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Effect of spatial adaptation measures on flood risk in the coastal area of Flanders

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Summary

Flood risk in coastal zones can increase due to climate change induced sea-level rise and socioeconomic changes. Over the last decades, population growth, increases in wealth and urban expansion have been found to be the main cause for increasing losses in coastal zones. These changes may, however, be offset by appropriate adaptation measures. The main goal of this study is therefore to assess the effectiveness of flood risk adaptation measures for the Flemish coastal zone, considering future climate and land-use change. In order to achieve this, we set up a modelling framework to assess the flood risk of the Flemish coast including climatic and socio-economic projections, and used this model to test 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 the flood risk, in terms of expected annual damage, for those different situations.

The results show that without adaptation measures, future flood risk will increase between 40-50% by the year 2040. Of that increase, between 30-40% is the result of socio-economic changes, compared to an approximate 6% increase due to climate change. Only when considering a scenario of extreme sea-level rise does climate change increase the flood risk more than socioeconomic change. Compartmentalization resulted in an average risk reduction of approximately 50% for both the baseline situation and for future scenarios. With the exception of the most extreme climate change scenario, compartmentalization successfully offsets the combined adverse effects of socio-economic growth and climate change on flood risk for this case study. Land-use zoning resulted in lower risk reductions compared to compartmentalization as it can only reduce the increase in risk. Land-use zoning resulting in reductions of future flood risk averaging between 6-10%. When only looking at the increase in risk, land-use zoning could offset about 15-20% of the increase in flood risk due to land-use change. For both compartmentalization and zoning, large differences have been found in their effectiveness between different locations.

Flood risk can also be reduced by strengthening the primary defences. In this study flooding starting from return periods of 100 years has been considered. If primary defences would be improved to withstand any water level with return periods up to 1000 years, flood risk will be reduced by almost 80%. Clearly, a variety of measures should be investigated for each area, in order to judge which measures are most effective in which location. Combining feasibility and costs could then result in an optimal combination of measures to manage flood risk for the Flemish coast.

Lastly, it should be noted that port areas constitute a large part of the total flood risk. In our calculations the flood risk in port areas actually surpassed that of the embanked parts. Despite this high potential damage, we did not test adaptation measures in this area because the investigated adaptation measures are not well suited for port areas and 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, more research has to be done to correctly simulate flood risk in these areas and consequently be able to test appropriate adaptation measures for ports.

1 Introduction

Coastal zones, such as the coastal zone of Belgium at the North Sea, are one of the most vulnerable areas to flooding (e.g. Nicholls et al., 2010). Flood risk in coastal zones will increase due to climate change and sea level rise (Gaslikova et al., 2011; Ponsar et al., 2007; Philippart et al., 2007). Furthermore, continuous socioeconomic growth in these coastal regions increases exposure to coastal flooding (McGranahan et al., 2007). Over the last decades, population growth, increases in wealth and urban expansion have been found to be the main cause for increasing losses in zones at risk from flooding (Bouwer et al., 2007; Nicholls et al., 2008).

These projected trends have led to research to assess what measures may be developed to reduce flood risk. However, accurate flood risk assessments for future developments and quantification of the effect of possible adaptation measures are often a complicated task and surrounded by uncertainties. Various studies have attempted to combine projections of climate change and socioeconomic trends to estimate future flood risk. These studies vary from assessment on a national or European scale (e.g. Hall et al., 2005; Klijn et al., 2012; Feyen et al., 2009), to studies focused on a regional scale (e.g. Maaskant et al., 2009; Bouwer et al., 2010; Mokrech et al., 2008; te Linde et al., 2011). These studies, however, mainly focused on the assessment of future flood risk and few looked into possible adaptation measures to lower this risk. There have been some studies that quantified the effect of adaptation measures on flood risk. These include for instance Bouwer et al. (2010) for a dike ring area in the Netherlands and De Kok and Grossmann (2010) in the Elbe region.

For the coast of Flanders, there have been various studies into baseline and future flood risk (Kellens, 2011; Van der Biest et al., 2009a; Verwaest et al., 2009) and the effect of possible adaptation measures (Van der Biest et al., 2009b). All studies took different approaches to calculate this risk, but none took different future socioeconomic scenarios into account and the specific adaptation measures that have been tested in this study.

The main goal of this study, therefore, is to assess effectiveness of flood risk adaptation measures for the Flemish coastal zone, considering future climate and land-use change. In order to achieve this goal, the research objectives are to set up a flood risk model for the Belgium coast and use this model to test the effectiveness of flood management measures in terms of risk reduction. This will be done in a few steps: (1) potential flood events will be simulated using an inundation model based on De Moel et al. (2012).(2) With these simulated flood events, potential flood damage will be calculated using a damage model based on methods developed by De Bruijn (2006) and Klijn et al. (2007). (3) Inundation depths and potential flood damage will be assessed for the baseline situation, as well as under future climate-change (sea-level rise) and land-use change scenarios. Finally, (4) two types of spatial adaptation measures, compartmentalization of the coastal area and land-use zoning, will be implemented in the model to compare them with the baseline situation to see how effective they are in mitigating flood risk in the Belgian coastal zone.

These activities, performed within WP1 of the CcASPAR project, are strongly linked with WP5 (the coastal case study), which addresses spatial adaptation measures for, amongst others, flood risk using 'research by design'; where compartmentalization of the coastal region is a key theme.

This report is organized as follows. Chapter 2 provides an overview of the case-study area. Chapter 3 provides a description of methods used with a description of the flood risk model, the socio-economic- and climate scenarios and the potential measures Chapter 4 describes the results and Chapter 5 provides a discussion and recommendations Chapter 6, concludes.

2 Study Area: Coastal Flanders

The Belgian coast, the most western part of Flanders, is situated in the southern part of the North Sea between The Netherlands and France. The low-lying coastal area has a length of approximately 65km and an average width of 20km (Verwaest et al., 2007). The coastal region can be defined, according to Provoost and Hoffman (1996), as "an ecological coherent and functional area, consisting of marine environment, beaches, mud flats, salt marshes, dunes and polder areas". For this analysis, we base our coastal area on the sixteen municipalities that are defined in Van der Biest et al. (2008) as coastal municipalities[1] (Figure 2.1). In this chapter, we will briefly discuss the socio-economic, land-use and geographic characteristics of the Flemish coastal zone.

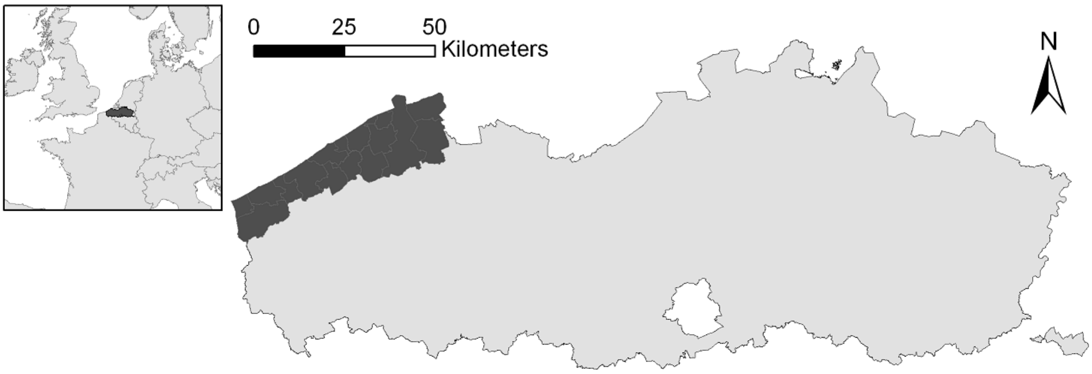

Figure 2.1 Coastal zone of Flanders (in dark grey)

2.1 Socio-economic characteristics

The coastal area of Flanders is a region with a relatively high population density compared to the rest of Flanders, respectively 678 inhabitants per km^2 versus 306 inhabitants per km^2 (Breyne et al., 2007). Due to the limited length of the coastline and the increasing population pressure, most of the coast has become urbanized. With around 120.000 inhabitants, Bruges (Figure 2.2) is the largest city in the region and with around 65.000 inhabitants is Oostende the largest city on the Flemish coastline (Kellens et al., 2011). In total, approximately 400.000 people live in this region (Mertens et al., 2010).

The main sectors of economic activity for the coastal region are tourism, agriculture and port industry. The coastal municipalities attract millions of tourists every year, resulting in a large amount of seasonal work in spring and summer. In 2007, the tourism in the coastal region has generated a turnover of approximately 2.6 billion Euros and 13.000 direct jobs (Volckaert and De Sutter, 2009). The downside, however, is a lot of housing vacancy in the low season during the winter (Breyne et al., 2007).

Due to the presence of highly fertile polder soil, the coastal plains of Flanders feature substantial amounts of farmland. The region of West-Flanders accounts for around 35% of the Flemish agricultural area, playing an important role in the Flemish agricultural

[1] The following municipalities are included (from south to north): De Panne, Veurne, Kokszijde, Nieuwpoort, Middelkerke, Gistel, Oostende, Oudenburg, Bredene, Jabbeke, De Haan, Zuienkerke, Brugge, Blankenberge, Damme and Knokke-Heist.

sector. In the coastal area, about 40% of the farmland constitutes of pastures and grassland, whereas the other 60% is mainly used as arable land to cultivate grain crops (Belpaeme and Konings, 2004).

Moreover, main industry 'hubs' in the region are the ports of Zeebrugge and Oostende, both specialized in roll-on-roll-off (short: RoRo) port activities. In 2006, Zeebrugge was the largest RoRo-port of Europe handling more than 1.9 million new cars. In Oostende, 78% of the total throughput (6.2 million tonnes) was roll-on-roll-off. Zeebrugge also plays a key role in the European gas network and is a large distributer of containers (Breyne et al., 2007). In 2007, the ports together accounted for 7.7% of the total value added produced in Flanders. Other industrial activities are spread across the region and are generally concentrated in local small and medium enterprises (Van der Biest, 2008).

2.2 Land-use characteristics

The land use of the coastal area of Flanders is diverse. One the hand, we see a relatively high building density in cities such as Oostende and Zeebrugge. On the other hand, we see a large amount of nature area and farming land. Directly on the coast, the high building density is for a large part the result of the large amount of holiday accommodation and second houses. The industry in the region is mostly located near the ports of Zeebrugge/Bruges and Oostende, with a few small exceptions in Nieuwpoort and Veurne.

The core nature is primarily located directly near the coast, in and around the dunes and beaches, whereas the recreational nature is mainly located directly near the cities and villages. More inland, the land use further away from the villages and cities is mostly farmland. However, the type of farmland varies throughout the region. More in the south-western part of the region, we find mainly regular cropland and pastures. In the northern part of the region, there is much more cropland with a nature function. The most common cultivated crops in this area are corn and grain (Van der Biest, 2008).

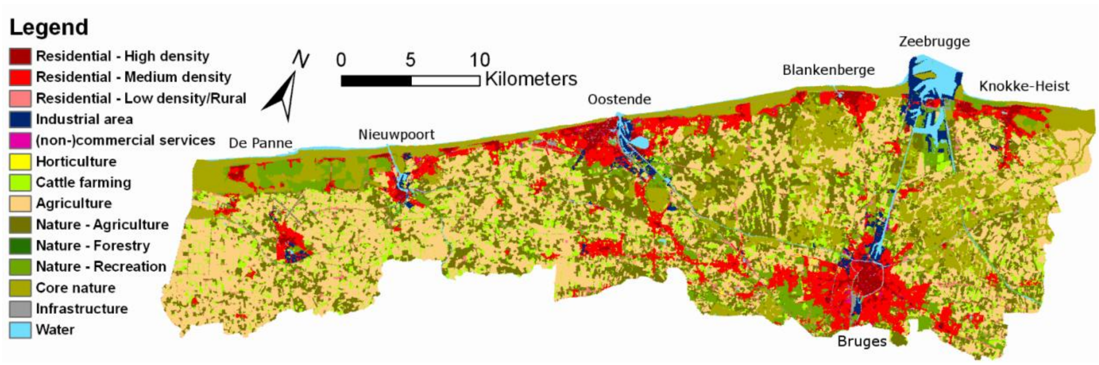

Figure 2.2. Land use of Coastal Flanders in 2005

When focussed more specifically on the ports of Zeebrugge and Oostende, we see that the port of Oostende is much more diverse. Whereas the main industrial land use in the port of Zeebrugge is Roll-on Roll-off Industry, is the main industrial land use in Oostende 'other industry'. This 'other industry' can be defined as a clustered land use of relatively small and diverse companies. Another interesting difference is the clustering of the port activities as a whole. In Zeebrugge, we see a relative high clustering of industrial activities, with a few (clustered) residential areas. In Oostende, on the other hand, we see much more residential areas in between the industrial areas.

