# 2.  EFFECT OF SPATIAL ADAPTATION MEASURES ON FLOOD RISK: STUDY OF COASTAL FLOODS IN BELGIUM

**Abstract:**

Flood risk in coastal zones is projected to increase due to climate change and socioeconomic changes. Over the last decades, population growth, increases in wealth, and urban expansion have been found to be the main causes for increasing losses in coastal areas. These changes may, however, be offset by appropriate management measures. The main goal of this chapter is to assess future changes in flood risk and the effectiveness of flood risk adaptation measures for the coastal zone in Flanders, Belgium. In order to achieve this, we set up a modelling framework to assess the future flood risk of the Belgian coast including climatic and socioeconomic projections, and use this model to assess the effectiveness of two spatial adaptation measures: compartmentalization and land-use zoning. In this modelling framework, a land-use model, an inundation model, and a damage model were combined to calculate expected annual damage. Results show that without adaptation measures, future flood risk would increase substantially. Compartmentalization would result in an average flood risk reduction of approximately 50% for both the baseline situation and future scenarios. Land-use zoning would result in smaller flood risk reductions, averaging between 6% and 10%. Except for the most extreme climate change scenario, compartmentalization would successfully offset the combined adverse effects of socioeconomic growth and climate change on flood risk for this case study. For both compartmentalization and zoning, large differences have been found in their effectiveness at the local level, implying that the choice of adaptation measures should be tailored to local characteristics.

# 2.1. INTRODUCTION

Over the last decades, population growth, urban expansion and increases in wealth have been found to be the main causes for increasing economic losses in flood-prone areas (Nicholls et al., 2008; Bouwer, 2011). Coastal zones are among the places most vulnerable to flooding (Nicholls & Cazenave, 2010) and here flood risk is projected to increase due to climate change and sea-level rise (Gaslikova et al., 2011; Philippart et al., 2011). In addition to climate change, continuous socioeconomic growth in these regions also increases flood risk (McGranahan et al., 2007; Aerts et al., 2008b; Te Linde et al., 2011).

Various studies have attempted to assess the impacts of these future trends, at national and European scale (Hall et al., 2005; De Moel et al., 2011; Feyen et al., 2012; Klijn et al., 2012), and the regional scale (Mokrech et al., 2008; Maaskant et al., 2009; Bouwer et al., 2010; Te Linde et al., 2011). Most studies, however, focus on the assessment of future flood risk only and just a few look into the effectiveness of adaptation measures to lower this risk (Bouwer et al., 2010; De Kok & Grossmann, 2010).

Some studies have been conducted to assess present and future flood risk for the coastal region of Belgium. Kellens (2011) focused on current flood risk and risk of human casualties; (Van Der Biest et al., 2009b) considered one 'super storm'-related flood event and two future scenarios; while Verwaest et al. (2008) focused on a methodology for calculating flood risks for the Belgian coast. (Van Der Biest et al., 2009a) looked into the possible adaptation measures for the Belgian coast, but did not analyse their risk reduction benefits. All three studies, however, have not assessed the effect of future socioeconomic development on flood risk, or the effectiveness of risk reduction and adaptation measures.

Therefore, the main goal of this chapter is to assess the effectiveness of flood risk adaptation measures for several weak segments along the Belgian coastline, considering both future climate and land-use change. A modelling framework is used for this purpose, consisting of three steps: (1) simulation of potential flood events using an inundation model; (2) estimation of potential flood damage for current and future situations using a damage model; and (3) estimation of effects of two types of spatial adaptation measures: compartmentalization and land-use zoning for mitigating flood

risk in the Belgian coastal zone. While there are many possible adaptation measures, in this chapter we focus on two adaptation measures specifically pertaining to spatial planning.

Section 2.2 of this chapter provides an overview of the case-study area. Section 2.3 provides a description of the methods used with an explanation of the modelling framework, the socioeconomic and climate scenarios and the adaptation measures. Section 2.4 describes the results and Section 2.5 provides a discussion and some recommendations. Finally, and Section 2.6 concludes.

# 2.2. CASE STUDY AREA: THE BELGIAN COASTAL ZONE

The Belgian coast is the most western part of the Flanders region. It is situated in the southern part of the North Sea between The Netherlands and France (Figure 2.1). The region can be characterized as "an ecologically coherent and functional area, consisting of marine environment, beaches, mud flats, salt marshes, dunes and polder areas" (Provoost et al., 1996). The area is considered geologically stable, with little land subsidence (Lebbe et al., 2008). The low-lying coastal area has a length of approximately 65 km (Verwaest et al., 2007). Due to the limited length of the coastline and the increasing population pressure, most of the coastline is heavily urbanized with a population density of 678 inhabitants per km2, compared to 306
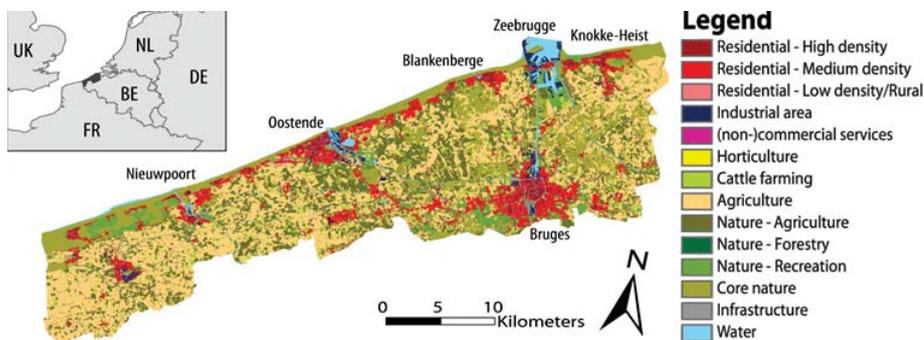


**Figure 2.1** Land-use map of the Belgian coastal zone.

inhabitants per km2 on average in Flanders (Breyne et al., 2007). Bruges is the largest city in the region, and Oostende with some 65,000 inhabitants is the largest city on the Belgian coastline.

