on Vaes et al. 2002. This methodology consisted of generating QDF (Quantity—Duration—Frequency) relations for each of the boundary conditions. QDF relations give the frequency of the discharge in relation to the time period over which the discharge is averaged. These relations can be transformed into composite hydrograms/limnigrams which contain for each return period for all averaging intervals the appropriate discharge/water level. When these types of boundaries are applied to a hydrodynamic model, the model results in all nodes of the model have the same return period. This results in a uniform flooding map for the river and the floodplains.

To account for climate change, a sea level rise of 60 cm by 2100 was included in the downstream boundary condition of the hydrodynamical model as an average value. This value falls within the ranges of 0.09 and 0.88 m given in the Third Assessment Report of the IPCC (IPCC 2001) and Belgian assessments between 0.40 and 0.70 m made by Schoeters and Vanhaecke in 1999. For 2050 the same IPCC reports indicate an average sea level rise of 22 cm.

For each scenario, 24 simulations were done: 12 for a set of boundaries representative for the current situation and 12 for a set of boundaries representative for the situation in 2100 in which the impact of climate change and a 60-cm sea level rise on the downstream

Table 2 Agricultural losses for crops situated inside flood control areas for different frequencies of flooding (4% discount rate, 2100)

Land use	Yearly	4-Yearly	10-Yearly	Daily (RTA)
Pasture	€ 16,920	€ 7,012	€ 3,255	€ 21,689
Grassland	€ 17,918	€ 9,759	€ 4,629	€ 22,688
Maize	€ 17,959	€ 10,057	€ 4,778	€ 22,729
Cereals	€ 29,142	€ 21,981	€ 9,274	€ 33,912
Sugar beet	€ 29,145	€ 21,984	€ 9,286	€ 33,915
Potato	€ 39,311	€ 32,150	€ 46,191	€ 44,081
Vegetables	€ 36,428	€ 29,268	€ 24,137	€ 41,198
Orchards	€ 65,078	€ 57,918	€ 52,787	€ 69,848

boundary was included. On the basis of these results, 24 flood maps were calculated for each 20 × 20 m cell of the DEM.

2.5.2 Flood damage assessment

The methodology applied to estimate the avoided flood damages in the Flemish region is described in Vanneuville et al. 2003 and builds further on the Dutch HIS-GIS method (Kok et al. 2002). The total damage in a certain area depends on the water depth, number of units of a damage class within the area and the maximum damage or replacement value. Damage factors indicate the percentage of the replacement value at risk as a function of the inundation depth.

$$D_{\mathrm{w}} = \sum_{i=1}^{n} (\alpha_{i,h} \times n_i \times D_{\max,i})$$

with D_{w} total damage in a certain flood event; $\alpha_{i,h}$, % damaged for damage class i as a function of water depth h (between 0 and 1); n_i, number of units damage class i within a certain area (number, surface, …); $D_{\max,i}$, maximum damage per unit of damage class i.

Table 3 gives an overview of the damage factors for the different land use classes. Table 4 shows for each damage class the maximum damage and the damage factors applied. A distinction is made between direct and indirect damages. Indirect damages reflect mainly clean-up costs (houses, industry, agriculture), reduced production in and outside flooded areas (industry) and fertility losses (agriculture).

Table 3 Damage functions (Vanneuville et al. 2003)

Waterdepth (cm)	Housing	Household furniture	Vehicles	Industry (surface)	Industry (employee)	Recreation	Agriculture
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.01	0.12	0.13	0.10	0.03	0.50	0.25
50	0.03	0.24	0.25	0.20	0.05	1.00	0.50
75	0.04	0.35	0.38	0.30	0.08	1.00	0.58
100	0.05	0.47	0.50	0.40	0.10	1.00	0.64
125	0.06	0.48	0.63	0.50	0.12	1.00	0.70
150	0.08	0.49	0.75	0.60	0.13	1.00	0.76
175	0.09	0.49	0.88	0.70	0.15	1.00	0.82
200	0.11	0.50	1.00	0.80	0.16	1.00	0.88
225	0.17	0.54	1.00	0.83	0.18	1.00	0.91
250	0.23	0.58	1.00	0.85	0.19	1.00	0.93
275	0.29	0.62	1.00	0.88	0.21	1.00	0.95
300	0.35	0.66	1.00	0.90	0.22	1.00	0.96
325	0.43	0.70	1.00	0.93	0.32	1.00	0.98
350	0.52	0.75	1.00	0.95	0.42	1.00	0.99
375	0.60	0.79	1.00	0.98	0.51	1.00	1.00
400	0.68	0.83	1.00	1.00	0.61	1.00	1.00
425	0.76	0.87	1.00	1.00	0.71	1.00	1.00
450	0.84	0.92	1.00	1.00	0.81	1.00	1.00
475	0.92	0.96	1.00	1.00	0.90	1.00	1.00
≥500	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 4 Damage function and maximum damage for different damage classes (Vanneuville et al. 2003)