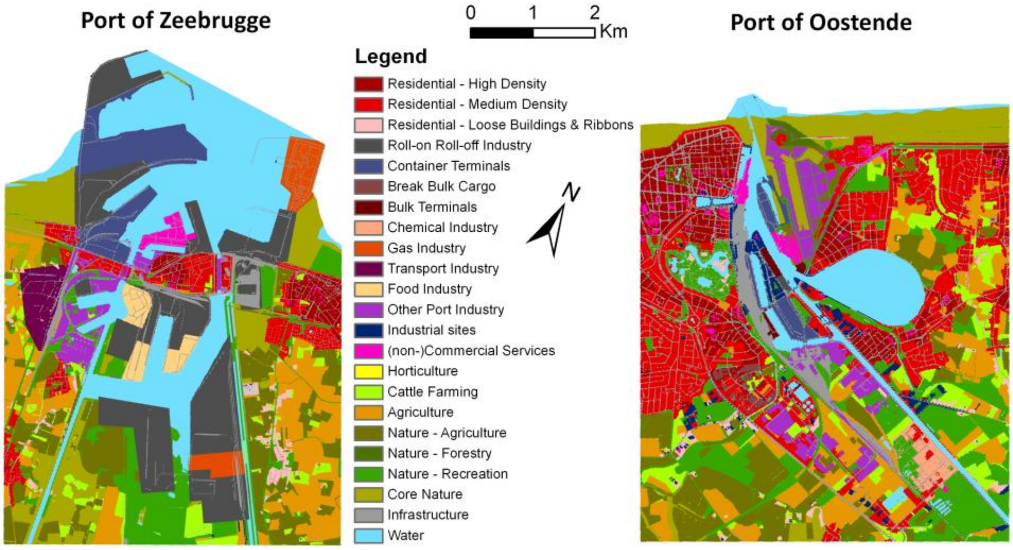

Figure 2.2. Land use in the Ports of Zeebrugge and Oostende in 2005

2.3 Geographic characteristics

As previously been said, the coast of Flanders has a length of approximately 65km and an average width of 20km. The elevation of most of the coastal zone is about two meters below the annual storm surge level of 5,5m TAW (Verwaest et al., 2005) and without the appropriate coastal protections, this area would flood every year (Mertens et al., 2010).

As we can see in Figure 2.4, the digital elevation map of the Belgian coastal zone, most of the coastal area is relatively flat. There are, however, a couple of exceptions. Near Bruges, we see the start of the higher sandy and sandy loam soils, which mark the end of the low-lying coastal zone. In the south-west, we clearly see the dunes between De Panne and Nieuwpoort. This thick strip of dunes is part of a natural coastal defence against floods. More to the north, we see again a similar strip of dunes between Oostende and Blankenberge and near Knokke. All the way up to the north, there is a tidal inlet at the border with the Netherlands, called the Zwin (Mertens et al., 2010). Moreover, other higher parts of the coastal zone that can be seen in Figure 2.4 can be defined as built up areas in and around the coastal cities.

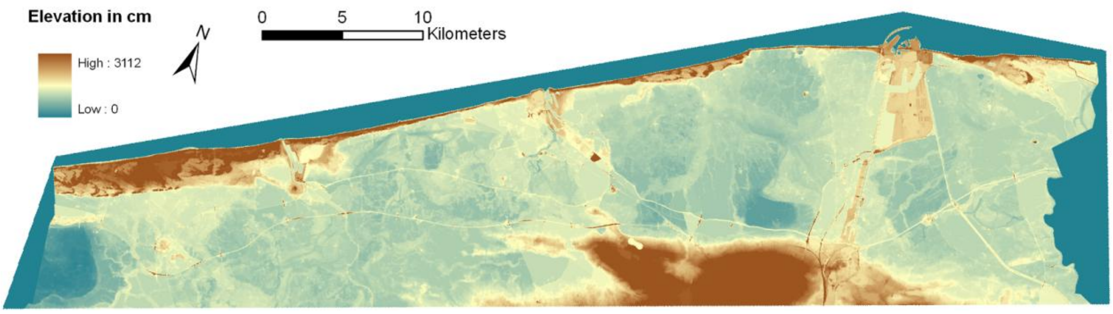

Figure 2.4. Digital Elevation Map of Coastal Flanders

3 Future developments

When one wants to correctly measure the effectiveness of spatial adaptation measures, a valuable tool is the use of scenario analysis. Scenarios provide alternative views of the future, which can be used to test the influence of, for example, adaptation measures (Carter et al., 2001). In this report, we will be using different socio-economic and climate scenarios to measure the effect of spatial adaptation measures for the Belgian coastal zone in the future. As described by Berkhout et al. (2001), climate impact assessments require a clear picture of both climate and socio-economic changes. Combining the two makes it is possible to evaluate the exposure to harm from climate change and how future societies may adapt to these impacts. To do this, the socio-economic scenarios will be used as input for the land-use model to simulate several land-use projections for Flanders, whereas the climate scenarios will be used to determine different possible inundation levels in the coastal area.

3.1 Socio-economic scenarios

In the second valorisation report (VR2) of the CcASPAR project (De Moel et al., 2012), we set up four socio-economic scenarios for the future of Flanders. These scenarios are used to develop four future land-use maps of Flanders. These scenarios are based on the quadrants of the two axes developed by SRES (IPCC, 2000) and used, amongst others, by WLO in the Netherlands (WLO, 2006). These two axes define the scale at which society makes decisions and policy (national vs. international) and the involvement of central government to steer developments (public vs. private). The narratives are in broad lines similar to those as in other studies, but are made Flanders specific. Below a brief explanation of each scenario:

<u>Global Economy (A1)</u>

The Global Economy scenario is characterized by a relatively weak governmental influence and strong globalisation. The Global Economy scenario has the largest growth in population and economy, resulting in the largest pressure on the finite amount of land in Flanders. Because of scaling up processes and increased global trade, agricultural land use is the least competitive and is the main component making space for other components. Environmental awareness is relatively low and nature is not seen as an important land use.

<u>Transatlantic Market (A2)</u>

In the Transatlantic Market scenario, there is a relatively little governmental interference, but unlike the A1 scenario, there is a more regional focus. Population growth is relatively low in this scenario compared to A1 due to less immigration, but because of strong reduction in the size of households, there is still a decent demand for new residential land use. The regional character of this scenario puts agriculture at a higher priority because of the wish to remain (largely) self-sufficient in food production. Combined with low environmental consciousness, this means that natural areas are under strong pressure to convert to other types. Areas of cultural heritage are protected up to a certain degree because of the regional focus of this scenario.

<u>Strong Europe (B1)</u>

In contrast to the A2 scenario, the Strong Europe scenario is characterized by strong governmental influence and globalisation. This globalisation results, via immigration, in a strong demand of urban land use, though the reduction household size is not as big as in the A-scenarios. Urban development is, however, much more steered to combat urban sprawl and develop compact cities. Also designated natural areas are much better protected, though this is less the case for cultural heritage. Like in the A1 scenario, agricultural land use is the least competitive and most likely to decrease.

Regional Communities (B2)

The Regional Communities scenario denotes strong governmental influence and a regional focus. Like in the B1 scenario, environmental consciousness is large in this scenario. This result in the protection of natural areas (VEN), but also areas of cultural heritage are considered important. The amount of urban development is the least in this scenario, because of low population growth, low immigration and a limited reduction in household size. The focus of new nature development is on the combination with agriculture in order to limit foreign dependency for food security.

Figure 2.3 show the future land-use projections, based on the four socio-economic scenarios, for the coastal area of Flanders. In the A-scenarios, we see a typical pattern of urban sprawl occurring and a strong increase in the typical Flemish ribbon development, as expected in these scenarios. For coastal Flanders, this pattern is the most visible in the outskirts of Bruges, where new residential areas are build in former pastures and cropland. In contrast, the B-scenarios show much denser residential areas, which is expected with more strict policy rules. Moreover, we see in the A-scenarios a large increase in recreational nature areas. This increase is not only in the coastal areas at the expense of core nature areas, but also at the expense of pastures and cropland around the larger cities.

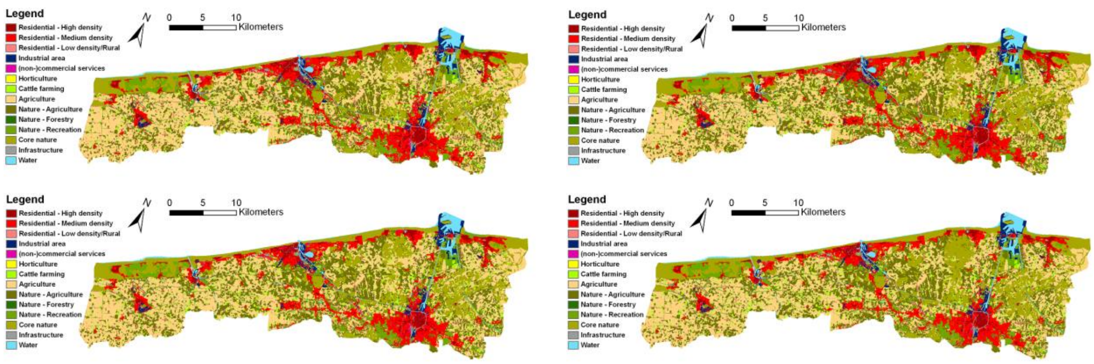

Figure 3.1. Land use of Coastal Flanders in 2040, according to the four different scenarios. Clockwise starting in the upper left corner: A1, B1, A2 and B2.

In all scenarios we see an increase in built up area, ranging from a large increase in the Global Economy scenario to a relative small increase in the Regional Communities scenario. Still, in all future scenarios we see a stronger pressure on the available land, varying from the need for residential area in the more trade-oriented scenarios, to the need to preserve nature area in the somewhat more self-sufficient scenarios. For an extensive explanation of the scenarios, we refer to the second valorisation report (De Moel et al., 2012).

3.2 Climate change

The last decades, we've seen a change in the earth's climate and a rise in global mean sea level. From 1961 to 2003, there was an average rate of sea level rise between 1.3 and 2.3 mm yr^{-1} (Bindoff et al., 2007). For the Belgian coast in particular, we observed the last century a mean sea-level rise of approximately 1.7 mm yr^{-1} (Ozer et al., 2008). As it is expected that climate change and sea-level rise will continue (IPCC, 2007), the danger of flooding will increase for the Belgian coast. For the coast of Flanders, a mean sea level rise of at least 60cm can be expected by 2100 (Ponsar et al., 2007). Consequently, this can result in an increased flood probability due to higher sea levels, waves and storm surges.

At present, some parts of the coastal defence system of the Belgian coast can utmost withstand a storm surge with a probability of occurrence of once every 100 years (Verwaest et al., 2008). In the integrated Master Plan for Coastal Safety, however, it was stated that the government of the Flemish region defined a minimum safety level of the coastal defence at once in every 1000 years. Unfortunately, this safety standard is not implemented in any law or decree (Mertens et al., 2008). More than half of the Flemish coast is protected against flooding by reinforcement measures, such as dikes, jetties, weirs, locks and quay walls (Belpaeme and Konings, 2004). Nevertheless, some weak links have been identified along the Flemish coast line (Van der Biest et al., 2009). In every harbour and in several coastal cities, the quay walls and dyke levels are not able to withstand extreme storms, resulting in an overflow or breach during storm surges (Mertens et al., 2011). See Figure 3.2 for the possible breaches in the Belgian coast that will be used in this study.

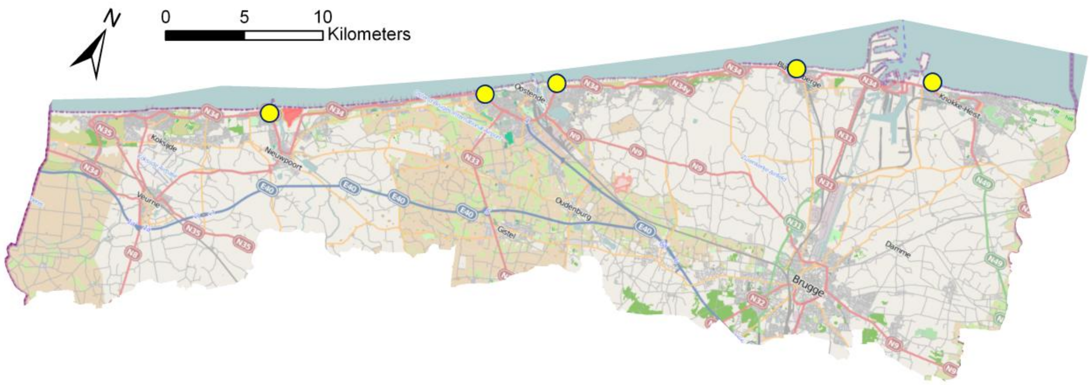

Figure 3.2. Weak links for the Belgian coast. From left to right: Nieuwpoort, Ravenszijde, Bredene, Blankenberge and Knokke-Heist.

To estimate future changes in flood probabilities along the coast of Flanders, we used two climate scenarios, based on a moderate and worst case scenario defined in the CLIMAR project for the Belgian coast (Ponsar et al., 2007). These scenarios are calculated for both 2040 and 2100. Moreover, these two scenarios are similar to the ones used in Van der Biest et al. (2009).

Table 3.1. Climate scenarios for coastal Flanders (after 2100)

	M – 2040	M – 2100	W – 2040	W – 2100
Air temperature	+ 1°C	+ 2°C	+ 2°C	+ 4°C
Sea water temperature	+ 1,2°C	+ 2,5°C	+ 1,7°C	+ 3,5°C
Change in air circulation	Yes	Yes	Yes	Yes
Change in wind speed	+ 2%	+ 4%	+ 4%	+ 8%
Change in winter precipitation	+ 7%	+ 14%	+ 14%	+ 28%
Change in summer precipitation	– 10%	– 20%	– 20%	– 40%
Average sea-level rise	30 cm	60 cm	50 cm	200 cm

As can be seen in Table 3.1, Scenario ‘M’ is a scenario with moderate changes in climate, whereas Scenario ‘W’ is a worst case scenario with extreme changes in temperature, precipitation and sea-level rise. These climate scenarios will be used to define the amount of water inflow per breach and the related inundation levels in the area.