More than half of the Belgian coast is protected against flooding by reinforcement measures, such as dikes, jetties, weirs, locks and quay walls (Belpaeme et al., 2011). Nevertheless, some parts of the coastal primary defence system of the Belgian coast can at most withstand a storm surge with a return period of 100 years (Verwaest et al., 2008). In the integrated Master Plan for Coastal Safety (Mertens et al., 2008) the government of the Flemish region stipulates that the minimum safety level for coastal defences must be for floods of return periods of 1,000 years. This primary safety standard is, however, not implemented yet in any law or decree (Mertens et al., 2008), nor is it fully implemented in practice. Some weak stretches of coastal protection have been identified along the Flemish coastline and are planned to be strengthened (Verwaest et al., 2008).

# 2.3. DATA AND METHODS

To assess the effect of spatial adaptation measures a modelling framework was set up, combining a land-use model, an inundation model and a damage model. These models are based on methods that have been developed and used in areas similar to the Belgian coastal zone (e.g. Dutch coast, Northwestern Europe) and have been adjusted to meet its characteristics. Using this modelling framework, flood risk is calculated for current and future scenarios, with and without spatial adaptation measures (Droogers & Aerts, 2005). Flood risk can be defined as a function of the hazard's probability, the exposure, and the vulnerability of the exposed socioeconomic system (Klijn et al., 2004; Samuels et al., 2006) and is commonly expressed in terms of expected annual damage (EAD) of flooding in a certain region (Meyer et al., 2009; Ward et al., 2011). EAD is defined as the sum of the effects of all possible flood events and their probabilities, or as the integral below the probability-loss curve (Grossi & Kunreuther, 2005). For a consistent comparison between all the possible outcomes, a comparison will be made in terms of relative changes in flood risk, following Bubeck et al. (2011). The purpose of this chapter is therefore not to establish a best estimate of current risks in absolute terms.
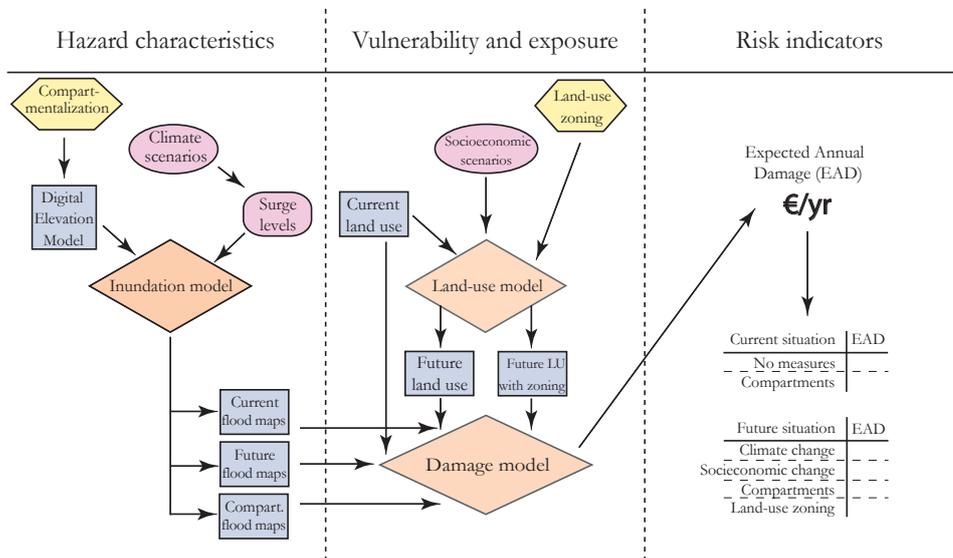
**Figure 2.2** Schematic representation of components and links of the flood risk modelling framework as will be used in this study (Diamonds are the models, squared boxes are the maps, ellipses are scenarios and the polygons are the adaptation measures).

Figure 2.2 presents an overview of the methodological framework which is used in this study. To begin with, a land-use model is used to create land-use maps for the year 2040, and an inundation model is used to generate inundation maps for different return periods. Next, flood damages are calculated using a flood damage model which combines land-use maps and inundation maps. Information on the vulnerability of the different land-use classes to flooding is provided using depth-damage functions. EAD is calculated using damage estimates for floods of different return periods. The two spatial adaptation measures, land-use zoning and compartmentalization of low lying polder areas, are included in the land-use model and inundation model, respectively. Land-use zoning is implemented by restricting future urban development in flood prone zones, whereas compartmentalization is implemented by using existing line elements to create closed compartments.

### 2.3.1.  LAND-USE MODEL

The land-use model is a raster based model called the Land Use Scanner, which integrates and allocates future land-use demand from different sectors with information on land-use suitability (Hilferink & Rietveld, 1999; Dekkers & Koomen, 2007). External regional projections on land-use demand and claims by sectors are used as input for the model. These claims result in land-use changes from the present land-use distribution. If, for example, additional space is 'claimed' for two land-use types (e.g. urban area and nature reserve), the model allocates new land-use to individual grid-cells based on the suitability of those cells for the new land-uses. Land-use suitability is based on spatial datasets such as the current land-use, physical properties (i.e. soil characteristics), operative policies, and market forces which are generally expressed in distance relations to nearby land-use functions. Since future land use is inherently uncertain (Van Asselt et al., 2007), four different scenarios are used to explore possible futures. Future land-use claims are formulated in line with the global IPCC SRES (IPCC 2000) and Dutch WLO scenarios (WLO 2006), using the scenario information from MIRA (Goffin et al., 2007) developed for Flanders. The four scenarios are as follows: Global Economy (A1), Transatlantic Markets (A2), Strong Europe (B1) and Regional Communities (B2). For a complete explanation of these socioeconomic scenarios and the land-use model application, the reader is referred to (De Moel et al., 2012b).