Damage class	Unit	Maximum damage	Damage function
Houses, real estate	house	€ 95,569,00	Houses
Houses, furniture	house	€ 47,784,50	Houses, furniture
Houses, indirect	house	1–15% direct	
Cars	car	€ 4,627,00	Vehicles
Industry, direct	m^2	€ 96.23	Industry surface
Industry, direct	employee	€ 175,820,00	Industry employee
Industry, indirect		35–45% direct	
Arable land direct	m^2	€ 0,704	Agriculture
Arable land indirect	m^2	10% direct	
Pastures direct	m^2	€ 0,196	Agriculture
Pastures indirect	m^2	10% direct	
Orchards direct	m^2	€ 3,010	Agriculture
Orchards indirect	m^2	10% direct	
Surface water	m^2	€ 0,000	None
Recreation	m^2	€ 0,054	Recreation
Airport	m^2	€ 96,23	Industry surface
Highway	m	€ 3,000,00	Industry surface
Secondary roads	m	€ 800,00	Industry surface
Other roads	m	€ 650,00	Industry surface
Railroads	m	€ 7,500,00	Industry surface

In addition to monetary damage, the expected number of casualties was also included. The damage function for victims depends both on water depth and on rising speed and was derived from Vrisou van Eck and Kok 2001.

The number of victims N is calculated as:

$$\begin{aligned} N &= f_d \times f_w \times A \\ f_d &= \exp(1.16 \times d - 7.3) \\ f_w &= 0 \quad \text{for } w \le 0.3 \\ f_w &= 0.37 \times w - 0.11 \quad \text{for } 0.3 < w < 3.0 \\ f_w &= 1 \quad \text{for } w \ge 3.0 \end{aligned}$$

with A number of people present in a certain area, f_d the drowning factor as function of water depth, f_w drowning factor as function of rising speed, d flood height in metres and w rising speed in metres/h. A value of a statistical life of € 1 million was applied, based on Bickel et al. (2001). Though disputable, no attention was given to further elaborate on this value as simulations showed a very low number of victims due to the low water levels in case of flooding in Flanders.

A combination of the Corine land cover and the Small Scale Land Use map for Flanders was used. Both are derived from Landsat TM and Spot images. The resolution is too low to see linear structures as roads, railroads and waterways. This is why topographical maps of the Belgian National Geographic Institute are used as an additional data sources. An overlay of these 3 data sources was made to assess the dominating land use in each grid cell (25 × 25 m). To estimate the amount of houses, employees, people and cars present in a certain grid cell, total amounts listed in municipal statistics are divided among the total amount of relevant grid cells within this municipality. Evidently, the numbers of houses are assigned to grid cells classified as houses, and employees are divided among grid cells classified as industry. People and cars are divided equally among industry, houses and infrastructure.

2.5.3 Flood risk Flanders

The damage calculations were performed for several flooding scenarios with a specific probability of occurrence in both 2000 and 2100 with a sea level rise of 60 cm.

The total annual risk is equal to the probability of occurrence multiplied by the corresponding damage and this for the total range of possible occurrences. The total annual flood risk can be calculated using equation;

$$R = \sum_{i=1}^{n} \frac{1}{i} (D_i - D_{i-1}) \tag{1}$$

with D_i the damage related to a flood with a return period of i years. As not all return periods can be estimated, a relationship based on linear interpolation between two known return periods is assumed:

$$R = \sum_{i=x_i} \left[\left(\frac{\frac{1}{x_{i-1}+1} + \frac{1}{x_{i-1}+2} + \cdots + \frac{1}{x_i}}{x_i - x_{i-1}} \right) \times (D_{x_i} - D_{x_{i-1}}) \right] \tag{2}$$

with x_i, x_{i-1} consecutive simulated return periods, D_{xi} the damage related to a flood with a return period of x_i years. Simulations were made for 1, 2, 5, 10, 100, 500, 1,000, 2,500, 4,000 and 10,000 years.

The total annual risk was estimated for the years 2000 and 2100 (after a sea level rise of 60 cm). The difference between the annual risk in the reference scenario and the annual risk after implementing measures equals the annual safety benefit. The safety benefits for intervening years are interpolated based on the estimated annual increase in the sea level.

To account for the increase in the number of people and economic assets located in flood risk zones, long-term economic growth scenarios were applied on the estimated safety benefits. These were based on 3 long-term global development scenarios for Europe determined by the Netherlands Bureau for economic policy analysis (Jansen et al. 1996). The average growth scenario assumed yearly economic growth of 2.4% until 2020 and 1.8% between 2020 and 2030. The same yearly growth was applied for the period after 2030. The other scenarios were tested in the sensitivity analysis (see Sect. 3).