4 Methodology

To analyze the effect of spatial adaptation measures for the Belgian coastal zone, a modelling framework is set up to assess their effects in both the current and future situations, taking possible future climate and socioeconomic changes into account. To do this, flood risks will be calculated for the current and possible future situations, with and without spatial adaptation measures. In general terms, flood risk can be defined as a combination of the probability of a flood event and its consequences (Kron, 2002; Samuels & Gouldby, 2005). More specifically; the flood risk is a function of the flood hazard's probability, the exposure and the vulnerability of the exposed socioeconomic system (Klijn et al., 2004, Samuels et al., 2006). Consequently, the flood risk will be expressed in terms of the expected annual damage (EAD) of flooding in a certain region, one of the common risk indicators used (Meyer et al., 2009; Ward et al., 2011). The expected annual damage can be defined as the sum of all possible flood risks or the integral below the probability-loss curve (see formula 1). To calculate this expected annual damage, we will be using a combination of a land-use model, inundation model and a damage model. For a consistent comparison between all the possible outcomes, a comparison will be made in terms of relative changes in flood risk. The comparison using relative changes is chosen as research shows that relative changes are more robust (Bubeck et al., 2011).

$$EAD = \sum_{i=1}^{n} \left(\frac{D_i - D_{i+1}}{2}\right) + (P_{i+1} - P_i) * D_{i+1} \tag{1}$$

Equation (1) with:

EAD = Expected Annual Damage

n = number of flood events

i = flood events

D = Damage for flood event

P = Probability for flood event

Figure 4.1 presents an overview of the modelling framework which is used in this study. To begin with, land-use maps and inundation maps will be created, which need respectively a land-use model and an inundation model. Following, a map with flood damages will be created with the use of the damage model, which combines the land-use maps and inundation maps with information of the vulnerability of the different land-use classes to flooding. Finally, with the calculated flood damages and the regarding flood probabilities, the Expected Annual Damage is calculated as defined in formula (1). The spatial adaptation measures will both be implemented on the input side of the model. Land-use zoning is expected to influence the land-use patterns (and will thus be implemented in the land-use model), whereas compartmentalization is expected to influence the inundation patterns of the area (and will thus be implemented in the inundation model).

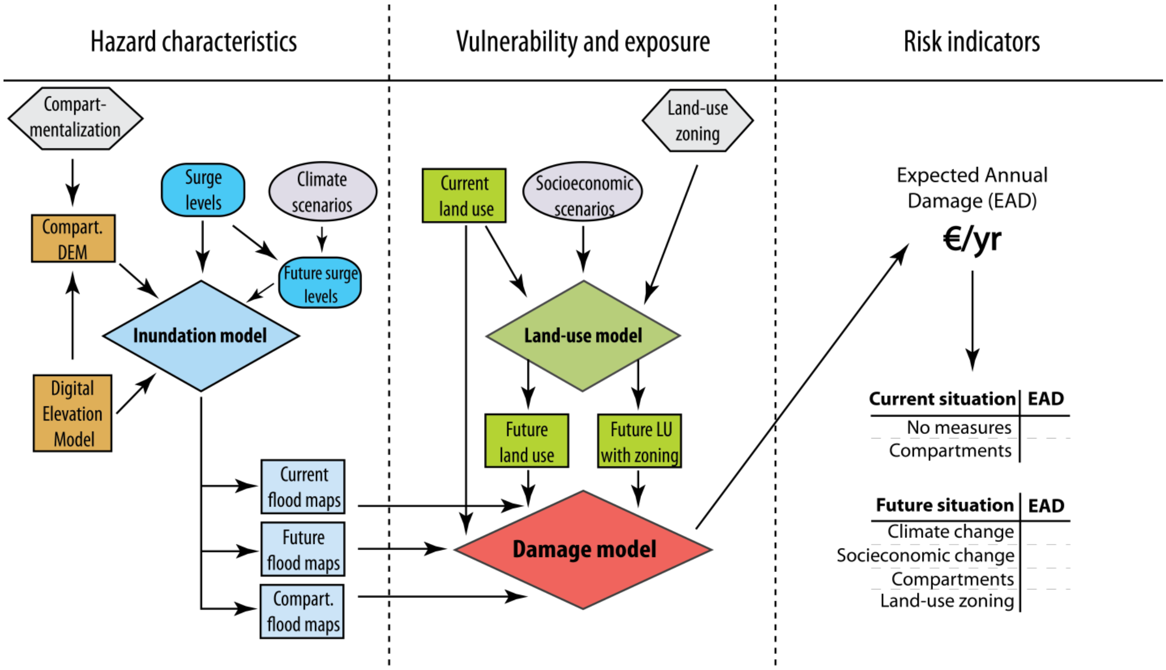

Figure 4.1 Schematic representation of the used modelling framework.

4.1 Land-use model

The land-use model that will be used for the coastal area is based on the Land Use Scanner for the whole of Flanders, which is a GIS-based land-use model that simulates future land use. The Land Use Scanner is developed to integrate and allocate future land-use demand from different sector-specific models or experts (Dekkers and Koomen, 2007; Hilferink and Rietveld, 1999). External regional projections of land-use change, which are usually referred to as demand or claims, are used as input for the model. These are land-use type specific and can be derived from, for example, sector-specific models. The projected land-use changes are considered as an additional claim for the different land-use types as compared with the present area in use for each land-use type. The total of the additional claim and the present area for each land-use function is allocated to individual grid-cells based on the suitability of the cell. This local suitability may incorporate a large number of spatial datasets such as the current land use, physical properties, operative policies and market forces (generally expressed in distance relations to nearby land-use functions) (see Figure 4.2 for an overview of the model). For the future land-use projections, we use the four socioeconomic scenarios of Flanders, as described in Section 3.1. For a complete explanation how this model works and how the land-use maps are created, the reader is referred to VR2 (De Moel et al., 2012). However, in contrast to De Moel et al. (2012), only future projections are made for the province of West-Flanders. Consequently, claims used in De Moel et al. (2012) were recalculated from the whole of Flanders to West-Flanders specific. This made it possible to better steer the projections according to the future socioeconomic scenarios as described in Section 3.1. For this analysis, calculations are made for the years 2040 and 2100. For 2100, the same land-use maps are used as for 2040. The main reason for that choice is the high uncertainty of how land use will develop in the next 90 years (Klijn et al., 2012).

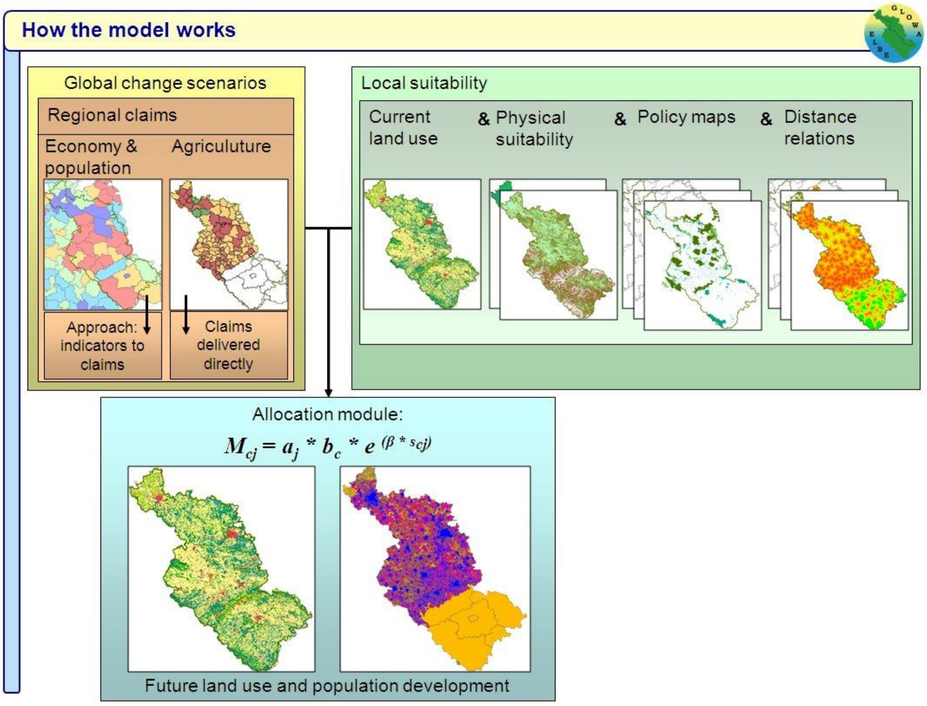

Figure 4.2. Basic layout of the Land Use Scanner model (GLOWA-Elbe project, 2012)

4.1.1 Land-use zoning

Additionally, the model will be extended by implementing a spatial adaptation measure: land-use zoning. Land-use zoning can be defined as the concept of local planning and restrictive building of, for example, residential and industrial area. With more local planning and more restrictive building, there are possibilities to reduce the flood risk in a region. For example, instead of building in the areas with the highest inundation depths, new building sites are restricted to areas with relatively low or no inundation. Areas with a high flood probability and high inundation depths can, for example, better be used for nature of recreational land-use then for residential or industrial land-use.

Figure 4.3 Areas (in red) which are not suited for future developments in built-up area.

The concept of zoning will be implemented in the land-use model by restricting certain areas for future residential, (non-)commercial and industrial development. This is done by giving a negative local suitability to the areas defined in Figure 4.3. These restricted areas have either high flow velocities (i.e. areas very close to weak links in the coastal defence) or high inundation depths. Due to the restriction of building in these areas, we expect to reduce the consequences of floods and consequently the flood risk itself for coastal Flanders.

4.2 Inundation model

The inundation model that is used to determine the amount of inundation in the coastal area is based on the inundation model developed by De Moel et al. (2012). As can be seen in Figure 4.4, first the hydraulic load, which is the water level during a storm surge event, and the size of the breach have to be determined. This is needed to estimate the volume of water flowing into the area after a breach. The amount of inflowing water depends on both the size of the breach and the difference in water level outside and inside the embankment. This difference in water level determines both breach growth and discharge through the breach. The material of the embankment itself also plays in important role in how fast the breach grows. The total amount of water which enters through the breach is calculated by integrating the discharge through the breach over time.

The next step, the inundation model itself, calculates the maximum inundation depth of an area after flooding, given the total volume calculated with the use of the hydraulic load and breach growth. The inundation model is mainly based on an inundation model, in this case the ´Digitaal Hoogte Model´, which has a resolution of 10m by 10m and gives elevation in centimetres above TAW. The first step in the model is to split the area into numerous individual micro-basins. In total, the coastal area was divided into thousands of micro-basins, varying in size between 100 m^2 for areas with a lot of relief and 15 km^2 or more for large flat polder areas. After this, the total volume is divided 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 of the inundation model, the reader is referred to De Moel et al. (2012). Important to note, is that this model is only being used for ‘inner dike’ areas. For the port areas (e.g. Zeebrugge), this flood simulation was not possible, because they have an open connection to the sea. Therefore, these areas are entirely inundated by the maximum water level of the storm surge.

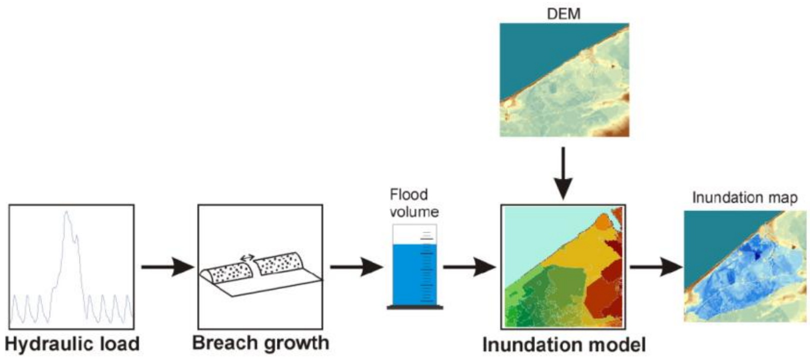

Figure 4.4 Basic layout of the Inundation model, based on the framework developed in De Moel et al. (2012)

In this study, several inundation scenarios have been used to simulate possible floods in coastal Flanders, based on Willems (2007). In Figure 4.5, the blue line represent the used return periods for the baseline situation in this study, varying from flood probabilities of 1/100 up to 1/100000. To extrapolate these water heights to future scenarios, we added the amount of sea-level rise (in centimetres) to the probability curve of the baseline situation, resulting in higher water levels for the different return periods.