### 2.3.2.  INUNDATION MODEL

The inundation model is a simple approach developed by De Moel et al. (2012a) for polder areas like the Dutch and Belgian coastal zones. The model uses detailed digital elevation data and dynamically distributes volumes of flood water over an area. In a first step, the hydraulic load resulting from the high water level during a storm surge event and the size of the breach are determined in order to estimate the volume of water flowing into the area after a breach. The total amount of water which enters through the breach is calculated by integrating the discharge through the breach over time. For this simplified inundation model, specific 'weak segments' need to be defined manually in order to inundate the area (De Moel et al., 2012a).

Therefore, breach scenarios are assumed for individual breaches occurring near the cities of Nieuwpoort, Oostende, Blankenberge and Knokke-Heist (Figure 2.1), based mainly on the breach locations identified by Van Der Biest et al. (2009b).

In the next step, the maximum inundation depth of an area is calculated using the total flood volume from the first step. The model uses a Digital Elevation Model (DEM) with a resolution of 10 by 10 m (AGIV, 2011) and gives elevation in cm above TAW (Tweede Algemene Waterpassing), the Belgian national ordnance datum. Using the DEM, the model splits the area into numerous individual micro-basins. In total, the coastal area is divided into thousands of micro-basins, varying in size between 100 m2 for areas with considerable relief and 15 km2 or more for large flat polder areas. The total flood volume is distributed over the micro-basins, starting with the micro-basin next to the breach location and subsequently filling micro-basins until the total volume is met (for a more detailed description see De Moel et al. 2012b). This modelling approach has some disadvantages compared to 2-dimensional hydrodynamic models, such as a single flow direction. Also, the hydraulic interaction between neighbouring breaches is not taken into account. However, because of these generalizations, it allows for fast, and therefore many, calculations related to different breach locations, water levels and sea-level rise scenarios, as required in this study.

In this study, seven flood events are used to create inundation maps, based on storm surge heights developed by Willems (2007). These flood events vary from a probability of 1/100 up to a probability of 1/100,000, assuming that the weak coastal segments will always fail under a 1/100 per year storm. This is based on studies of Verwaest et al. (2008) and Mertens et al. (2008), who state that the Belgium coast has a minimum safety level of 1/100 per year. The influence of climate change on flooding at a breach location is addressed by accounting for sea-level rise, which increases the inflow of water into the coastal zone. Possible changes in failure probabilities have not been investigated assuming that coastal management will not allow failure probabilities to drop below 1/100 per year. To create future inundation scenarios, the height of sea-level rise (in centimetres) is added to the current storm surge heights. Future sea-level rise estimates are based on different scenarios for 2040 and 2100: 30 cm rise is based on a moderate scenario for 2040; 60 cm rise is based on a worst-case scenario for 2040 and a moderate scenario for 2100; 200 cm sea-level rise is based on a worst-

case scenario in 2100, as defined in Ponsar et al. (2007). This study does not take into account the possibility of an increase in the number of breaches due to increasing surge heights.

### 2.3.3.   DAMAGE MODEL

To determine the amount of flood damage, a damage model is created similar to the Damage Scanner (Klijn et al., 2007). The Damage Scanner has often been used to estimate the effect of land-use and climate change on flood damage in the Netherlands (Klijn et al., 2007; Bouwer et al., 2009; De Moel & Aerts, 2011) and a similar model has been applied for Belgium by Vanneuville et al. (2006). This approach estimates damage per land-use class from land-use and inundation maps. These estimates are based on depth-damage curves and maximum damages per land-use class. The depth-damage functions indicate the vulnerability of each land-use class by relating the inundation depth to a fraction of the maximum damage at that inundation level Koks et al. (2012). While this approach has been used in various applications, the method has some limitations that should be remembered when interpreting the results. There are, for instance, considerable uncertainties in maximum damages and the depth–damage curves as well as in the detail of the damage categories (Merz et al., 2004; Merz & Thieken, 2009; De Moel & Aerts, 2011), because of which these absolute estimates are very uncertain. However, when comparing two situations relatively to each other (i.e. with or without measures), this is less of an issue (De Moel & Aerts, 2011).

The maximum damages (Table 2.1) and depth-damage curves used in this study are based on De Moel et al. (2014), Vanneuville et al. (2006) and Kok et al. (2005). For residential land-uses, industrial sites and commercial and non-commercial land-uses, three types of maximum damages are used: the maximum damage of the structure of the buildings, the maximum damage of the content of the buildings, and the maximum damage of the areas between each building (open space). As shown in Jongman et al. (2012), maximum damages of aggregated land-use classes depend very much on asset densities specific for the class. To get a maximum damage for each of these land-use classes, a weighted sum is taken from the three maximum damages. To obtain this weighted sum, the potential damages to buildings and open space are
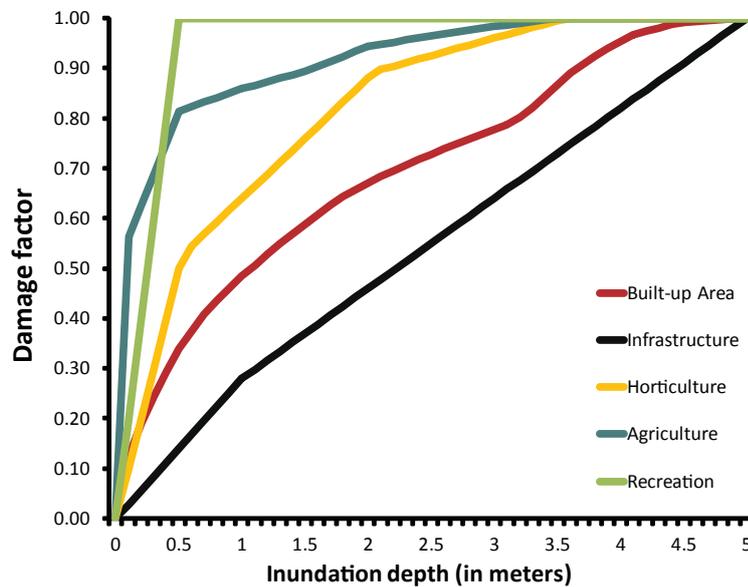
**Figure 2.3** Depth-damage curves for the different land-use classes. The horizontal axis represents the inundation depth; the vertical axis represents the damage fraction corresponding to the inundation depth for a specific land-use class.