The applied methodology to estimate flood damage is limited at estimating the total monetary damage and casualties inside the inundated area. This means that other non-monetary damage such as emotional damage was not assessed. Bouma et al. 2005 mention that this kind of damage could be of the same magnitude as direct material damage. Including these effects could significantly increase the benefits.

2.5.4 Reduction costs dyke heightening in the Netherlands

Some of the measures also affect the flood risk in the Netherlands. Whereas the Overschelde and floodplains nearby the border were expected to have a positive impact on the water levels of the Dutch part of the Scheldt, a storm surge barrier was expected to have a negative impact as the ability to store water in the Flemish region would be reduced.

The policy concerning the limitation of flood risk differs significantly between the Netherlands and Flanders. Whereas a risk-based approach with alternating protection levels had to be applied for the Flemish region, policy within the Netherlands stipulates that a minimal protection level along the Scheldt against storms with a recurrence period of 1 in 4,000 years is required. Consequently, a different methodology had to be applied to estimate the impacts of measures on flood risks in the Netherlands.

Due to sea level rise, it was expected dykes had to be heightened by a further 1 m around 2,030 and again around 2,080 to maintain a 1/4000 safety level in the Netherlands. If, however, water levels change due to measures aimed at improving the safety against flooding in the Flemish region, a change in the investment scheme of dyke heightening will be necessary. The estimated time shift along various parts of the Dutch part of the Scheldt for different measures is represented in Fig. 3.

2.6 Ecosystem benefits of floodplains

To assess the ecosystem benefits of newly planned floodplains, the so-called “ecosystem services” methodology was used (De Groot et al. 2002; Millennium Ecosystem Assessment 2005). Three groups of ecosystem services were identified: provisioning services, regulating services and cultural services. The so-called supporting services were not considered in the CBA because this value is already integrated in the other three groups. Adding their value with the other ecosystem services would lead to double counting.

Valuing these ecosystem services consists of two steps:

- Quantifying the potential impact using as much as possible area-specific models, but where these are missing using indicators from literature and expert judgement.
- Putting monetary values on the services using market prices, original valuation studies and indicators from literature.

Potential provisioning services of floodplains would be reed, osier, salt crops and possibilities for aquaculture. However, these benefits were not included in the cost-benefit analysis as during debates with stakeholders, it became clear that it was unlikely that the new floodplains would be specifically developed for reed production or aquaculture rather than for natural development.

The new floodplains were expected to have an impact on the water quality through nutrient recycling, aeration and sedimentation, and on climate regulation through fixation of carbon dioxide by photosynthesis of reed and willow and C-burial. This impact on the regulation services was mainly estimated by the MOSES model (Soetaert and Herman 1995a, b; Van Damme and Meire 2001). This ecosystem model was developed for the Scheldt estuary in order to study the possible impact of different water management strategies and to prepare a management plan of the estuary. The MOSES model makes distinctions between the impacts of riverine wetlands in the fresh water, brackish and salt zone of the river.

Average values show improved aeration of 10 mol O_2/ha year, denitrification of 176 kg N/ha year for fresh water marshes and 107 kg N/ha year for salt water marshes, an average N-burial of 252 kg/ha year and C-burial of 1500 kg/ha year. For the regulation services that were not modelled, we used indicators from literature and expert judgement. Local experts estimated the impact on sedimentation at 200 m^3/ha. C-capture was based