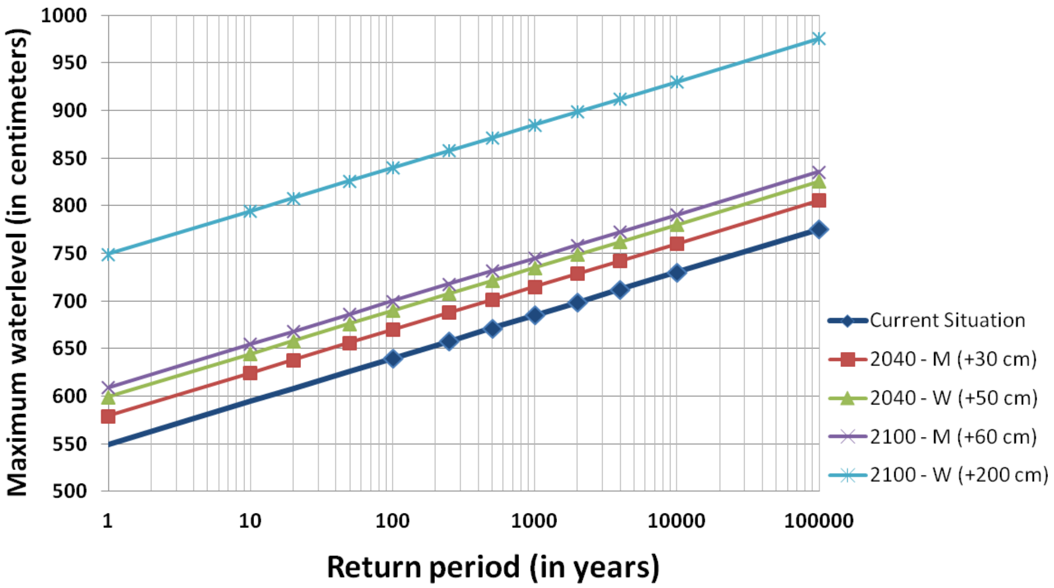

Figure 4.5 Overview of the different maximum water heights per return period for the baseline scenario.

4.2.1 Compartmentalization

Compartmentalization can be defined as the splitting of a 'system' in multiple parts. In the case of flooding, compartmentalization can be used to diminish the surface area that will be flooded due to a single flood event. Consequently, by reducing the surface area that will be flooded, the consequences of a flood will be smaller and the flood risk will reduce (Klijn et al., 2010). The most convenient way of implementing this adaptation measure is to use, for example, old dikes, roads, railways, and other line elements that are already present. This is also in line with various other studies (Alkema and Middelkoop, 2005; Oost and Hoekstra, 2009; Theunissen et al., 2006) Often, these structures are already higher in the landscape and can thus be relatively easy transformed into secondary water defence structures. In this study, two types of compartmentalization will be tested. In the first compartmentalization measure (which will be named 'Compartments'), we raised each line element up to the maximum current height of the element to close the line element. By doing this, we created for the whole coastal region enclosed compartments. For the second compartmentalization measure (which will be named 'Compartments Plus'), we raised the created line structures of the first compartmentalization measure by another one meter.

To implement the concept of compartmentalization into the model, two new digital elevation maps have been created with closed/elevated line elements. In these new digital elevation maps, we made use of line structures that are already elevated in the map. See Figure 4.6 for an overview of the used line elements.

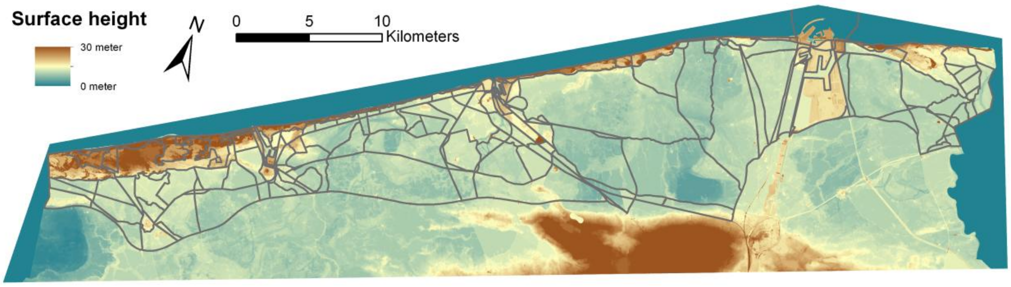

Figure 4.6 Digital Elevation Map of Coastal Flanders with compartmentalization

4.3 Damage model

The final part of the calculations is to estimate the flood damage in the area. This can be calculated with the input maps that are created in the previous two models. To determine the amount of flood damage, we created a damage model which is based on the Damage Scanner. This model has originally been developed by De Bruijn (2006) and calculates the damage per land-use class, with the use of a land-use and inundation map. These maps are then combined using depth-damage curves and maximum damages per land use class. For each land-use class, there is a different maximum amount of possible damage and a different damage function. These depth-damage functions indicate the vulnerability by relating the inundation depth to a damage factor, which constitutes the fraction of the maximum damage that will be sustained at that inundation level (Koks et al., 2012). For a more detailed description of the Damage Scanner the reader is referred to De Bruijn (2006), Bouwer et al. (2009) and De Moel and Aerts (2011).

The maximum damages and damage functions were created using various sources. As can be seen on the land-use map in Figure 2.2, maximum damages and damage functions need to be defined for the thirteen land-use classes that are used in this study. First, we will derive the maximum damages based on the maximum damages defined in various other studies (e.g. de Bruijn, 2006; Klijn et al., 2007; Koks et al., 2012; Vanneuville et al., 2006). After that, we can define the depth-damage curves that are needed to correctly assess the flood damage that corresponds to a specific inundation depth.

4.3.1 Maximum damages

Maximum damages have been defined for each land-use class considered by the land-use model (see Table 4.1). The values are based on existing models and studies from the Netherlands (Kok et al., 2005; Tebodin, 1998, 2000), the United Kingdom (Penning-Rowsell et al., 2010), Belgium (Vanneuville et al., 2006) and the United States (FEMA, 2007). For the calculation of maximum damages for the residential land uses, industrial sites and (non-)commercial land use, maximum damages from the Multi-Coloured Handbook (Penning-Rowsell et al., 2010), HAZUS damage model (FEMA, 2009) and Dutta et al. (2003) have been applied into this study. For each of these land-use classes, three types of damages are used: the maximum damage of the structure of the building, the maximum damage of the content of the building and the maximum damage of the area between each building (open space). To get a maximum damage for a land-use type, a weighted sum is taken from these three maximum damages. The share of building/content/open space is used as weight and taken from a high resolution land-use map (Top10vector).

For (non)-commercial services, however, this approach was not as straight forward as for residential and industrial land use. A similar approach is conducted, but with the addition of taking the share of each type of land use within this land-use class into account (i.e. commercial, cultural, sports and governmental land use). This resulted in a weighted average for the maximum damage of these different land uses. For the different port industries, the maximum damages are based on studies from Tebodin (1998, 2000). Finally, the maximum damages for the different types of natural land use (e.g. core nature and forest) are set to zero, since no economic value can be attached to these areas. This is consistent with studies of Briene et al. (2002), Trouw et al. (2005) and Vanneuville et al. (2006).

Table 4.1 Maximum flood damage per land-use class

	Land-use class	Max damage per m^2 (in Euros)
1	Residential – high density	560
2	Residential – medium density	300
3	Residential – loose buildings & ribbons	300
4	Roll-on Roll-off industry	490
5	Container terminals	540
6	Break bulk cargo	690
7	Bulk terminals	340
8	Chemical industry	390
9	Gas industry	390
10	Transport Industry	490
11	Food industry	490
12	Other port industry	490
13	Industrial sites	740
14	(non-)Commercial services	750
15	Horticulture	65
16	Cattle farming	0.1
17	Agriculture	0.5
18	Nature – Agriculture	0.5
19	Nature – Forestry	0
20	Nature – Recreation	0.03
21	Core nature	0
22	Infrastructure	40
23	Water	0

4.3.2 Depth-damage curves

In this study, depth-damage curves are being used to calculate the flood damage per land-use for a specific flood. Each damage function used is defined by its land-use class. Residential land use, industrial sites and (non-)commercial land use have the same depth-damage curve, derived from the Multi-Coloured Handbook (Penning-Rowsell et al., 2010), HAZUS model (FEMA, 2009) and Dutta et al. (2003).

As can be seen in Figure 4.7, the 'Built-up Area' curve grows fairly quickly up to 1.5 meter. After that, it slows down up to three meters of inundation, where after it shortly grows much quicker again. The reason for this is that we expect that around three meters of inundation, we arrive at the first floor of the building, where new content and parts of the structure will be destroyed (De Moel et al., submitted). The depth-damage curve for horticulture is based on the assumption that glass green houses will get more easily destroyed than the concrete buildings in the normal built-up area, but slower than agricultural land use. For this depth-damage curve, we assume that up to half a meter the damage increases fairly quickly, but after that it will increase somewhat slower until it will reach the maximum damage around 3.5 meters of inundation. €/m2

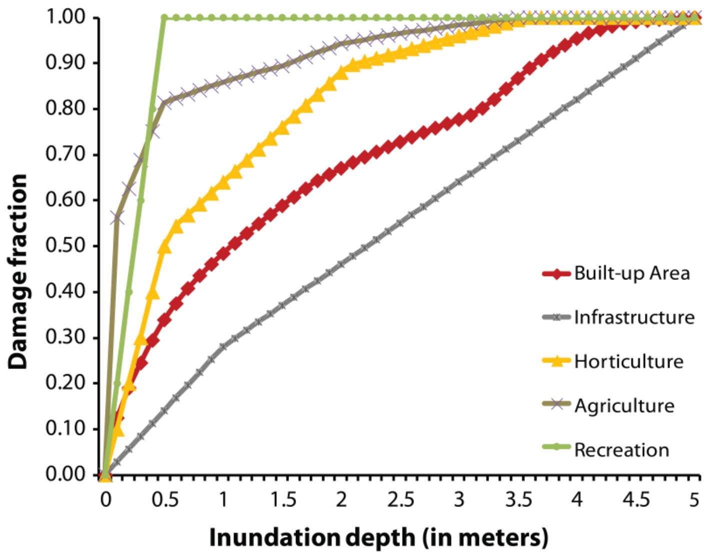

Figure 4.7 General depth-damage curves for the damage model

Infrastructure is expected to increase fairly linear, following Kok et al. (2005). Cattle farming, agriculture and nature-agriculture are all clustered in the 'agriculture' curve, based on Koks et al. (2012) and Hoes (2007). Since crops and grass grow often very near the ground, it is expected that most of the damage will already occur in low inundation depths. For recreation, the curve is based on depth-damage curves created by Vanneuville et al. (2005). It is assumed that after a low inundation depth, no extra damage will occur. The only costs that will occur are clean-up cost. For the other nature land uses and water, no depth-damage curves are created, as it is expected that no damage occurs to these land uses. For the different industrial land-use classes in ports, the depth-damage curves are based on Tebodin (1998, 2000). See Figure 4.8 for an overview of the used depth-damage curves for these classes.

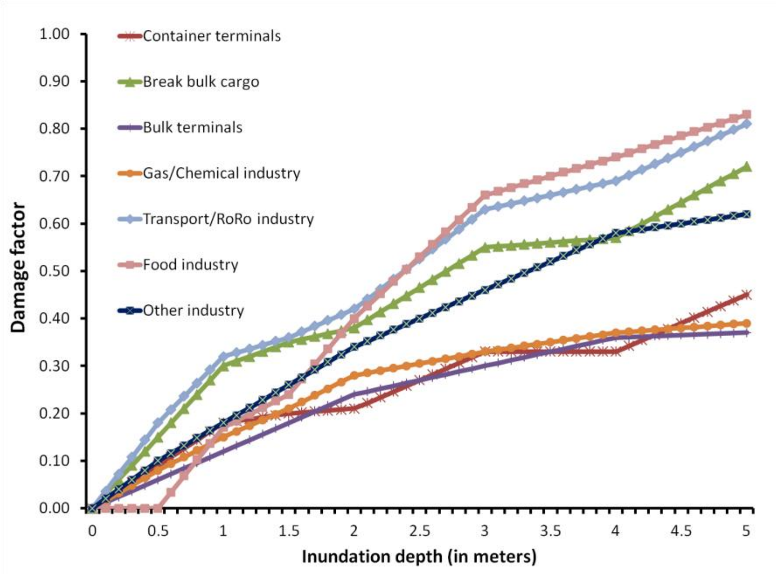

Figure 4.8 Industrial depth-damage curves for the damage model

5 Results

In this chapter, we will describe the results of the analyses. We will start with briefly describing the damage calculations for the reference situation (the land-use map for the year 2005 combined with floods in the baseline situation). These reference calculations are then used to compare the results for the future land-use maps, the future climate scenarios and the spatial adaptation measures. Finally, results will be described where ports are taken into account.

5.1 Baseline situation (2005)

For the reference situation, flood damages are calculated by using the land-use map of the year 2005 and flood events with return periods as shown in Figure 4.5 (i.e. return periods from 1/100 up to 1/100,000). Figure 5.1 shows an example of the results. As can be seen in the figure, a storm with a probability of 1/100,000, most of the flood damage occurs around Oostende. Interestingly, the highest inundation depths can be found near Blankenberge, with depths up to 125 centimeters for most of the inundated area. This is in contrast to the other breaches, where often only a small part of the area has large inundation depths. However, as most of the damage near Blankenberge occurs outside the built-up area, the damage is rather low.