summed using the average ratio of open space versus buildings in urban land-use cells. This share of buildings versus open space is obtained from a high resolution land-use map which distinguishes individual buildings. The maximum flood damages for the different types of natural land-use (e.g. nature and forest) are set to zero, which is consistent with studies by Briene et al. (2002), Trouw et al. (2005) and Vanneuville et al. (2006).

The curves for residential land-use, industrial sites, commercial and non-commercial services are derived from De Moel et al. (2014), and represented by the 'Built-up area'-curve (Figure 2.3). The damage increases rapidly up to a 1.5 meter inundation depth. Above 1.5 meter, the increase slows down up to three meters of inundation depth, where after it shortly grows much quicker again. This is because around three meters of inundation, we arrive at the first floor of the building, where new content and parts of the structure are destroyed (De Moel et al., 2014). Maximum damage is reached at five meters depth. The depth-damage curve for horticulture is based on the assumption that glass greenhouses can be more easily damaged than concrete buildings in built-up areas. Damage to infrastructure is projected to increase linearly,

**Table 2.1** Maximum damage and corresponding depth-damage curve per land-use class (values in 2005 euro).

|   | Land-use class | Maximum damage (Euros/m²) | Depth-damage curve |
|---|---|---|---|
| 1 | Residential – high density | 560 | Built-up Area |
| 2 | Residential – medium density | 300 | Built-up Area |
| 3 | Residential – loose buildings & ribbons | 300 | Built-up Area |
| 4 | Industrial sites | 740 | Built-up Area |
| 5 | Commercial and non-commercial services | 750 | Built-up Area |
| 6 | Horticulture | 65 | Horticulture |
| 7 | Cattle farming | 0.1 | Agriculture |
| 8 | Agriculture | 0.5 | Agriculture |
| 9 | Nature – Agriculture | 0.5 | Agriculture |
| 10 | Nature – Forestry | 0 | N/A |
| 11 | Nature – Recreation | 0.03 | Recreation |
| 12 | Core nature | 0 | N/A |
| 13 | Infrastructure | 40 | Infrastructure |
| 14 | Water | 0 | N/A |

following Kok et al. (2005). Cattle farming, agriculture, and nature-agriculture are clustered in the 'agriculture' curve, based on Koks et al. (2012) and Hoes (2007). Since crops and grass often have low heights, it is expected that most of the damage occurs already at low inundation depths. The curve for recreation is based on a depth-damage curve created by Vanneuville et al. (2006). It is assumed that above a low inundation depth (i.e. 0.5 meters), no extra damage will occur. The only costs that will occur are clean-up costs. For other natural land-uses as well as for water areas (e.g. lakes, ponds), no depth-damage curves are used as it is expected that no damage occurs to these land-uses (Kok et al., 2005a; Vanneuville et al., 2006; Koks et al., 2012).
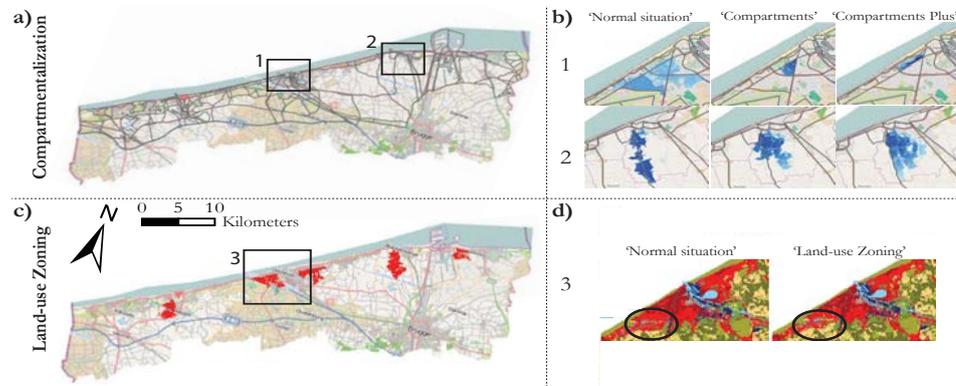
**Figure 2.4** Overview of the spatial adaptation measures used in this study. The panel a) and b) show the compartmentalization measure, panel c) and d) show the land-use zoning measure. The left-hand side of the figure shows the measures for the whole coastal area, the right-hand side shows the adaptation measures on a local scale.

## 2.3.4. SPATIAL ADAPTATION MEASURES

### ❧ COMPARTMENTALIZATION

Compartmentalization can be used to decrease the area that will be flooded, or contain it to an area where it does least damage, which potentially reduces the consequences of a flood (Klijn et al., 2010). In line with other studies (Alkema & Middelkoop, 2005; Theunissen et al., 2006; Oost & Hoekstra, 2009), this adaptation measure is included in the model by upgrading old dikes, roads, railways, and other 'line elements' that are already present in the landscape, into flood protection elements. As these structures already have higher heights, they can easily transform into (secondary) water defence structures. In this study, two types of compartmentalization will be tested. For the first compartmentalization measure (further referred to as 'Compartments'), each line element is raised up to a uniform height equal to the maximum current height. By doing this, enclosed compartments are created for the whole coastal region. For the second compartmentalization measure ('Compartments Plus'), the created line structures of the first compartmentalization measure are raised by one extra meter.