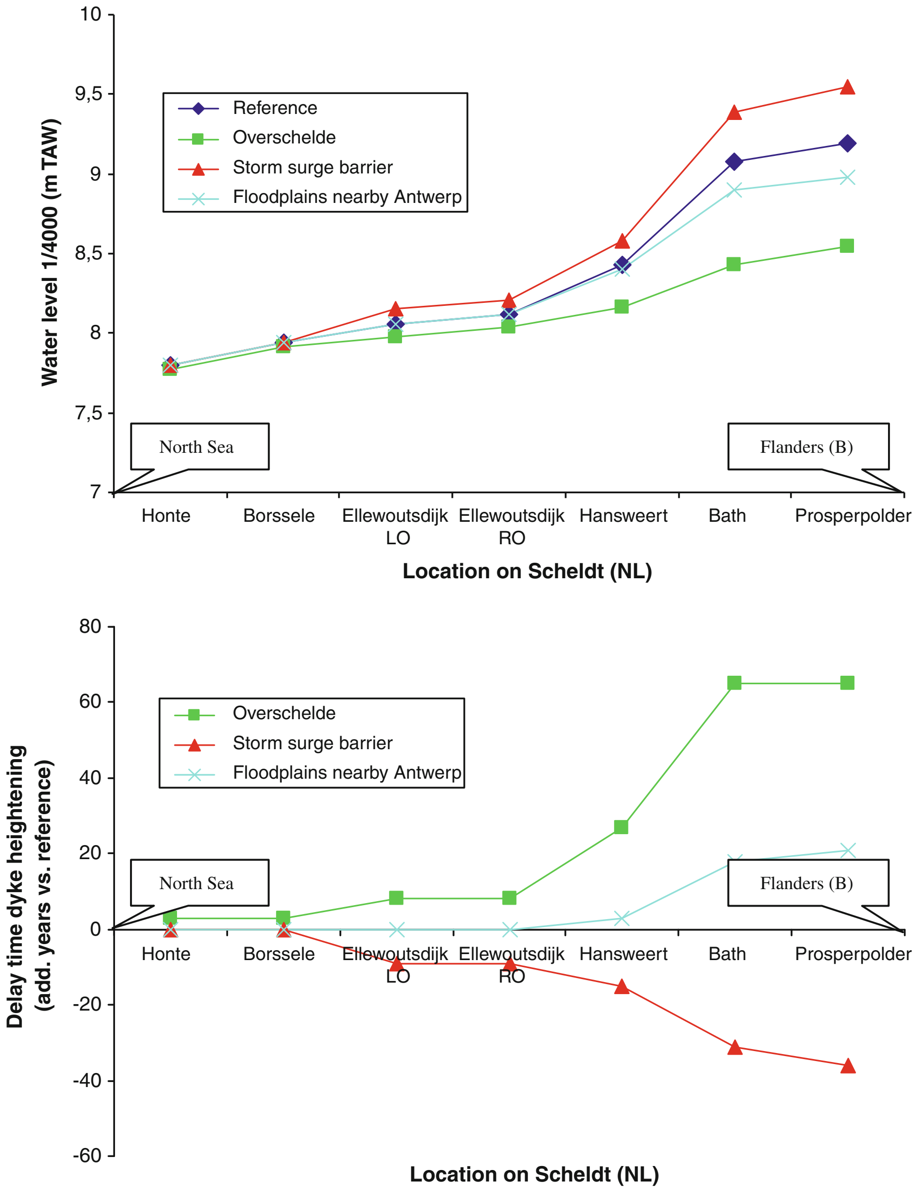

Fig. 3 Impact of measures on investment scheme dyke heightening in Dutch part of the Scheldt

on De Groot et al. 2002 and estimated at 6.8 ton C/ha year. P-burial was taken from Dennhardt and Meyerhoff 2002 (4–56 kg P/ha year).

The monetary values were estimated using the avoided cost or damage approach. Benefits of nutrient regulation an aeration were based on the costs of wastewater treatment in the Netherlands (2.2 €/kg N, 8.5 €/kg P based, 0.14 €/mol O_2, CIW 1999). A monetary estimate of damage cost avoided of 20 €/t CO_2 or 66 €/t C (Bickel and Friedrich 2005) was used to value the reduced amount of carbon. An extensive literature review performed by

Tol in 2004 resulted in an average mean value of approximately 67 €/t C (93 $/t C) and a median of approximately 10 €/t C (14 $/t C). The estimate used is comparable with the average value. The value of soil retention was based on the avoidance of dredging costs (7 €/m^3, expert judgement).

To determine the effect of the planned areas on recreation, the number of visitors the area would attract and the value that people attach to a visit were estimated. To quantify the number of visitors, estimations were based on the accessibility of the new areas (length of walking trail in the planned area) and the amount of annual visits on the existing walking trails (25 visits/day km walking trail). The willingness to pay for the recreation function was valued by performing a contingent valuation study (approx. 800 surveys) among recreants and potential recreants (Ruijgrok and Lorenz, 2004). The willingness to pay to visit newly developed flood control areas within the study area was asked. The average willingness to pay for a visit was 1.68 €. Results showed no significant difference between controlled inundation areas, reduced tidal areas or wetlands. This can be explained by the fact that people attach already a high value to the existing landscape and they perceive the view over the landscape while walking on the inland dyke as a surplus. Depending on the amount of flood control areas (the length of the dykes was used as a proxy for the length of the walking trail), the estimated amount of visitors was multiplied with the average willingness to pay for a visit.

To estimate the non-use value, a CVM study with approximately 1600 surveys was carried out specifically for this study. The non-use value was determined by asking respondents how much they would be willing to pay per year even if they were not allowed to visit the newly developed areas as described in Ruijgrok 2001. The average willingness to pay per household to develop more wetland or reduced tidal areas in the Flanders region was 15.5 €. No significant differences occurred between wetlands and reduced tidal areas. These values were also not considered in the cost-benefit analysis. First, because no distinction could be made on a ha basis and second, to avoid the danger of double counting as discussed in Barbier 1994 and Andrews et al. 2006. A benefit could be included twice within the evaluation process as people might for instance think of improved water quality and the creation of new habitats when valuing the non-use value. This benefit of improved water quality was already included in the regulation functions (Table 5).