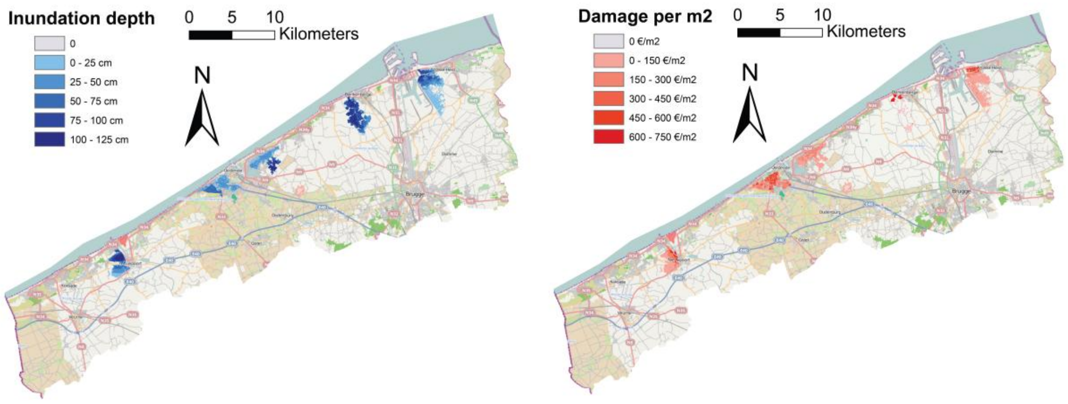

Figure 5.1 Inundation depth and flood damage for coastal Flanders in the baseline situation with a 1/100,000 flood event

Table 5.1 shows the total results for the baseline situation. The total expected annual damage for the coast of Flanders is approximately 25 million euro per year. As can be seen from the fourth column (EAD for residential area), almost all of the damage occurs in residential area. The agricultural area clearly has the lowest share in the total damage, with less than 0.02 million Euro per year. The breach south west of Oostende has the highest share of damage, taking up almost 60% of the total damage. This is related to a large amount of built-up area and a relatively large inundated area. Interesting is to compare the total EAD with the average area inundated area per breach. The average area inundated is the arithmetic mean over the inundated area of the eight flood events used in this study. Even though the southern breach near Oostende clearly has the highest share in expected annual damage, it has only a 1% higher share in the average inundated area compared to the second largest inundated area (the northern breach near Oostende). This is in contrast to a difference of three times in expected annual damage between the two breaches. Notable is also the large share of industrial damage in Nieuwpoort, which makes up a quarter of the total damage there, much more than at the other breach locations.

Table 5.1 Expected Annual Damage for the baseline situation (in brackets the share of each breach compared to the total number at the top of each breach)

	EAD (10^6 €/yr)		Average area inundated (in km^2)		EAD for residential area (10^6 €/yr)		EAD for industrial area (10^6 €/yr)		EAD for infrastructure (10^6 €/yr)		EAD for agricultural area (10^6 €/yr)	
Total	**25.4**		**17.2**		22.6	(89%)	2.1	(8%)	0.5	(2%)	0.02	(0.1%)
Nieuwpoort	2.1	(8%)	1.6	(9%)	1.58	(75%)	0.52	(25%)	0.03	(1%)	0.002	(0.10%)
Oostende SW	14.7	(58%)	5	(29%)	13.01	(89%)	1.3	(9%)	0.31	(2%)	0.002	(0.01%)
Oostende NE	4.9	(19%)	4.8	(28%)	4.65	(95%)	0.1	(2%)	0.1	(2%)	0.01	(0.22%)
Blankenberge	0.65	(3%)	3.1	(18%)	0.63	(97%)	0.01	(2%)	0.01	(2%)	0.002	(0.31%)
Knokke-Heist	2.93	(12%)	2.7	(16%)	2.74	(94%)	0.15	(5%)	0.04	(1%)	0.001	(0.03%)

As the circle diagram on the left hand side of Figure 5.2 shows, almost 50 percent of the inundated area is built-up area and more than 30 percent farmland. Even though the built-up areas take up 'only' 47 percent of the inundated area, the sum of these categories takes up almost 100 percent of the expected annual damage. This is in expense of the agricultural and nature areas, which is mainly the result of the much higher maximum damages for the built-up areas.

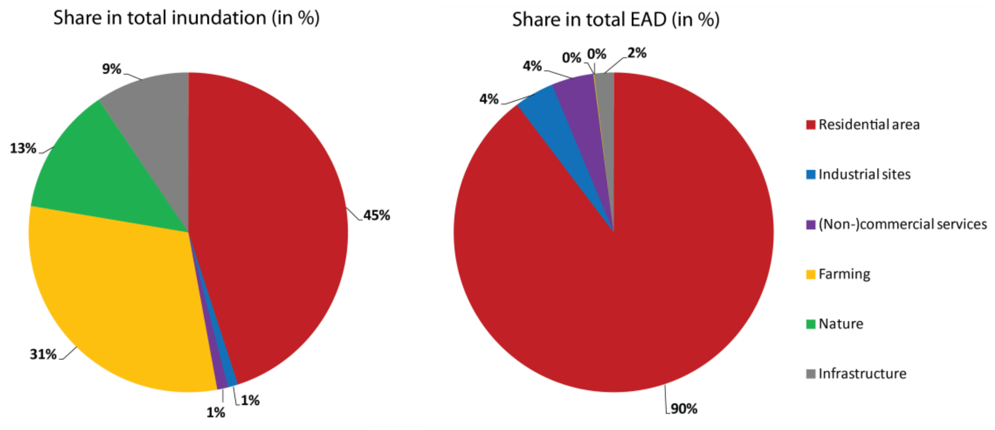

Figure 5.2 Amount of inundation per land use versus the EAD per land use in the baseline situation

5.2 Future scenarios

Expected annual damages for the future scenarios are calculated using the estimated damages under future land-use change and changes in sea-level rise due to climate change. For each scenario, a significant increase in flood risk can be observed. As can be seen in Table 5.2, most of the increase in expected annual damage occurs due to socioeconomic changes rather than climate change. For the year 2040, climate change only results in a 5-7% increase in damage, while socioeconomic changes result in a 33-41% increase in expected damage. The M-scenario in 2100 shows similar results, which is not surprising given that the sea-level rise of 60cm is not too different from the W-scenario for 2040 (50cm). The W-scenario for 2100, however, has a much larger sea-level rise assumption (200cm) and shows completely the opposite. Here, climate change results in a 65% increase in damage, compared to a 33-41% increase in damage due to socioeconomic changes. Regarding the differences in in the share of each breach location to the total EAD, the share of Oostende stays similar for all scenarios except for the worst-case scenario in 2100. In the worst-case scenario for 2100, the share of Oostende in the EAD decreases with almost 10%, while the other breach locations all increase with a couple percent. This indicates that a 2 meter sea-level rise results in a relatively low increase in flood damage for the Oostende region in comparison with the other breach locations.

Table 5.2 Expected Annual Damage (10^6 €/yr) and percent change (between brackets), under climate change, socioeconomic change, and combination.

	Socioeconomic scenario										
		Baseline (2005)		A1		A2		B1		B2	
Climate scenario	Baseline situation	**25.3**		35.8	(+41%)	34.6	(+37%)	35.5	(+40%)	33.6	(+33%)
	M-Scenario 2040	26.6	(+5%)	38.0	(+50%)	36.7	(+45%)	37.7	(+49%)	35.6	(+41%)
	W-Scenario 2040	26.9	(+6%)	38.5	(+52%)	37.2	(+47%)	38.2	(+51%)	36.0	(+42%)
	M-Scenario 2100	27.1	(+7%)	39.0	(+54%)	37.6	(+49%)	38.6	(+52%)	36.4	(+44%)
	W-Scenario 2100	41.7	(+65%)	68.4	(+170%)	64.7	(+156%)	67.9	(+168%)	59.3	(+134%)

When plotting the storm surge height versus the flood damage (Figure 5.3), it becomes clear that between 7.8 en 8 meters of inundation, a significant increase in damage occurs. This is in contrast to the storm surge heights between 6.5 and 7.8 meters and between 8 and 9.5 meters, where only a relatively slow increase in flood damage is observed. This implies that after a storm surge height of 7.8 meters, the inundated area increases considerably. Results show that this is indeed the case for the breaches near Oostende and Blankenberge.

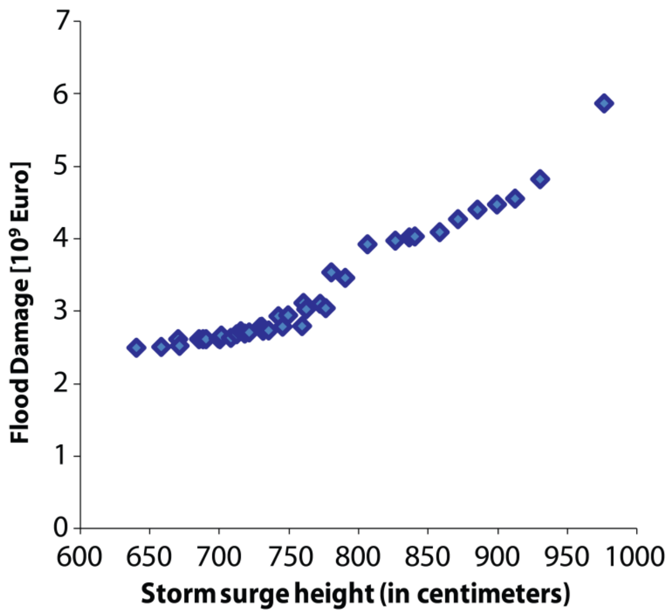

Figure 5.3 Storm surge height versus flood damage in billions of Euros

The increase in damage due to socioeconomic changes is mainly the result of increases in residential areas. For all the scenarios, the increase in residential areas account for between 65-70% of the increase in flood risk. Similar to the baseline situation, this is again at the expense of agricultural and natural area. Figure 5.4 illustrates the contribution to the change in expected annual damages from climate change only (red), socioeconomic change only (green) and the combination of both impacts (purple) for scenario A1. The base risk (blue) reflects the situation for he baseline (2005). As can clearly be seen from the figure, the influence of the socioeconomic change is for the 2040-scenarios and the M-scenario for 2100 significantly larger than changes in climate, while for the W-Scenario in 2100 the influence of climate change is significantly larger. Even though this graph only shows the changes for the A1-Scenario, the contributions of both socioeconomic and climate change are for the other socioeconomic scenarios similar.

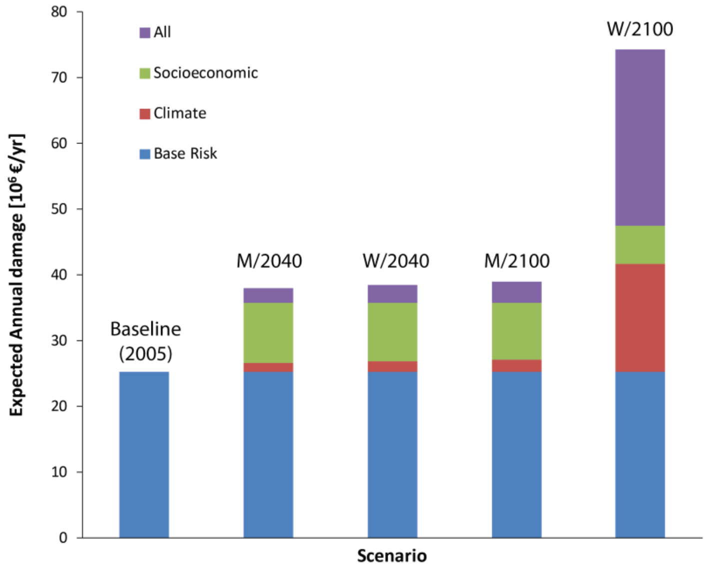

Figure 5.4 Projected expected annual damages for the A1-scenario compared to the baseline (2005) and their components.

5.3 Spatial adaptation measures

5.3.1 Compartmentalization

As described in section 4.2.2, two different compartmentalization measures will be tested in this study. In the first compartmentalization measure (‘Compartments’), each line element is raised to the highest elevation of that line element. By doing this, we created for the whole coastal region enclosed compartments. For the second compartmentalization measure (‘Compartments Plus’), the created line structures of the first compartmentalization measure are raised by one meter. Figure 5.5 shows the result of both measures for the southern breach near Oostende and the breach near Blankenberge for a flood event with a probability of 1/2000 without climate change. As can be seen, the results differ a lot on a local level. At Oostende, the exposure significantly decreases to only a very small area due to compartmentalization. However, as can be seen from the figure, the inundation depth decreases and stays within a certain compartment. At Blankenberge, on the other hand, the inundation extent actually increases due to compartmentalization as floodwater is kept out of a deep polder area and has to find its way elsewhere. The main differences for these two cases are the size of the compartments (much more and smaller compartments around Oostende) and the height of the compartments (the original line structures around Oostende are in general higher). See Figure 4.6 for the overview of all the line structures that are used in this study.