To implement the concept of compartmentalization into the model, two new digital elevation maps are created with closed/elevated line elements, based on Lierman et al. (2012). See panel a) in Figure 2.4 for an overview of the used line elements.

### ❧ LAND-USE ZONING

Land-use zoning can be defined as local planning and restrictive building policies which are meant to prohibit residential and industrial developments in flood zones. Instead of building in areas that potentially have the highest inundation depths during a flood, new building sites are restricted to areas with preferably no inundation or relatively low inundation depths. Areas with a high flood probability and high inundation depths can be developed as nature or recreational land-use. The concept of zoning will be implemented in the land-use model by restricting future residential, industrial, commercial and non-commercial developments in certain areas. This is done by giving a low suitability to the areas defined in panel c) in Figure 2.4. These restricted areas can have high flow velocities of flood waters (i.e. areas very close to potential breaches in the coastal defence) and/or high inundation depths. Panel d) in Figure 2.4 shows the result of implementing the zoning measure around Oostende: the left map is a simulation without zoning; the right map is a simulation with the zoning restrictions.

## 2.4. RESULTS

This section presents the results of the damage and risk calculations for the five different breach locations, starting with a brief description of the results without adaptation measures. Subsequently, the effect of the adaptation measures under current and future conditions are addressed. Even though five different breach locations are addressed in this chapter, some of the results will be shown in an aggregated way to illustrate the overall effect of future developments and/or adaptation measures. It should be noted, however, that this analysis is not comprehensive for the entire coast as different amounts of breaches could occur with different hydraulic boundary conditions (i.e. surge level at sea), which are also influenced by climate change (i.e. sea-level rise).

**Table 2.2** Expected Annual Damage ($10^6$ €/yr) and average inundated area for the baseline situation with and without compartmentalization per breach location. The average area inundated is the arithmetic mean over the inundated area of the eight flood events used in this study.

| Breach locations | Baseline (2005) | | 'Compartments' | | | | 'Compartments Plus' | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | EAD ($10^6$ €/yr) | Average area inundated (in km²) | EAD ($10^6$ €/yr) | | Average area inundated (in km²) | | EAD ($10^6$ €/yr) | | Average area inundated (in km²) | |
| All locations | 25.3 | 17.2 | 12.2 | (-52%) | 10.7 | (-38%) | 12.5 | (-51%) | 10.3 | (-40%) |
| Nieuwpoort | 2.1 | 1.6 | 2.0 | (-5%) | 1.1 | (-31%) | 2.0 | (-5%) | 1.1 | (-31%) |
| Oostende SW | 14.7 | 5.0 | 0.1 | (-99%) | 0.2 | (-96%) | 0.4 | (-97%) | 0.2 | (-96%) |
| Oostende NE | 4.9 | 4.8 | 8.7 | (+78%) | 5.2 | (+8%) | 8.7 | (+78%) | 5.2 | (+8%) |
| Blankenberge | 0.7 | 3.1 | 0.4 | (-43%) | 3.5 | (+13%) | 0.5 | (-29%) | 3.3 | (+6%) |
| Knokke-Heist | 2.9 | 2.7 | 1.0 | (-66%) | 0.8 | (-70%) | 0.9 | (-69%) | 0.5 | (-81%) |

## 2.4.1.  NO ADAPTATION MEASURES

For the baseline situation, expected annual damages are calculated using the land-use map for the year 2005 and flood events with return periods as described in Section 2.3.2 (i.e. flood probabilities from 1/100 to 1/100,000 years). Table 2.2 (columns 2 and 3) shows the results for the baseline situation. The aggregated EAD for the breaches considered in this study is approximately €25 million/yr for the baseline situation. The breach southwest of Oostende (Oostende SW) generates the highest share of damage, taking up almost 60% of the total damage. This is related to a relatively large inundated area with a large percentage of built-up area.

EAD values for future scenarios are calculated using future socioeconomic changes and changes in sea-level rise due to climate change. For each scenario, a substantial increase in the aggregated flood risk can be observed (Figure 2.5, blue bars). For all the breach locations and scenarios, most of the increase in EAD occurs due to socioeconomic changes rather than climate change. With 30 cm and 60 cm sea-level rise, the aggregated EAD increases by 5% to 7% due to climate change, while socioeconomic change results in a 33% to 41% increase in EAD. Only for 200 cm
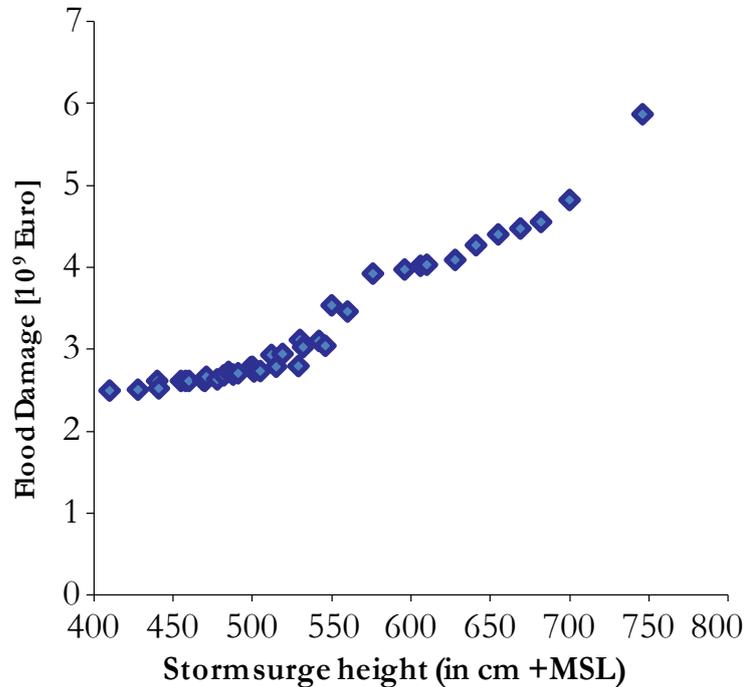
**Figure 2.6** Storm surge height vs. flood damage. The flood events and their flood damage have been ranked from low to high storm surge heights, which corresponds to ranking flood events from 1/100 in the current situation to 1/100,000 in the +200 cm sea-level rise scenario.

sea-level rise, the aggregated EAD increases substantially more due to climate change. The increase in damage due to socioeconomic changes is mainly the result of an increased rate of flooded residential areas, for each of the breach locations. For all the scenarios, the increase in flooded residential areas account for between 65% and 70% of the increase in flood risk.