2.7 Shipping

On the basis of the experience of building a similar storm surge barrier in Rotterdam in 2003, it was estimated that the waterway would be closed approximately 850 h during construction and testing. On the basis of the current shipping movements, it was estimated that additional internal and external costs of approximately 800 k€ would be caused due to this additional delay time. Compared to the construction costs of the storm surge barrier, this is a relatively small amount (Scheltjens and Vande Wielle 2004).

2.8 Visual intrusion

The impact of visual intrusion due the construction of new dykes around floodplains is based on a hedonic pricing methodology (Luttik 2000) on 3,000 house transaction in the Netherlands. In this study, it was estimated that open space increased housing prices between 6 and 12%. To estimate the number of houses that would suffer from a loss of open space, it was assumed that all houses situated within a buffer of 50 m and having

Table 5 Valuation of ecosystem benefits (€/ha year) for newly developed ecosystem types (controlled inundation areas, reduced tidal areas, wetlands)

Function	Quantification (unit/ha.year)					Valuation (€/unit)	
Ecosystem type *Watertype*	*FCA* *Fresh*	*CRT* *Fresh*	*CRT* *Salt-brackish*	*Wetland* *Fresh*	*Source*	*Value*	*Source*
Production functions (fish, aquaculture, wood)	pm	pm	pm	pm	pm	pm	pm
Regulation functions							
Denitrification		176 kg	107 kg	102 kg	MOSES: Soetaert and Herman (1995a, b)	2.5	CIW (1999)
Decrease in N washed away		252 kg	252 kg	252 kg	VMM (2003)	2.5	CIW (1999)
Decrease in P washed away		31 kg	31 kg	31 kg	VMM (2003)	8.5	CIW (1999)
Aeration	pm	23 mol/ha/year	10 mol/ha/year	pm	MOSES: Soetaert and Herman (1995a, b)	0.14	Witteveen and Bos (2004)
Erosion protection		2 m^3	2 m^3	2 m^3	Expert judgement	5	Witteveen and Bos (2004)
Climate		6.8 ton/ha/reed	6.8 ton/ha/reed	pm	Goosen et al. (1996)	66	Bickel and Friedrich (2005)
Regulation functions only first 15 years after construction							
Sedimentation		200 m^3	200 m^3	4 m^3	Expert judgement	5	Witteveen and Bos (2004)
C-burial		1.5 ton	1.5 ton	pm	MOSES: Soetaert and Herman (1995a, b)	66	Bickel and Friedrich (2005)
N-burial		148 kg	148 kg	pm	MOSES: Soetaert and Herman (1995a, b)	2.5	CIW (1999)
P-burial		25 kg	25 kg	pm	Dennhardt and Meyerhoff (2002)	8.5	CIW (1999)
Recreational amenities	25 Visits/day/km dyke				Witteveen and Bos (2004)	1.68	Witteveen and Bos (2004)
Non-use value						*pm*	

direct vision on new dykes (no other houses in between) would be subject to a loss of property value.

3 Results

3.1 Phase 1: Fixed safety standards

As mentioned before, the first phase consisted of a comparison between typical alternative protection schemes.

Table 6 shows that the dominant categories are investment costs and flood protection benefits. The impacts of sea level rise on the flood risk are very high and result in a significant increase in the safety benefits. Other impacts such as the ecological benefits from additional floodplains are less significant.

The storm surge barrier near Antwerp has a pay back period around 40 years, which is much shorter than originally assessed in 1981 (Berlamont et al. 1982). This is mainly due to sea level rise. Although the Overschelde could generate safety benefits for both Flanders and the Netherlands, the large investment costs to realise this project do not outweigh the benefits.

Policy measures based on higher dykes and floodplains offer substantial flood protection benefits at relatively low costs compared to a storm surge barrier. Although these projects do not guarantee full protection against flooding for very strong and exceptional storms with a recurrence period of 10,000 years, these projects would prevent most of the damage caused by these storms.

Table 6 suggests that floodplains are more cost effective then dykes. This conclusion cannot be generalised. Due to the large number of options available for construction additional flood control areas or heightening dykes, the costs and flood protection benefits are very location specific. Therefore, a risk optimisation approach was applied to find the most cost efficient combination of dykes and floodplains.

The scenario with reduced tidal areas (scenario 5) creates more net benefits than a similar scenario with flood control areas (scenario 4c). The additional ecological benefits outweigh the additional agricultural losses and investment costs.

3.2 Phase 2: Risk optimisation

The aim of the bottom-up approach was to find the optimal combination of dykes and floodplains. In a first step, the best combination of measures in downstream zone 1 was searched, by trial and error. Starting from the best combination in zone 1, alternative measures in zone 2 were tested and this stepwise until zone 5. As measures from zone 3 and 5 have hardly any influence on the water levels in zone 4, both zone 3 and zone 4 built further on the best measures from zone 2.