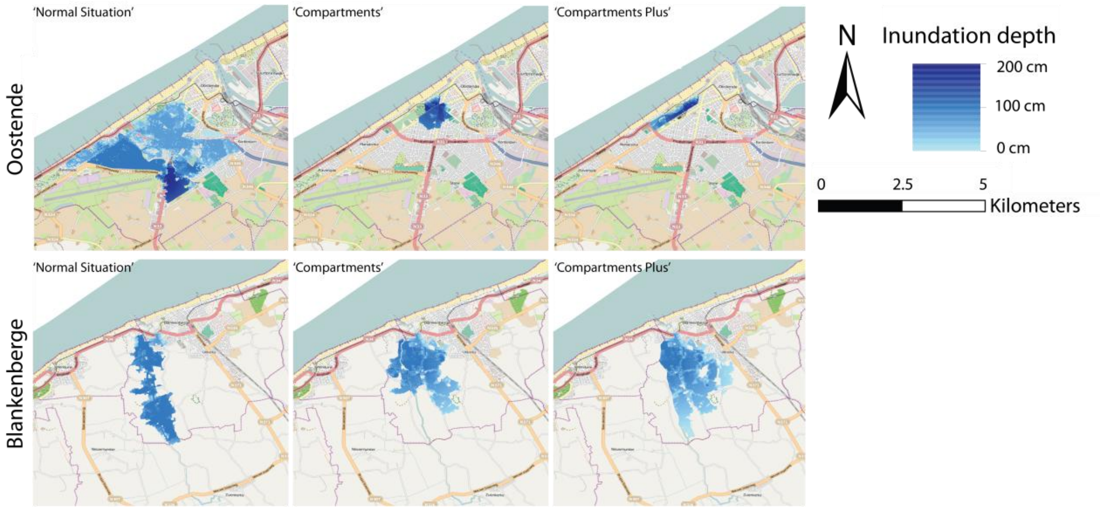

Figure 5.5 Difference in flooding due to compartmentalization for a flood with a 1/2000 probability

For the baseline situation both compartmentalization measures show a significant but more or less similar decrease in flood risk (Table 5.4). Both types of compartmentalization result in a more than 50% reduction in expected annual damage for the baseline situation (Table 5.4). Nevertheless, there are a lot of differences on a local level. For example, the EAD for the breach southwest of Oostende decreased by almost 100%, but increased by almost 80% for the breach northwest of Oostende. Even though the average area inundated increases by only 8%, almost all of this increase occurs in residential area, resulting in a large increase in damage. Interesting is the decrease of the expected annual damage for the breach near Blankenberge, despite the increase in inundated area (Figure 5.5). Due to compartmentalization, the floodwaters are directed around the village instead of through the village of Blankenberge. Although more (low-lying) agricultural land got inundated, the total damage reduced. Overall, the difference of the one meter extra elevation on the line elements (i.e. compartmentalization vs. compartmentalization plus) is rather limited.

Table 5.4 Expected Annual Damage (10^6 €/yr) and average inundated area for the baseline situation with compartmentalization per breach location.

	Baseline (2005)		'Compartments'				'Compartments Plus'			
	EAD (10^6 €/yr)	Average area inundated (in km^2)	EAD (10^6 €/yr)		Average area inundated (in km^2)		EAD (10^6 €/yr)		Average area inundated (in km^2)	
Total	**25.3**	**17.2**	12.2	(-52%)	10.7	(-38%)	12.5	(-51%)	10.3	(-40%)
Nieuwpoort	2.1	1.6	2	(-5%)	1.1	(-31%)	2	(-5%)	1.1	(-31%)
Oostende SW	14.7	5	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	(-66%)	0.8	(-70%)	0.9	(-69%)	0.5	(-81%)

Another option is to compare the compartmentalization measures using loss-probability curves. These curves show all the potential flood damages and their probabilities, including the extreme events. By collating all the flood damages, together with their flood probabilities, a loss-probability curve can be constructed (Figure 5.6). As can be seen in the figure, the baseline curve shows the relation between the flood probability and the amount of damage for the year 2005. Due to compartmentalization, a downward shift of the curve can be observed, indicating that less flood damage occurs for each flood event. Interestingly, even though the expected annual damages for both compartmentalization measures are similar, the ‘Compartments’ measure has a much higher flood damage for the most extreme flood event (p = 1/100,000). However, as the ‘Compartments Plus’ measure has slightly larger damages for the higher probability flood events (on average less than 1% higher), the EAD for both measures are eventually similar.

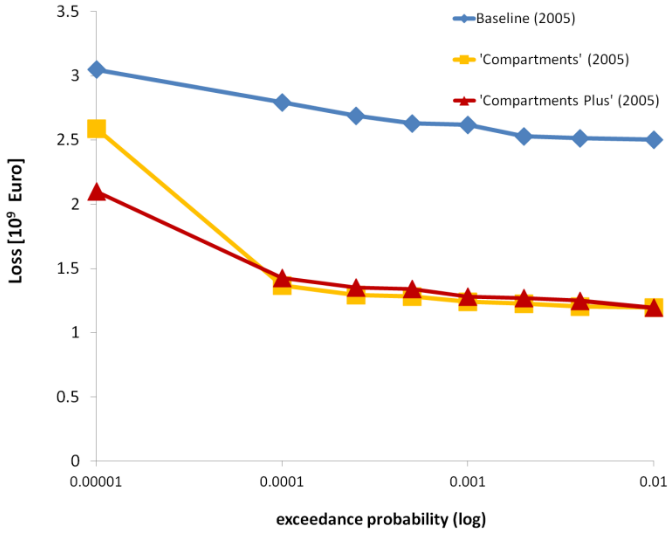

Figure 5.6 Loss-probability curves for the baseline situation with and without compartmentalization measures.

As described in Chapter 4, the compartmentalization measures are implemented in the inundation model. Thus, the measures will affect the result from the different flood events and therefore they will also be clearly visible in the future climate scenarios. For the future scenarios, Table 5.5 and Table 5.6 show the results. As can be seen in the tables, indeed a much lower flood risk is observed for the different scenarios compared to the future scenarios where no compartmentalization is implemented. When looking only to the effect of climate change, three out of four scenarios show an actual reduction in flood risk of about 50%, compared to the 5-7% increase in the ‘no adaptation’- situation (see Table 5.2). For the worst-case scenario in 2100, the reduction because of compartmentalization is much smaller, around 11%, indicating that this measure becomes less effective with really high sea-level rise. Compared to the baseline risk, the risk-reducing effect of compartmentalization would more than offset the adverse effect of sea-level rise on the flood risk for both 2040 scenarios and the M-2100 scenario (13.3-14.2 vs. 25.3 million Euros per year). The W-2100 scenario, on the other hand, would still see an increase in absolute flood risk (37.2 vs. 25.3 million Euros per year). The results for the ‘Compartmentalization Plus’ measure under current land-use (Table 5.6) are very similar to those of the ‘Compartmentalization’ measure. The most notable difference is that the risk reduction for the W-2100 scenario is much larger for the ‘Compartmentalization Plus’ scenario than for the ‘Compartmentalization’ scenario. The risk-reducing effect is there much more in line with the other climate scenarios (-36%). This implies that for high sea-level rise, extra elevation of the line elements is necessary to effectively counteract the increased flood risk.

When looking at the flood risks in the future scenarios where climate change and socioeconomic changes are combined, the results show that compartmentalization would more than offset the increase in flood risk due to socio-economic change. For both 2040 and the M-2100 scenarios, both compartmentalization measures would roughly half the risk as opposed to without the measure. Under these climate change scenarios, compartmentalization would even decrease the flood risk below the baseline level despite the risk increase because of both climate change and socio-economic change. Only under the W-2100 scenario, the combined effect of climatic and socio-economic change is not offset by the compartmentalization measures. Nevertheless, the compartmentalization measures still have a considerable risk reducing effect under the W-2100 scenario, around 25% for 'Compartmentalization' and around 50% for 'Compartmentalization Plus'. This again shows that to combat very high sea-level rise, line elements need to be extra elevated with respect to their current maximum elevation.

Table 5.5 Expected Annual Damage (10^6 €/yr) and percent change (between brackets) for the 'Compartments' measure under climatic and socio-economic change. The change percentages are with respect to the same socio-economic and climate-change scenario without adaptation (see Table 5.2).

		Socioeconomic scenario									
Climate scenario		Baseline (2005)		A1		A2		B1		B2	
	Baseline situation	12.2	(-52%)	16.5	(-54%)	15.8	(-54%)	16.3	(-54%)	15.7	(-53%)
	M-Scenario 2040	13.3	(-47%)	19.0	(-50%)	18.3	(-50%)	18.7	(-50%)	18.1	(-49%)
	W-Scenario 2040	13.7	(-46%)	19.5	(-49%)	18.8	(-49%)	19.2	(-50%)	18.6	(-48%)
	M-Scenario 2100	14.2	(-44%)	20.1	(-48%)	19.3	(-49%)	19.8	(-49%)	19.1	(-47%)
	W-Scenario 2100	37.2	(-11%)	51.2	(-25%)	48.8	(-25%)	51.3	(-25%)	46.1	(-22%)

Table 5.6 Expected Annual Damage (10^6 €/yr) and percent change (between brackets) for the 'Compartments Plus' measure under climatic and socio-economic change. The change percentages are with respect to the same socio-economic and climate-change scenario without adaptation (see Table 5.2).

		Socioeconomic scenario									
Climate scenario		Baseline (2005)		A1		A2		B1		B2	
	Baseline situation	12.5	(-51%)	16.2	(-55%)	15.5	(-55%)	16.0	(-55%)	15.4	(-54%)
	M-Scenario 2040	13.5	(-47%)	17.7	(-54%)	17.0	(-54%)	17.4	(-54%)	16.8	(-53%)
	W-Scenario 2040	13.8	(-46%)	18.1	(-53%)	17.3	(-53%)	17.8	(-53%)	17.1	(-52%)
	M-Scenario 2100	14.1	(-44%)	18.5	(-53%)	17.8	(-53%)	18.2	(-53%)	17.5	(-52%)
	W-Scenario 2100	26.5	(-36%)	35.6	(-48%)	33.9	(-48%)	35.6	(-47%)	32.4	(-45%)

From Figure 5.7 it becomes quite clear that the 'Compartments' measure results in an overall smaller reduction in flood risk than the 'Compartments Plus' measure. For all the future scenarios there is clearly a lower flood risk due to the 'Compartments' measure compared to the 'Compartments Plus' measure. For the worst-case scenario in 2100, the differences are the largest. Although the flood risk doesn't actually decrease compared to the baseline situation, it is clear that the 'Compartments Plus' measure decreases the flood risk the most. Next to that, also the influence of the different socioeconomic scenarios becomes clear. For example, the A1-scenario, which has the highest socioeconomic increases, also has the least reduction in flood risk due to compartmentalization. This is in contrast to the B2-scenario, with the lowest socioeconomic increases. This smaller decrease in flood risk for the A1-scenario can be explained by the larger amount of built-up area in the areas at risk, compared to the B2-scenario. Therefore, the adaptation measures have less effect.

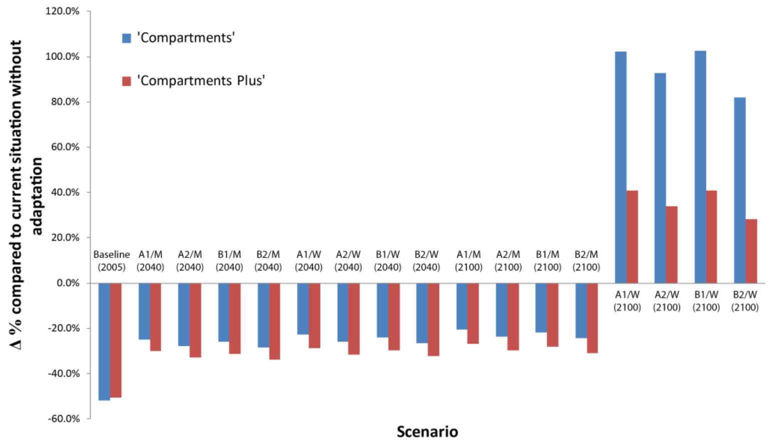

Figure 5.7 Percentage change in flood risk for each scenario in the areas where compartmentalization is implemented

5.3.2 Zoning

As described in section 4.1.2, land-use zoning will be implemented in the land-use model by restricting certain areas for future residential, (non-)commercial and industrial development. These restricted areas are areas that have either high flow velocities (i.e. areas very close to weak links in the coastal defence) or high inundation depths. Due to the restriction of building in these areas, it is expected that the consequences of floods will lower and consequently also the flood risk itself for coastal Flanders. See Figure 5.8 for an example how land use has changed in coastal Flanders.

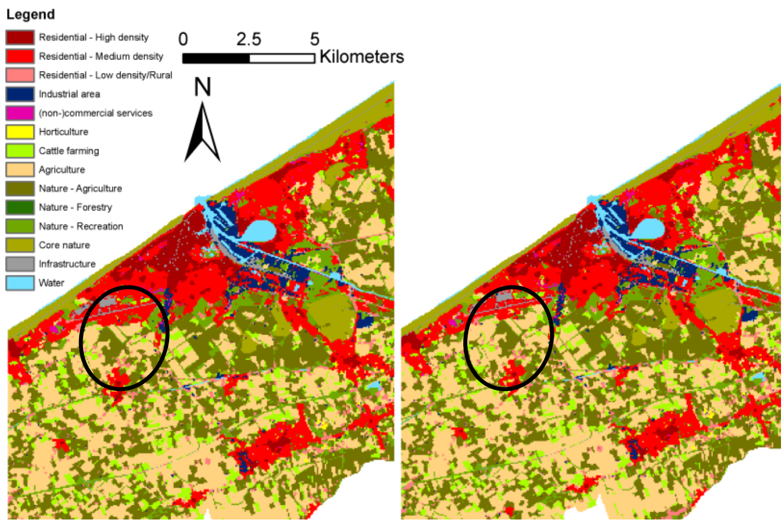

Figure 5.8 Example of land-use zoning near Oostende in the A1-scenario The left panel is a simulation without zoning, and the right panel with the zoning restriction.