As can be seen from Figure 2.5, there is a large difference between the worst-case scenario with 200 cm of sea-level rise and the other scenarios. When plotting the storm surge height versus the aggregated flood damage of the considered breach locations (Figure 2.6), it appears that between storm surge heights of 5.5 m and 6 m, a significant increase in damage occurs. This is related to a relatively large increase in the size of the inundated area for storm surges with heights above 5.5 m for the breaches near Oostende and Blankenberge.

## 2.4.2. COMPARTMENTALIZATION

For the baseline situation, both compartmentalization measures show a significant and similar decrease in flood risk (Table 2.2), and result in a reduction of the aggregated EAD by more than 50%. Nevertheless, a number of differences can be observed at the different breach locations. Panel b) of Figure 4 shows the breach near Oostende and the breach near Blankenberge for a flood event with a probability of 1/2000 without climate change. At Oostende (SW), the flood extent significantly decreases to only a very small area due to compartmentalization. At Blankenberge, on the other hand, the inundation extent increases due to compartmentalization as floodwater is kept out of a deep polder area and has to find its way elsewhere (Figure 2.4). This still results in a decrease in EAD due to the water now flooding the agricultural area behind the village instead of the village itself. The EAD for the breach Oostende NE, however, increased by almost 80%. Even though the average area inundated increases only by 8% near the Oostende NE breach, almost all of this increase occurs in residential areas, resulting in a large increase in damage. For all breach locations, the impact on EAD reduction of the one meter extra elevation on the line elements (i.e. compartmentalization plus) is limited. Though compartmentalization shows overall high risk reduction levels, results show that there can be large differences between different breach locations, varying from larger inundated areas to higher inundation depths. This is consistent with results found in Alkema and Middelkoop (2005), Oost and Hoekstra (2009) and Klijn et al. (2010).

Figure 2.5 shows that for future conditions compartmentalization can reduce the aggregated flood risk by about 50% for 30 cm and 60 cm increases in sea-level. For a 200 cm sea-level rise, the reduction in EAD through compartmentalization is much smaller, around 25%, indicating that this measure becomes less effective with extreme high sea-level rise. Nevertheless, the compartmentalization measures still have a considerable risk reducing effect under the worst-case scenario, for both 'Compartmentalization' and 'Compartmentalization Plus'. Compared to the baseline risk, the risk-reducing effect of compartmentalization would, for most of the breach scenarios considered, more than offset the adverse effect of sea-level rise on the flood risk for both the 30cm and 60cm sea-level rise scenarios. Only under extreme sea-level rise, the combined effect of climatic and socioeconomic change is not offset by the compartmentalization measures.

**Table 2.3** Expected Annual Damage ($10^6$ €/yr) and relative EAD reduction for the zoning measure compared to the 'no-adaptation' situation (between parentheses) for the A1-scenario and B2-scenario in 2040 and for the different breach locations with 30 cm sea-level rise.

|  | A1-scenario | | | B2-scenario | | |
|---|---|---|---|---|---|---|
|  | No adaptation | Zoning | | No adaptation | Zoning | |
| Total | 38 | 36.4 | (-4%) | 35.6 | 33.5 | (-6%) |
|  |  |  |  |  |  |  |
| Nieuwpoort | 3.0 | 2.9 | (-3%) | 2.7 | 2.7 | (0%) |
| Oostende SW | 19.9 | 19.4 | (-3%) | 18.6 | 18.2 | (-2%) |
| Oostende NE | 8.4 | 7.7 | (-8%) | 8.1 | 6.8 | (-16%) |
| Blankenberge | 1.1 | 0.9 | (-18%) | 0.9 | 0.9 | (0%) |
| Knokke-Heist | 5.7 | 5.4 | (-5%) | 5.3 | 4.9 | (-8%) |

## 2.4.3. LAND-USE ZONING

Overall, land-use zoning results in a much smaller decrease in EAD than the risk reducing effect of compartmentalization measures. The large difference between compartmentalization and land-use zoning is mainly related to the fact that zoning only influences the flood risk of new urban development and does not influence the risk of the existing building stock. When only looking at the increase in future risk (i.e. the difference between the baseline situation and the future situation), land-use zoning could offset about 15% to 20% of the increase in flood risk due to land-use change. However, if we consider the decrease as compared to the future risk (similar to Section 2.4.2.), a decrease of 4% to 6% in flood risk for 30 cm and 60 cm sea-level rise can be seen, compared to the same socioeconomic scenarios without zoning (Table 2.3). For the worst-case sea-level rise scenario (200 cm sea-level rise), the risk reduction is higher, between 6% and 11%. Due to the larger flood extent in this scenario, more areas that are restricted for new urban developments are flooded compared to the other climate scenarios. This results in a relatively larger effect of the land-use zoning measure.