Dyke heightening is clearly the preferred option in zone 1, as the safety benefits of dyke heightening clearly outweigh the safety benefits from flood control areas. Also, the investment costs for dyke heightening are lower. Increasing dyke heights until 10 m TAW (Belgian ordnance level, which is about 2.3 m below local mean sea level) creates additional benefits compared to 9.25 m TAW. The costs for this additional height are however higher than the safety benefits.

The biggest flood risks in the reference scenario were estimated for zone 2. The potential safety benefits within this zone are large, as is shown in Table 7. Contrary to

Table 6 Costs and benefits of the policy options fixed safety standard approach (mln €)

Scenario	1	2	3a	3b	4a	4b	4c	5
Description	Storm surge barrierl	Overschelde	Dyke heightening T4000	Dyke heightening T2500	Flood control areas T4000	Flood control areas T2500	Flood control areas T1000	Controlled reduced tidal areas T4000
Investment and maintenance	387.35	1597.24	255.04	240.53	216.59	177.41	140.33	233.08
Agriculture	0.74				30.36	28.64	23.22	57.92
Flood protection benefits								
Flanders	739.11	665.11	710.76	691.62	707.39	648.39	624.79	709.79
Netherlands	−11.10	94.87			23.60	23.60	23.60	23.60
Other impacts								
Visual intrusion					−6.68	−6.50	−3.71	−6.68
Ecological benefits					13.35	11.94	8.25	70.62
Shipping	−1							
Total net benefits	339.92	−837.27	455.72	451.09	490.72	471.38	489.38	519.76
Payback period (years)	41	/	28	27	24	22	17	20

Figures are net present values in million € 2002, based on central estimates for sea level rise (60 cm in 2100), economic growth (1.8% long term) and discounting (4%)

zone 1, dykes achieve much less benefits than flood control areas. The main impact of dykes within this zone was a shift in the flooding location, causing important flood damage elsewhere. The use of flood control areas proved to be the only option to reduce flood risk. Optimising the amount of flood control areas in this zone is less evident. A small amount of areas (scenario 2-1) achieves the best payback period. However, a larger amount of areas (scenario 2-2) achieves more net benefits. The additional safety benefits in scenario 2-2 were considered to be more important than a shorter payback period. Scenario 2-3 indicates that additional flood control areas will have less impact on safety.

Constructing a small barrier in zone 3 proved to be very inadequate. Though the barrier was able to protect a large zone upstream, the negative impacts downstream were more significant. The flood control areas selected in scenario 3-2 proved to be more efficient than areas selected in scenario 3-1.

Due to the construction of measures in zone 2, the flood risk was already reduced in zone 4. However, additional flood control areas achieved additional net benefits. Dykes within this zone had the same impact as in zone 2. They were able to move the floods but not reduce flood damage.

Scenario 5-1 is a combination of measures in all zones achieving the largest net benefits. In total, this scenario comprises the construction of 1,325 ha floodplains and a heightening of 24 km dykes. Compared with the policy option 4c in phase 1, this saves 475 ha floodplains. Compared to 3b, the length of dyke heightening reduced with 316 km. This leads to a cost saving of €8 million compared with the cheapest policy option of phase 1. The safety benefits are by far higher than phase 1 policy options with dykes and floodplains. They are even higher than the safety benefits of a large storm surge barrier although the costs are one-third of the costs for this measure.

3.3 Consequences of a risk-based approach

In the opinion of the Flemish government, the benefits of protecting the whole Scheldt River basin against tidal floods with an occurrence of 1/4000, as is the case in the Dutch part of the Scheldt, would not outweigh the costs. Therefore, a risk-based approach had to be applied for the Flemish region. To check the impact of this approach on the final results, it was tested how safety levels varied between regions after implementing the optimal combination of dykes and floodplains. This was estimated by calculating the return period which caused flooding of the regions. As only a limited number of return periods years were simulated, accuracy of the estimated safety level is limited. When in a certain region a safety level of 1/2500 is estimated, the actual safety level lies between 1/1001 and 1/2500 years.

After implementing the phase 2, optimal combination safety levels in the city of Antwerp would increase from approximately 1/100 years in the reference scenario to 1/4000 years. As most of the safety benefits could be achieved in this zone, this zone had the highest protection level. Rural zones had a safety level of about 1/1000 years. Small cities in the study area had a safety level of around 1/2500 years. These estimations were based on hydrological conditions during the year 2000. When using a 60-cm sea level rise, safety levels decreased until 1/50 to 1/500 years. This implies that it might be worthwhile to reassess flood protection measures around the year 2050, as more will be known about the exact impacts of climate change and more accurate estimations can be made which eventually might lead to additional measures. The possibility to spread projects in time is also one of the advantages of investing in multiple smaller scale projects instead of a single large-scale project such as a storm surge barrier.

