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FLOOD RISK MODELLING

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1 Introduction

Flooding poses serious threats to coastal cities, including both economic damage and loss of lives (Nicholls, 2004; Nicholls et al, 2008; Dasgupta et al, 2009). More than 50 per cent of the world's population live in cities, and worldwide more than 40 million people living in coastal cities are exposed to floods with a return period of 100 years (Nicholls et al, 2008). Within the next 30 years, more than two-thirds of the world's cities will be vulnerable to flooding due to factors including sea-level rise, climate change, subsidence and socio-economic changes (Rosenzweig and Solecki, 2001; Bouwer et al, 2007; IPCC, 2007b).

In the past, flood management has concentrated on providing protection against floods through technocratic measures such as storm surge barriers and dikes (Aerts and Droogers, 2004). These measures were aimed at maintaining clear borderlines between land and water. However, fuelled by the knowledge that climate change, and broader environmental and socio-economic changes, will make it increasingly expensive to provide the desired safety standards, and the recognition that the probability of flooding can never be reduced to zero, there is currently an international shift towards a more integrated system of flood risk management (Few, 2003; Merz et al, 2004; de Bruijn, 2005; Büchele et al, 2006). In this context, flood risk is defined as the probability of flooding multiplied by the potential consequences, such as economic damage or loss of lives (Smith, 1994). The level of flood risk therefore depends on:

** the hazard characteristics, such as flood depths and extent, flood duration or flow velocity (Milly et al, 2002; Kundzewicz and Schellnhuber, 2004);
** the exposure characteristics in flood-prone areas, such as number of people, land use and value of assets (Kundzewicz and Schellnhuber, 2004); and
** the vulnerability of the exposed assets and population to the hazard, which can vary largely depending upon the location (e.g. in developed or developing countries) (Kron, 2005).

This move from traditional flood management to flood risk management can be seen at several scales, ranging from international to local. For example, in Europe flood risk management has been given added impetus by the European Flood Directive (EFD) (Directive 2007/60/EC), which requires member states to assess whether water courses and coastlines are at risk from flooding, to map the flood extent, and to take measures to reduce flood risk. At the city level, some cities are developing and implementing ambitious plans to become 'climate-proof' (Aerts et al, 2009), and one element of this may be to develop long-term visions, including flood risk reduction measures, such as is the case in the Rotterdam Climate Initiative (RCI) and PLANYC 2030 (New York).

Nevertheless, the scientific field of flood risk assessment (and, as part of this, the related science of flood damage assessment) lags behind the better developed fields of hydrology and hydraulics (Büchele et al, 2006). As a consequence, there has been more and more attention focused on flood risk and damage assessment in both the scientific and policy spheres during recent years. A risk-based approach is advantageous as it can allow us to gain a better understanding of the effects of physical and socio-economic change on both the flood hazard and its consequences. It therefore provides the opportunity to evaluate risk-reducing strategies for both now and in the future. It can provide data for different purposes, such as the support of decisions on the allocation of tax money or the implementation of insurance premium differentiation.

In this report we provide an overview of some of the main terminologies and approaches that are being used and developed in this field. In section 0 we begin with a definition of the key terms, before describing the main generic applications of flood risk modelling in section 0. The general methodological framework of flood risk assessment is presented in section 0. In section 0, there is a discussion on how scenarios can be used to evaluate flood risk developments over time. Several case study examples are presented in section 0, followed by a brief discussion of how several studies have addressed uncertainty in section 0. Section 8 gives an example of the assessment of the impact of climate change in the North Sea region. Finally, the report ends with conclusions on the main points in section 9.

2 Definitions

In this report, we define flood risk as the probability of flooding (hazard) multiplied by the consequences of flooding (damage) (Smith, 1994). Flood risk can therefore also be given as the average total expected flood damage per year. This is represented conceptually in Figure 1, whereby the total risk is represented by the integral of the area under the damage-probability curve. In practice, practical considerations of time and resource availability dictate the number of points that are used to develop such a damage-probability curve; for example, in Figure 1 the damage has been calculated for four flood probabilities, and the curve interpolated between these points. An important facet is to define the probability at which damage begins to occur, and also to estimate damage for flood events with low probabilities since these are the events where the highest damage occurs.

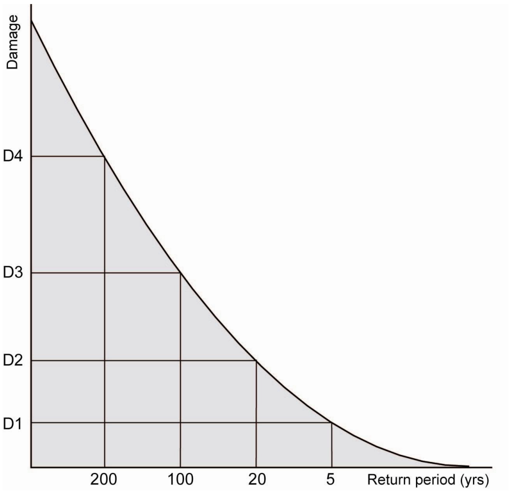

Figure 1 *Theoretical damage-probability curve: The area under the curve (in grey) represents the risk, expressed as the average total expected damage per year*