Table 2.3 presents the results for the A1-scenario and B2-scenario in the 30 cm sea-level rise scenario per breach location. As can be seen from Table 2.3, there are large differences in EAD reductions between the two scenarios and between each

breach location. In the A1-scenario, the largest decrease in EAD can be found near Blankenberge with an 18% decrease compared to the 'no adaptation' situation. This decrease is the result of a 15% decrease in residential flood damage. By contrast, no risk reduction is found at Blankenberge and Nieuwpoort for the B2-scenario, implying that zoning has no effect on urban development there in the B2 scenario. This may be explained by the fact that in the B2-scenario, also without the restriction on urban development, no new built-up areas are modelled. As a result, land-use zoning has no effect. At the other locations, the impact of zoning varies. It is most pronounced at the breach location of Oostende NE, where zoning results in a 16% decrease compared to the 'no-adaptation' situation, which results from a 90% decrease in industrial flood damage.

# 2.5. DISCUSSION

Several studies have calculated flood risk and flood damages for coastal Belgium (Verwaest et al., 2008; Van Der Biest et al., 2009a, 2009b; Kellens, 2011). Flood damages in Van Der Biest et al. (2009b) are calculated by using a 'super storm' event. For the present situation, their total flood damage results are around €400 million. When comparing this with an event with similar storm surge levels, we find that the total flood damage results are almost eight times higher. This can be explained by two factors. First, in our study, a larger area was flooded in the baseline situation (approximately three times larger), due to the use of a different type of inundation model. Second, there are large differences in the flood damage calculations, such as differences in maximum damages and depth-damage curves, which may explain the remaining differences in total flood damage.

Most of the adaptation measures studied by Van Der Biest et al. (2009a) were focused on improving the coastline protection to reduce the flood hazard. Although one measure was similar to the land-use zoning measure used in our study, their results are different. According to Van Der Biest et al. (2009a), spatial planning restrictions are more difficult to implement in built-up areas, such as Oostende, compared to areas where natural defences are relatively intact. Nevertheless, our study shows that the largest decrease in flood risk is achieved when such restrictions are implemented around built-up areas (like Oostende).

When comparing the results of Kellens (2011) with the result of this study, somewhat similar results can be observed when it comes to the distribution of the flood risk over the coastal zone. In both studies, Oostende represents the largest share in the calculated flood risk. The total risk, however, is different. In this study, a flood risk of around €25 million/yr without the ports is observed for the baseline situation. A similar result has been found in Kellens (2011), even though in that study ports are included in the calculation of the risk. An additional calculation was conducted in our study to estimate the damage to the ports, using uniform water levels equal to the storm surge level, which results in approximately €69 million/yr, a 2.75 times larger EAD than the one estimated by Kellens (2011). One of the reasons for this large difference is the more aggregated land-use in our approach, which can result in significant higher damage estimates (Jongman et al., 2012).

Given the nature of the spatial adaptation measures considered, the analysis in this study focused on damages that occur in the coastal areas, excluding ports. Nonetheless, calculations have also been performed including the ports of Oostende and Zeebrugge. As the inundation model is not able to simulate water levels outside the embankments, the maximum storm surge level was used to derive inundation depths. These calculations show that flood risk estimates increase by more than 170%. This suggests that ports are clearly at risk. Not only because of their open connection with the sea, but also because of the high economic activity and value of the assets at risk in these areas (Nicholls et al., 2008). Therefore, more research into appropriate – or combinations of (Aerts et al., 2008a) – measures to reduce flood risk in these areas is needed.

### 2.5.1.  FEASIBILITY OF SPATIAL ADAPTATION MEASURES

In the Master Plan for Coastal Safety, it is stated that the Belgian coastline should be able to withstand at least a storm with a probability of 1/1,000 (Mertens et al. 2008). In this study, it is assumed that the weak stretches of the coastline are currently able to withstand storms with a maximum probability of 1/100. If the safety levels for the considered weak segments would be 1/1,000 per year, the total aggregated flood risk could decrease by almost 80%. This means that EAD in the baseline situation would be reduced from €25.3 million/yr to approximately €5 million/yr. Compared to the

results for spatial adaptation measures this is a much larger reduction in flood risk, as the best spatial measure (e.g. compartmentalization) results in an average reduction of EAD of around 50%. As current safety levels are still relatively low, it might be more effective for some locations to invest in reducing the probability of flooding first by raising and strengthening the primary coastal defences, then by reducing the exposure and consequences using compartmentalization and land-use zoning. Similar conclusions are drawn in Reyns et al. (2011). It should be noted, however, that there may also be additional benefits or consideration that would favour certain measures over strengthening the primary defences (i.e. undesirable to replace small dunes with concrete dam; historical/cultural value of certain coastline elements).

The concept of compartmentalization is a fairly easy and straightforward measure to include in the model. In this study, old embankments and existing line structures (e.g. roads, railways and old dikes) have been used to assess the effectiveness of this measure. No new dikes have to be built; only existing structures must be strengthened. The implementation costs, however, can become high due to possibly large amounts of materials needed to raise the dikes and the cost of maintenance (Theunissen et al., 2006; Klijn et al., 2010).

For land-use zoning, the assessment of benefits is more difficult. Future land-use change is uncertain and potential benefits of zoning are directly related to the amount of developments that can be restricted by the spatial zoning measure. With substantial socioeconomic growth, restrictions may considerably reduce the potential for increased flood risk. On the other hand, if there is little to no growth in the areas considered, the potential to reduce flood risk by zoning is low and restricting developments would be unnecessary. Land-use zoning might be an interesting measure when combined with other spatial adaptation measures, but not as a sole measure.

Klijn et al. (2010) describe a close relationship between the probability of failure of the primary defences and the benefits of compartmentalization. When primary flood defences are low, compartmentalization could deliver considerable benefits, while not being the measure showing the highest risk reduction. When the primary flood defences are designed for low probability storms (similar to the flood defences along the Dutch coast) the benefits of compartmentalization are small. To find the optimal safety level of protection, results from studies like this can be used to estimate benefits

of specific measures. Consequently, these benefits can be tested with methods such as cost-benefit analyses and evaluated at the local level. By looking at which measures are most effective in which areas, an optimal safety level of protection could be reached which could be more effective in reducing the risk than using one single measure in these areas (Janssen et al., 2008).