Table 7 Costs and benefits of the policy options risk-based approach (mln €)

Scenario	1-1	1-2	1-3	2-1	2-2	2-3	2-4	3-1	3-2	3-3	4-1	4-2	4-3	5-1
Zone	1	1	1	2	2	2	2	3	3	3	4	4	4	5
Description	FCA 1.024 ha	Dykes 10 m (24 km)	Dykes 9.25 m (24 km)	1-3 + FCA 274 ha	1-3 + FCA 521 ha	1-3 + FCA 1,042 ha	1-3 + dykes 8.5/9 m (119 km)	2-2 + FCA 210 ha	2-2 + FCA 212 ha	2-2 + barrier Niel	2-2 + FCA 336 ha	2-2 + FCA 684 ha	2-2 + dykes 35 km	3-2/4-1 + FCA 199 ha
Investment/ maintenance	77.81	26.17	18.25	43.36	73.46	128.41	74.23	100.52	91.52	59.02	92.37	104.87	110.73	131.71
Agriculture	20.17	0.00	0.00	2.07	3.70	5.45	0.00	3.80	6.26	0.00	8.83	15.04	3.70	12.37
Flood protection benefits	99.65	134.14	126.67	463.57	575.31	624.99	271.58	625.45	653.54	−186.5	606.22	609.37	569.00	736.75
Other impacts														
Visual intrusion	−0.50	0.00	0.00	−0.08	0.00	−2.84	0.00	−0.25	−1.00	0.00	−0.73	−1.13	−1.13	−5.18
Ecological benefits	1.92	0.00	0.00	2.40	−0.25	7.46	0.00	4.14	4.28	0.00	5.93	6.09	3.59	8.78
Total net benefits	3.09	107.97	108.42	420.46	501.59	495.75	197.35	525.01	559.04	−245.5	510.21	494.43	457.04	596.26
Payback period (years)	84	15	9	9	12	19	23	15	12	/	15	17	18	16

Figures are net present values in million Euro 2002, based on central estimates for sea level rise (60 cm in 2100), economic growth (1.8% long term) and discounting (4%)

3.4 Sensitivity analysis

3.4.1 *Discount rate and economic growth*

As mentioned before, a fixed discount rate of 4% and economic growth at 2.4% until 2020 and 1.8% after 2020 were assumed in the central estimates. As projects had a long lifespan and impact were considered until 2100, the combination of discount rates and economic growth scenarios had a large impact on results. Alternative discount rates of 3 and 7% were applied. This represented the range of discount rate applied mostly in both the Netherlands and Belgium. Alternative economic growth scenarios were taken from Saitua 2004. A low economic growth scenario assumed a growth of 1.4% until 2020 and 0.8% after 2020. A high economic growth scenario assumed a growth of 2.8% until 2020 and 2.3% after 2020.

Combining high economic growth estimates with low discount rates increased the safety benefits from 737 to 1,672 million € and net benefits from 596 million to 1,518 million €. Combining low economic growth estimates with high discount rates decreased the safety benefits to 144 million € and net benefits to 36 million €. Though the variation between these numbers was very large, net benefits were still positive when assuming low economic growth and high discount rates. Considering the ranking of measures mentioned in Tables 6 and 7, this remained unchanged. The net benefits of the optimal combination of phase 2 were in all cases larger than the net benefits of the phase 1 measures. Especially the fact that the optimal combination had larger benefits than the storm surge barrier under changing assumptions was of great importance for the policy makers. However, the combination of dykes and floodplains, which were optimal in the central estimate, did not produce the largest net benefits under all conditions. When assuming a low economic growth and a high discount rate, the safety benefits decreased and consequently a smaller amount of floodplains with lower costs resulted in larger net benefits.

3.4.2 *Sea level rise*

The previous estimates assumed that sea level would rise by 60 cm between 2000 and 2100. As this had large impacts on the results, a sensitivity analysis was performed ranging sea level rises between 0 cm and 120 cm by 2100. To perform this analysis, no additional flood simulations were made. Instead, the estimated total annual risks that occurred at a sea level in 2000 and after a sea level rise of 60 cm were shifted in time. This means that in case of a sea level rise of 0 cm, the total annual risk in 2000 is also valid for 2100, excluding the influence of the economic growth. In case of a sea level rise of 120 cm, the annual risks at a sea level rise of 60 cm occur in 2061. Safety risks for other years are interpolated or extrapolated based on the estimated annual increase in the sea level.