Because land-use zoning only restricts future expansion of built-up area, the adaptation measure will not influence the baseline situation. As described in Chapter 4, land-use zoning is implemented in the land-use model. Thus, the measure will affect the future socioeconomic scenarios and not the flood extents and depths. Table 5.8 shows the results of land-use zoning. Overall, land-use zoning results in a much smaller decrease than compartmentalization. For the future socioeconomic changes, there is a decrease of 4-6% in flood risk compared to the same socioeconomic scenario without adaptation. For the flood risks in the future scenarios where climate change and socioeconomic changes are combined, the future scenarios for 2040 and the M-scenario for 2100, flood risks reduce between 4-6% compared to the same future scenario without adaptation measures. However, when only looking at the increase in risk, land-use zoning could offset about 15-20% of the increase in flood risk due to land-use change. For the worst-case scenario in 2100, the reduction is somewhat higher, between 6-11%. Due to the larger flood extent in this scenario, more areas that are restricted for new urban developments are now flooded compared to the other climate scenarios. This results in a relatively larger effect of the land-use zoning measure. When looking at the different land-use types which are restricted for future building (e.g. residential, industry, commercial and non-commercial land-use), the highest decrease can be seen in residential land-use.

Table 5.7 Expected Annual Damage (10^6 €/yr) and percent change (between brackets), under climate change, socioeconomic change, and combination for land-use zoning.

		Socioeconomic scenario									
		Baseline (2005)		A1		A2		B1		B2	
Climate scenario	CS	**25.3**		34.3	(-4%)	32.8	(-5%)	34.0	(-4%)	31.7	(-6%)
	M-Scenario 2040	26.6	(0%)	36.4	(-4%)	34.7	(-6%)	35.9	(-5%)	33.5	(-6%)
	W-Scenario 2040	26.9	(0%)	36.9	(-4%)	35.1	(-6%)	36.4	(-5%)	33.9	(-6%)
	M-Scenario 2100	27.1	(0%)	37.3	(-4%)	35.5	(-6%)	36.7	(-5%)	34.2	(-6%)
	W-Scenario 2100	41.7	(0%)	62.2	(-9%)	57.9	(-10%)	60.5	(-11%)	55.6	(-6%)

As can be seen from both Table 5.8 and Figure 5.9, the B2-scenario has a similar decrease in flood risk for all climate scenarios, whereas the other scenarios have a much higher decrease in flood risk for the worst-case scenario in 2100 compared to the other three climate scenarios. The main reason is the difference in amount of built-up area with and without land-use zoning. In the A1-, A2- and B1-scenario without adaptation, there is overall more built-up area in the coastal zone than in the B2-scenario. Thus, when implementing restrictions on urban development, there will be a relative larger decrease in urban areas. Consequently, this results in a larger decrease in flood risk.

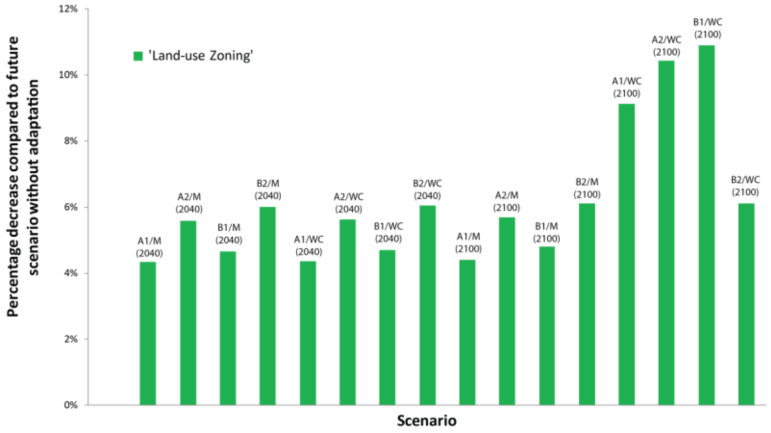

Figure 5.9 Percentage change in flood risk for each scenario in the areas where land-use zoning is implemented

Table 5.8 shows the results for the A1-scenario and B2-scenario in the M-2040 climate scenario per breach location. As can be seen from the table, there are differences between the two scenarios and even larger differences between each breach location. For example, in the A1-scenario the largest decrease can be found near Blankenberge (18% decrease compared to 'no adaptation'-situation), which is the result of a 15% decrease in residential flood damage. Contrastingly, no risk reduction is found at Blankenberge for the B2 scenario, implying that zoning had no effect on urban development there in the B2 scenario. Also for Nieuwpoort, no reduction in risk is found in the B2 scenario due to zoning. This can be explained by the fact that in the B2-scenario without adaptation, there was already no new built-up area compared to the baseline situation. At the other locations zoning does have an effect, which is most pronounced at the breach location northeast of Oostende, where zoning results in a 16% decrease compared to the 'no-adaptation'-situation, which is the result of a 90% decrease in industrial flood damage.

Table 5.8 Expected Annual Damage (10^6 €/yr) and percent change compared to specific scenario without adaptation (between brackets) for the different breach locations in the M-2040 climate scenario.

	A1			B2		
	No adaptation	Zoning		No adaptation	Zoning	
Total	38.0	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%)

5.4 Flood damage with ports included

Finally, results will be discussed where the ports of Oostende and Zeebrugge are included into the damage calculation. As can be seen in Figure 5.10, for a storm with a probability of 1/100,000, most of the flood damage occurs now around the ports of Oostende and Zeebrugge. This can be explained by two reasons.

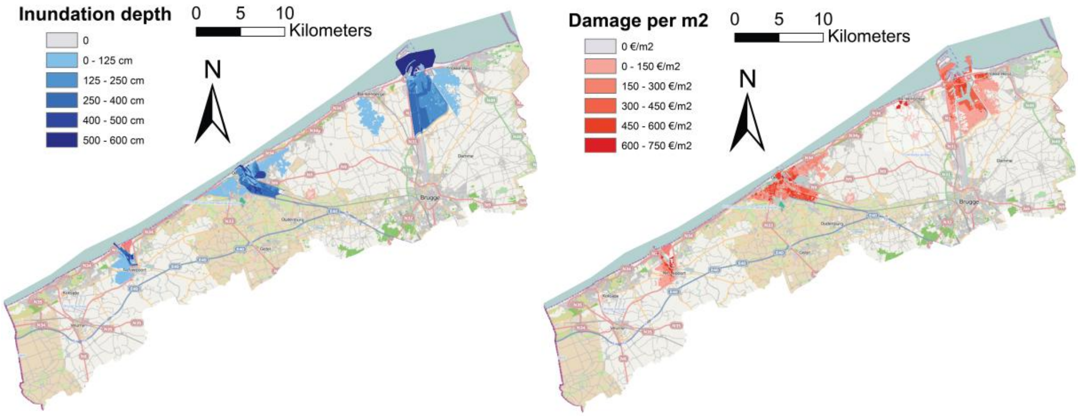

Figure 5.10 Flood damage for coastal Flanders in the baseline situation with a 1/100000 flood and ports included

First, due to the open connection with the sea, it is expected that both ports will be entirely inundated. Second, maximum inundation depths vary greatly between the port regions and the other breach locations, varying from 1 meter at the breach southwest of Oostende up to more than 5 meters in the port of Zeebrugge.

Table 5.9 shows the expected annual damage for the baseline situation. As can be seen in the table, more than 60% of the flood damage occurs in the port areas (as without ports included the EAD was 25.3 million euros per year). The main reason for this, as said in the paragraph above, is that the ports have an open connection with the sea. Therefore, the port areas will be flooded with higher inundation depths compared to the other breach locations, where there is a better protection from dikes or dunes. For ports, almost 70% of that flood damage occurs in the industrial areas. There are, however, also some residential districts outside the embankments, mainly at Oostende, which make up 29% of the flood damage there.

Table 5.9 Expected Annual Damage for the baseline situation, ports included

	EAD (10^6 €/yr)		Average area inundated (in km^2)		EAD for residential area (10^6 €/yr)		EAD for industrial area (10^6 €/yr)		EAD for infrastructur e (10^6 €/yr)		EAD for agricultural area (10^6 €/yr)	
Total	68.6		**31.7**		35.1	(51%)	32	(47%)	1.4	(2%)	0.05	(0.1%)
Nieuwpoort	2.1	(3%)	1.6	(5%)	1.58	(75%)	0.52	(25%)	0.03	(1%)	0.002	(0.10%)
Oostende SW	14.7	(22%)	5.0	(16%)	13.01	(89%)	1.3	(9%)	0.31	(2%)	0.002	(0.01%)
Oostende NE	4.9	(7%)	4.8	(15%)	4.65	(95%)	0.1	(2%)	0.1	(2%)	0.01	(0.22%)
Blankenberge	0.7	(1%)	3.1	(10%)	0.63	(97%)	0.01	(2%)	0.01	(2%)	0.002	(0.31%)
Knokke-Heist	2.9	(4%)	2.7	(9%)	2.74	(94%)	0.15	(5%)	0.04	(1%)	0.001	(0.03%)
Ports	43.3	(63%)	14.5	(46%)	12.5	(29%)	29.9	(69%)	0.88	(2%)	0.03	(2%)

Even though the built-up areas take up ‘only’ 45 per cent of the inundated area, the sum of these categories takes up almost 100 per cent of the expected annual damage (Figure 5.11). This is in expense of the agricultural and nature areas, which is mainly the result of the much higher maximum damages for the built-up areas. Interesting is to compare Figure 5.11 with Figure 5.2, the land-use shares in inundation and EAD without ports. The total share of built-up area in the total inundation is for both cases more or less the same. However, instead of 45% of residential area there is now a 23% share in residential area and a 20% in port industry. For the share in EAD, a similar observation can be found (90% residential area vs. 51% residential area and 39% port industry). The other land use shares stay in both figures almost the same.

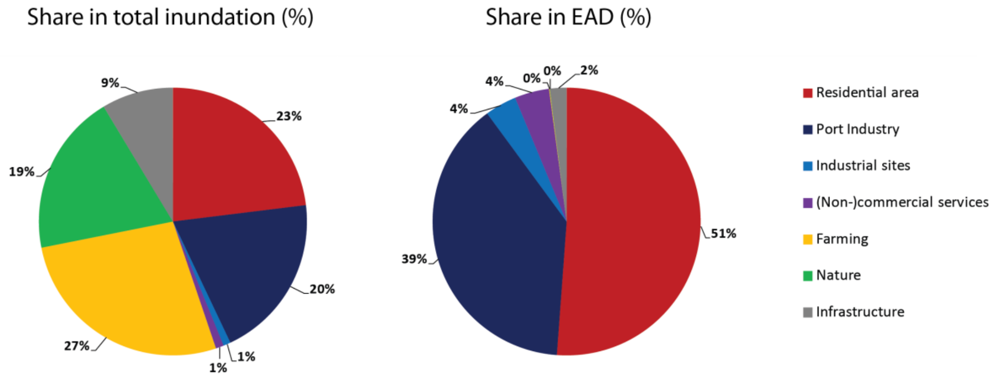

Figure 5.11 Amount of inundation per land use versus the EAD per land use in the baseline situation

For the port areas, three land-use categories take up most of the annual expected damage: 'RoRo'-industry, container terminals and other industry (Figure 5.12). This is mainly due to two reasons. First, they take up a large share in the port areas (see Figure 2.2) and consequently a large share in the total inundated area (83%). Second, a large share of the Roll-on Roll-off industry and container terminals is located in the reclamation ground outside the port of Zeebrugge, resulting in high inundation depths and high damages because it will get struck first by the storm surge wave.

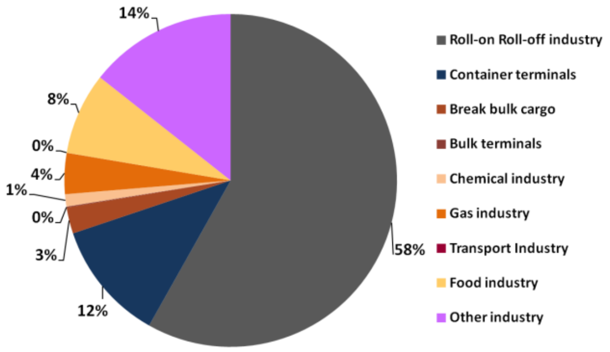

Figure 5.12 Share of EAD per port industry compared to the total EAD in the ports

The share of the port stays similar for all scenarios except for the worst-case scenario in 2100. In the worst-case scenario for 2100, the share of ports in the EAD decreases with 10%, while the other breach locations all increase with a couple percent. This can be explained by the larger flood extent in the embanked areas of the coastal area for the worst-case scenario in 2100. Because the unembanked area of the ports is already severely damaged with relatively low inundation depths, the flood damage increases fairly linear. The other breach locations, however, have low flood damages with relatively low inundation depths and therefore will see a significant increase in flood damage when suddenly the storm surge height greatly increases. Consequently, this results in a decrease in share for the ports and an increase in share for the other breach locations. The increase in damage due to socioeconomic changes (Table 5.10) is mainly the result of increases in residential areas. Similar to the baseline situation and to the calculations without ports, this is still in expense of agricultural and natural area.