The analysis has focussed on damages that occur in the coastal areas other than the ports. When taking the ports of Oostende and Zeebrugge into account, the baseline flood risk estimate increases by more than 170% compared to the flood risk for coastal Flanders without taking the damage in these ports into account. Clearly, these areas are very much at risk. Not only due to the open connection with the sea, but also because of the high economic activity and value of assets in these areas. However, due to the nature of the investigated spatial adaptation measures, it was not possible to apply them in these port areas. Port activities are almost by definition bound to unembanked areas, which means that compartmentalization is not a feasible option as that would result in the embankment of the area, hindering the daily activities. Also land-use zoning is limited in its potential in port areas because of the limited size and options for relocation there. Therefore, more research is needed into appropriate measures to reduce flood risk in those regions. Next to the problems with implementing the tested spatial adaptation measures in these regions, there is also the known difficulty with estimating flood damage to industrial areas, which are much more heterogeneous with specialised buildings and equipment as opposed to residential areas. Therefore, one has to be cautious with interpreting the damage results in these areas.

## 2.5.2.   METHODOLOGICAL ISSUES

The results show that future socioeconomic scenarios may result in considerable larger increases in flood risk compared to climate change scenarios. This is consistent with the observations of several other studies (Hall et al., 2005; Mokrech et al., 2008; Aerts & Botzen, 2011; Feyen et al., 2012; Klijn et al., 2012). The difference between socioeconomic scenarios in this study was, however, relatively small, implying it may not be required to study four different socioeconomic scenarios. This is in contrast to Hall et al. (2005) and Bouwer et al. (2010), who observe large differences in

EAD increase between socioeconomic pathways. Along the Belgian coast, this is the result of relatively small differences in the allocation of future urban expansion in the land-use model between the various socioeconomic scenarios. Also the influence of relatively low sea-level rise scenarios, 30 cm and 60 cm, is limited. Only the extreme sea-level rise scenario, 200 cm, differs considerably. This is related to a relatively large expansion in flooded area for storm surges over 5.5 m in this region.

Furthermore, some other limitations can be noted. First, the future land-use maps are based on the 2005 map, which contains potentially outdated information, and may be biased by uncertainties in the allocation of future land-use and linear extrapolation for future projections (see De Moel et al. (2012a) for an extensive description of these problems). Second, there are large uncertainties in the determination of the maximum damages and the depth–damage curves (Merz et al., 2004; Merz & Thieken, 2009; De Moel & Aerts, 2011), but also the determination of the volume of water that could enter the polder area (De Moel et al., 2012a). This may result in considerable uncertainties in risk estimates (De Moel & Aerts, 2011). Using relative changes estimated by the same model gets around some of this uncertainty though. Regarding the inundation model, it should be noted that the inundation model used is a simplification of 2-dimensional hydraulic models, which can better capture hydraulic dynamics during a flood event. Also, a fixed amount of breaches are assumed in the inundation model (the 'weak' coastal segments). This is a simplification of the reality, as it is expected that more breaches are formed in case of higher water levels (Van Der Biest et al., 2009b) and thus more and higher inundation might occur, resulting in a larger increase in flood risk. Finally, it is important to note that large uncertainties exist in the determination of the flood events with very low probabilities. However, as the probability is very low, these events have almost no influence on the total EAD (Ward et al., 2011). Nevertheless, they are taken into account, as their results give a general idea what might happen when such an extreme event occurs.

## 2.6. CONCLUSIONS

In this study, the impact of climatic change, socioeconomic change and the effects of two spatial adaptation measures on flood risk for the coastal area of Belgium

have been investigated. A flood risk model for the coast of Belgium was set up by combining a land-use model, inundation model and a damage model. This model was used to assess changes in risk according to three climate change scenarios, four socioeconomic scenarios, and two spatial risk reduction and adaptation measures: compartmentalization and land-use zoning.

The results showed that without adaptation measures, future flood risk for the investigated breach locations increased significantly. This increase in flood risk is largely the result of socioeconomic changes. Only when considering extreme sea-level rise, the effect of the inflow of extra flood water is more important than socioeconomic changes. This is illustrated by the results of the extreme sea-level rise of 200 cm, which resulted in an increase of more than 60% in expected annual damage.

When adaptation measures are being implemented, flood risk can be substantially reduced. Compartmentalization results in an average risk reduction of approximately 50% for both the baseline situation as well as for future scenarios. Land-use zoning results in much smaller reductions, averaging between 6% and 10%. Except for the most extreme climate change scenario, compartmentalization successfully offsets the combined adverse effects of socioeconomic growth and climate change on flood risk. For both compartmentalization and zoning, large differences are found in their effectiveness at the different breach locations. Compartmentalization can significantly decrease the flood risk in most areas, while it actually increases the flood risk in other areas as inundation heights may increase there. Similarly, the effect of land-use zoning depends very much on the location, as well as on the socioeconomic projection used. Large growth leads to larger damage as well as larger avoided damage for the land-use zoning measure.

Flood risk can also be reduced by strengthening the primary flood defences, which currently withstand 1/100 year water levels. If primary defences would be improved to withstand floods of return periods of up to 1,000 years, flood risk would be reduced by almost 80% for the considered breach locations. A variety of measures could be investigated for different locations in order to judge which measures are most effective in which location, implying that the choice of adaptation measures should be tailored to local characteristics. Combining feasibility and costs could result in an optimal choice or mix of measures to manage flood risk for the Belgian coast. Lastly,

it should be noted that the risk in port areas constitutes a large part of the total flood risk, and more research is needed to correctly simulate flood risk in these areas and consequently be able to test adaptation measures.