Table 8 shows how the safety benefits for the optimal solution in phase 2 are influenced when applying different assumptions for sea level rise. When no sea level rise was considered, benefits until 2100 did not outweigh costs. In case of a sea level rise of 1.2 m, the safety benefits increase tenfold compared with no sea level rise and the net benefits increase to 1.2 billion €.

Though the impact of sea level rise on the benefits is significant, the ranking of measures will not be influenced. An important policy question was whether a storm surge barrier would be more interesting if sea level rise is 120 cm instead of 60 cm in 2100. The results indicated however that the additional safety benefits in this case were 34 million € compared to the optimised scenario presented in Table 8. This still does not outweigh the additional costs required to construct the barrier. Depending on the rhythm of sea level rise,

Table 8 Sensitivity of costs and benefits of the optimal bottom-up solution for various assumptions on sea level rise

Sea level rise between 2100 and 2000	0 cm	30 cm	60 cm (baseline)	90 cm	120 cm
Investment and maintenance costs	132	132	132	132	132
Loss of agriculture	12	12	12	12	12
Flood protection benefits	138	437	737	1.036	1.335
Ecological benefits and visual intrusion	4	4	4	4	4
Total net benefits	−2	297	596	896	1.195
Payback period (years)	92	24	16	12	10

Figures are net present values in million Euro 2002, based on central estimates for sea level rise, economic growth and discounting (4%). Non-use values for nature development are not included in the figures

more (if >60 cm) or less (if <60 cm) flood control areas will be included in the optimised scenario.

4 Conclusion

The results demonstrate that the risk of flooding will increase significantly due to a combination of sea level rise and autonomous economic development. In view of this increasing risk, complementary measures are needed along the Scheldt River to achieve acceptable protection levels. Although more drastic measures as a storm surge barrier near Antwerp offer more protection for very extreme storms, an intelligent combination of dykes and floodplains can offer higher benefits at lower costs. One of the reasons why these smaller projects realise larger net benefits is because they allow for a differentiation in safety levels. Whereas little variation is possible in the location, size and hence costs and effectiveness of a storm surge barrier or Overschelde, many choices are possible with respect to the location and size of floodplains and dykes. Applying a risk-based approach with higher protection levels at high-value urban and industrial areas enables a more efficient allocation of investments. Especially in low-lying countries such as Belgium and the Netherlands, where at the moment a more uniform safety level is applied, a risk-based approach can lead to large cost savings.

As expected, the results show a large influence of sea level rise. The flood risk increased fivefold when a sea level rise of 60 cm was applied. Hence, the potential safety benefits increased significantly. As a consequence, a measure of the positive net benefits of a storm surge barrier is possible whereas this was not the case in a cost-benefit analysis 25 years ago where no sea level rise was considered. Another indication of the importance of sea level rise is shown in the sensitivity analysis. The safety benefits of the optimal solution increase tenfold when comparing a sea level rise of 1.2 m with a scenario without sea level rise. This all shows the importance of considering the impacts of sea level rise when developing long-term flood risk management plans.

An important result was that floodplains proved to be necessary to ensure safety levels in the longer term in the Scheldt basin. The simulations showed that floods could not be prevented only by heightening the existing dykes. In some cases the only consequence was a shift in the location of the flood event. As a result, scenarios including floodplains had higher net benefits than scenarios only using dyke heightening, even when only safety benefits and no ecological benefits were included in the analysis.

Though the usefulness of cost-benefit analysis in assessing long-term development plans is much debated, results of this cost-benefit analysis proved to be insightful for policy makers. The results have been used as a basis for the development of a bi-national long-term strategy for the Scheldt estuary and the allocation of the necessary budgets to protect the Scheldt estuary against flooding on a long-term basis. The measures which will finally be implemented do not correspond totally with the optimal combination as determined by the cost-benefit analysis. In some cases, the construction of floodplains conflicted greatly with certain stakeholder groups or ongoing policy on other domains. However, the cost-benefit analysis framework was still applied to check to which degree net benefits decreased compared with the optimal combination. A similar methodology is currently being applied to revise the long-term flood management plan for the Belgian coastal region.

Acknowledgments This paper builds on work and data of a study commissioned by the Waterways and Marine Affairs Administration of the Environment and Infrastructure Department of the Ministry of the Flemish Community (Belgium) and the Dutch-Flanders project organisation ProSes established by the Dutch and Flemish governments to develop the long-term vision for the Scheldt estuary. We acknowledge the input of many scientists and policy makers into these projects, especially CPB on the cost-benefit framework, Flanders Hydraulics Research for assessment of flood protection benefits, Prof. P. Meire and his team at the University of Antwerp for assessment of ecological effects, Dr. E. Ruigrok for her expertise on economic valuation of ecological benefits and the CVM studies and Dr. J. L. De Kok for editing the article. Our research profited from the remarks of the members of the scientific advisory board of ProSes and steering committees of both studies for the remarks.

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