Table 5.10 Expected Annual Damage (10^6 €/yr) and percent change (between brackets), under climate change, socioeconomic change, and combination.

		Socioeconomic scenario									
		Baseline (2005)		A1		A2		B1		B2	
Climate scenario	Baseline situation	**68.6**		91.9	(+34%)	87.3	(+27%)	89.6	(+31%)	85.9	(+25%)
	M-Scenario 2040	73.3	(+7%)	98.0	(+43%)	93.1	(+36%)	95.5	(+39%)	91.4	(+33%)
	W-Scenario 2040	75.2	(+10%)	100.4	(+46%)	95.4	(+39%)	97.9	(+43%)	93.6	(+37%)
	M-Scenario 2100	76.2	(+11%)	101.7	(+48%)	96.7	(+41%)	99.1	(+45%)	94.7	(+38%)
	W-Scenario 2100	97.6	(+42%)	135.1	(+97%)	127.3	(+86%)	131.2	(+91%)	123.7	(+80%)

6 Discussion

In this study, future flood risks are calculated for coastal Flanders by taking future socioeconomic and climate changes into account, using different scenarios. In total, four different socioeconomic scenarios and four different climate scenarios are used. Results show that due to climate and socioeconomic changes, flood risk in coastal Flanders will increase in the future, varying between 40 and 50% increases by the year 2040, compared to the baseline situation in 2005. Of that increase, between 30-40% is the result of socioeconomic changes, compared to approximately only a 6% increase due to climate change. Clearly, socioeconomic changes are the biggest influence for future increases in flood risk. This larger influence of projected socioeconomic changes on flood risk has also been observed in several other studies (Hall et al., 2005; Klijn et al., 2012; Feyen et al., 2009; Mokrech et al., 2008).

It is, however, doubtful if that many different scenarios are needed. Results are relatively similar between each socioeconomic scenario and between most of the climate scenarios. For example, the increase due to climate change varies between 5-7% for three out of four scenarios. The only real influence of climate change is in the worst-case scenario for 2100 where an increase in risk of more than 60% is observed. The socioeconomic scenarios differ even less. The difference between the two 'extremes' (A1 vs. B2) is less than 10%. This is, for example, in contrast to Hall et al. (2005), who state that there is a big difference between the socioeconomic scenarios used in the UK. The main reason for this small difference between the socioeconomic scenarios in this study is the relative small variation between the different scenarios for the coastal area of Flanders. This is in contrast with, for example, Bouwer et al. (2011) where a large difference in socioeconomic scenarios is observed.

A few studies have calculated flood risk and flood damages for coastal Flanders (Kellens, 2011; Van der Biest et al., 2009a and 2009b; Verwaest et al., 2009). All studies took different approaches to calculate this risk, but none took different future socioeconomic scenarios into account, or the specific adaptation measures that have been tested in this study. For example, Kellens (2011) only looked at the flood risk for the baseline situation. When comparing the results of Kellens (2011) with this study, somewhat similar results can be observed when it comes to the distribution of the flood risk around the coastline. In both studies, Oostende and the ports represent the largest share in the calculated flood risk. The total risk, however, is different. In this study, for the baseline situation a flood risk is observed of around 25 million Euros per year without the ports. A similar result has been found in Kellens (2011), but in that study ports are included in this risk. When ports are included in this study, the total flood risk for the baseline situation is almost 69 million Euros per year.

Van der Biest et al. (2009a) only looked at one specific flood event for the baseline situation and two future scenarios. The future scenarios used in that study are similar with the scenarios in this study for the year 2100. Flood damages in Van der Biest et al. are calculated by using a 'super storm' event with a probability of 1/17,000. For the baseline situation, this resulted in a total flood damage of around 400 million Euros, according to their study. In this study, different storm surge heights are used with different return periods. Therefore, the flood damage of the 1/100,000 flood event will be used for comparisons, which has a somewhat similar storm surge height. In this study, the total flood damage for this event is around three billion Euros, almost eight times higher than in the study of Van der Biest et al. (2009). This can be explained on two grounds. First, in our study, a larger area was flooded for the baseline situation (approximately three times larger). Second, there are large differences in maximum damages and depth-damage curves, which may explain the remaining difference. These differences in flood exposure and in damage calculations, also explain the differences in damage between the future situations. Van der Biest et al. (2009b) looked into the effect of adaptation measures to climate change impacts. Most of these adaptation measures were focused on improved coastline protection (reducing the flood hazard). But one, however, was similar to the land-use zoning measure used in this study. Nevertheless, the results are different. For example, according to Van der Biest et al. (2009b), no specific restrictions are needed near Oostende. This is in contrast to this study, where it was found that around Oostende the largest decrease in flood risk can be achieved when implementing restrictions for future developments in built-up area.

Next to the calculation of future flood risks, two spatial adaptations measures are tested: compartmentalization by improving existing linear landscape elements and land-use zoning. Results show that compartmentalization will result in the highest decrease in future flood risk, and indicate a decrease of more than 50% compared to the future scenarios without adaptation measures. Land-use zoning, on the other hand, shows the smallest decrease in future flood risk, between 4-10%. However, when only looking at the increase in risk, land-use zoning could offset about 15-20% of the increase in flood risk due to land-use change. This large difference is mainly related to the fact that zoning only influences the flood risk of new urban developments, and does not influence the risk of the current building stock, contrary to compartmentalization that affects the flood extent, and thus also the risk of existing built-up areas. This has a large influence, as flood waters are kept away from existing large residential areas (see e.g. Oostende in Fig. 5.5).

However, there can be large differences for compartmentalization on a local level, varying from larger inundated areas to higher inundated depths (Alkema and Middelkoop, 2005; Oost and Hoekstra, 2009; Klijn et al., 2009). Those results are also found in this study. For example, even though the flood extent near the south of Oostende significantly reduced and resulted in a large decrease in expected annual damage, the flood extent near Blankenberge and north of Oostende increased due to compartmentalization. For Blankenberge, this still resulted in a decrease in expected annual damage due to the water now flooding the agricultural area behind the village of Blankenberge instead of the village itself. In the north of Oostende, on the other hand, there was an actual increase in expected annual damage. Even though the average area inundated increases by only 8%, almost all of this increase occurs in residential area, resulting in a large increase in damage.

In the Master Plan for Coastal Safety, it is stated that the Flemish coastline should be able to withstand at least a storm with a probability of 1/1000 (Mertens et al., 2008). In this study, we assumed that the weak spots of the coastline are still only able to withstand storms with a maximum probability of 1/100. However, if Belgium would increase its safety levels for the entire coastline to 1/1000, the total flood risk will decrease by almost 80%. This means that annual expected damages in the baseline situation will reduce from 25.3 million Euros per year, to approximately 5 million Euros per year. Compared to the tested spatial adaptation measures, this is a much larger reduction in flood risk, as the best spatial measure (compartmentalization) resulted in an average reduction of expected annual damages of around 50%. As current safety levels are still relatively low, it might be more effective for some locations to invest first in reducing the probability of flooding by raising and strengthening the primary coastal defences, instead of reducing the exposure and consequences by compartmentalization and land-use zoning, respectively.

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.

6.1 Feasibility spatial adaptation measures

When integrating the tested spatial adaptation measures into flood risk management for a specific region, the economic feasibility to implement these measures has to be decided upon. For the coastal region of Flanders, results show that compartmentalization significantly reduces the flood risk. However, the effect of strengthening the primary defences in order to be able to withstand a storm with a probability of at least 1/1000 shows an even greater reduction in flood risk. Klijn et al. (2007) described a close relation between the failure probability of the primary defences and the benefits of compartmentalization. When the primary flood defences are still low, compartmentalization can deliver considerable benefits, but these might not be the measure with the highest possible benefits. However, when the primary flood defences are protected against very low probability storms (e.g. the strong flood defences along the Dutch coast), the benefits of compartmentalization will be also very small, as not much extra benefits can be achieved. Consequently, whether or not compartmentalization is effective should be assessed on a local level. As, for example, Figure 5.5 showed, large differences were found between different locations. For Blankenberge, it might be more beneficial if the primary defences will be upgraded to higher standards of protection. For Oostende, on the other hand, compartmentalization can reduce the flood risk significantly, without the need of considerable upgrades of the coastal defence, with detrimental effects of the current economic uses of the coastal fringe. By looking which measures is most effective in which area, an optimal safety level of protection can be reached that can be more effective in reducing risk than using a single measure in the entire area.

Nevertheless, compartmentalization is fairly easy to implement. In this study, old embankments and existing line structures (e.g. roads, railways and old dikes) have been used to test these measures. Therefore, no new dikes have to be build, only existing structures have to be strengthened. In the ‘Compartments Plus’ measure, these line structures have also been raised by one meter. This, however, only resulted in larger risk reductions compared to the ‘Compartments’ measure for the worst-case scenario in 2100, which is based on a sea-level rise of two meter.

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 zoning. If there is substantial socioeconomic growth, restrictions may reduce the potential of increased flood risk considerably. If there is, on the other hand, little to no growth, the potential to reduce flood risk by zoning is low and restricting developments is basically unnecessary. Therefore, land-use zoning might be an interesting option in combination with other spatial adaptation measures, but not as sole measure.

6.2 Methodological issues

This analysis is not without its limitations. For starters, there are several biases around the creation of the future land-use maps, such as outdated information for the base map of 2005, uncertainty in the allocation of future land use and the linear extrapolation for the future projections. See De Moel et al. (2012a) for a more extensive explanation of these problems. Second, research shows that there are high uncertainties in the derived flood damages in flood risk analysis such as these. This is mainly the result of large uncertainties in the determination of the maximum damages and the depth–damage curves (De Moel and Aerts, 2011; Merz et al., 2004; Merz et al., 2009), but also the determination of the volume of water that could enter the polder area (De Moel et al., 2012). Therefore, one has to be cautious when interpreting these results. To somewhat correct for these uncertainties, all results are compared in relative terms.

Also, studies have showed that when calculating the expected annual damage, one has to be careful with selecting how much flood events to use for calculating it. When calculation the expected annual with damage with only very few flood events in the tail of the curve, the flood risk can be highly underestimated (Ward et al., 2011).

A final limitation was the inundation of the ports of Zeebrugge and Oostende. For these areas that are not protected by flood defences, the inundation model was not able to simulate individual inundation events. Therefore, the maximum water level of the storm surge was applied on the entire unembanked area. This may have resulted in an overestimation of inundation depths, as the effect of the shape of the harbour and its entrance were not accounted for. Furthermore, 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.

7 Conclusion

In this study, the effect of climatic change, socio-economic change and two spatial adaptation measures on flood risk for the coastal area of Flanders have been investigated. In order to achieve this, we set up a flood risk model for the Flemish coast and used this model to test the effectiveness of two spatial flood management measures as how they reduce risk. This was done for four climate change scenarios and four socio-economic scenarios. A land-use model, an inundation model and a damage model were combined to calculate flood risk for coastal Flanders, which was quantified in terms of expected annual damage. The two spatial adaptation measures, compartmentalization and land-use zoning, were implemented in the inundation model and the land-use model, respectively. In this way, compartmentalization was assumed to limit the flood extent, and land-use zoning limits the (additional) exposure to flooding.

Results show that without adaptation measures, future flood risks will increase between 40-50% for the year 2040. Of that increase, between 30-40% is the result of socioeconomic changes, compared to an approximately 6% increase due to climate change. Climate change is assumed to affect only sea-level rise (i.e. inundation depth), and not the frequency of storm surges due to changes in extreme wind speeds during storms. Only when considering extreme sea-level rise does climate change increase the flood risk more than socioeconomic change. This is illustrated by the worst-case scenario for 2100 used in this study, which assumes a sea-level rise of two meter. When adaptation measures are being implemented, flood risks are substantially reduced. Compartmentalization resulted in an average reduction of approximately 50% of annual expected damages, for both the baseline situation as well as for future scenarios. Land-use zoning resulted in much lower reductions, averaging between 6-10%. Except for the most extreme climate change scenario, compartmentalization successfully offsets the combined adverse effects of socio-economic growth and climate change on flood risk. For both compartmentalization and zoning, large differences are found in their effectiveness for different locations. For example, compartmentalization significantly decreased the flood risk in most areas, while it actually increased in another area. Similarly, the effect of zoning also depends very much on the location, as well as on the socio-economic projection used. Large growth leads to larger avoided damages for the land-use zoning measure.

Flood risk can also be reduced by strengthening the primary defences. In this study flood events with return periods of 100 years and lower have been considered. If primary defences would be improved to withstand anything up to a return period of 1000 years, flood risk will be reduced by almost 80%. Clearly, a variety of measures should be investigated in various areas in order to judge which measures are most effective in which location. Combining feasibility and costs could then result in an optimal mix of measures to manage flood risk for the Flemish coast.

Lastly, it should be noted that port areas constitute a large part of the total flood risk. In our calculations the flood risk in port areas actually surpassed that of the embanked part. Despite this high potential damage, we did not test adaptation measures in this area. The main reason was the limitations of the inundation model to simulate floods correctly in these areas and the known difficulty with estimating flood damage to industrial areas, which are much more heterogeneous with specialised buildings and equipment compared to residential areas. Therefore, more research has to be done to correctly simulate flood risk in these areas and consequently be able to test adaptation measures.

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