Flood hazard can be defined as the exceedance probability of a potentially damaging flood situation in a given area and within a specified period of time (Merz et al, 2007). An example for coastal flooding is the water depth associated with storm surges with varying probabilities of occurrence, expressed as once per a given number of years (i.e. return periods). There are several indicators of flood hazard; but by far the most commonly used in flood risk assessment is the inundation depth (e.g. Smith, 1994; Merz et al, 2007; Middelmann-Fernandes, 2010). Several studies have found that for many cases the water depth is the flood characteristic that has the largest influence on flood damage (e.g. Penning-Rowsell et al, 1994; Wind et al, 1999). Other factors that have been found to be important flood hazard parameters include flow velocity (e.g. Sangrey et al, 1975; USBR, 1988; Clausen and Clark, 1990; Marco, 1994; Jonkman et al, 2008; Middelmann-Fernandes, 2010), inundation duration (Parker et al, 1987; Lekuthai and Vongvisessomjai, 2001; FEMA, 2005) and sediment or contamination load (Haehnel and Daly, 2002; Penning-Rowsell et al, 2003; Thieken et al, 2005).

In terms of the consequences of flooding, most flood risk assessments are limited to the detrimental effects (damages), although there may be positive consequences, such as the replenishment of groundwater, or the delivery of water and sediments to high biological diversity areas such as wetlands (Merz et al, 2004). The term flood damage refers to all varieties of harm caused by flooding. Flood damage can be divided into several categories; usually they are separated into direct and indirect flood damage, both of which are often further divided into tangible and intangible damages (Parker et al, 1987; Smith and Ward, 1998; Penning-Rowsell et al, 2003). Examples of these four categories are shown in Table 1, and each is described in more detail in the following paragraphs.

Table 1 *Classes of flood damage with examples*

		Evaluation	
		Tangible	Intangible
Categories	Direct	Physical damage to assets/properties: ** Buildings ** Contents ** Infrastructures ** Loss of agricultural production	** Loss of life ** Evacuees ** Health and physical effects ** Loss of ecological goods
	Indirect	** Loss of industrial production ** Traffic disruption ** Emergency costs	** Post-flood recovery ** Migration ** Psychological damages ** Increased vulnerability of survivors

Source: adapted from Messner and Meyer (2005); Merz (2006); FLOODsite (2007)

Direct damages are those that occur due to the physical contact of floodwater with humans, property or any other objects (Smith and Ward, 1998; Merz et al, 2004; Büchele et al, 2006). These can include damage to buildings, economic assets, loss of crops and livestock, immediate health impacts, loss of lives and loss of ecological goods. They are often measured as damage to stock values. Indirect damage is a damage that is induced by the direct impact, but occurs outside of the space and/or time of the flood event. Examples of indirect damage include disruption of traffic, trade and public services (Büchele et al, 2006). Indirect damages are often measured as loss of flow values.

Tangible damages are those that can be relatively easily evaluated in monetary terms (e.g. damage to assets, loss of production, etc.). They can be subdivided into direct damages (such as physical damage to properties, contents and infrastructure), and indirect damages (which can be more difficult to estimate and include damages such as traffic or industrial disruption, and emergency costs).

Intangible damages are more difficult to evaluate in monetary terms (Lekuthai and Vongvisessomjai, 2001). There are fewer studies on their valuation than for tangible damages. However, some authors still provide information on their valuation (e.g. Mitchell and Carson, 1989; Bateman et al, 2002; and Kahn, 2005). Intangible damages include social and environmental impacts of floods; again, they can be subdivided into direct and indirect intangible damages (see Table 1). Social impacts include health or psychological impacts (Smith and Ward, 1998), as well as loss of human lives. When describing flood damage, information on loss of lives is usually given separately from the calculated economic damage; examples of studies addressing loss of lives include Brown and Graham (1988), Funnemark et al (1998), DeKay and McClelland (1993) and Maaskant et al (2009).

It is clearly acknowledged in the flood damage assessment literature that direct intangible damage or indirect damage can play an important role in evaluating flood damage (Penning-Rowsell and Green, 2000). However, by far the largest part of the flood damage literature focuses on direct tangible damages, which are considered as a good indicator of the severity of flood disasters. Direct tangible damages will therefore form the main focus of this report.

3 Generic Applications

Flood risk modelling has become an important tool in flood risk assessment and management for three main reasons. First, it can help to gain a better understanding of current flood risk in vulnerable areas and provide data on how adaptation measures can reduce that risk. Second, flood risk modelling can be used to assess how the risk will change in the future as a result of environmental and socio-economic changes. Third, since the social purpose of flood risk management is to reduce flood damages, it can be used to determine the relative effectiveness of alternative intervention strategies both now and in the future (Zerger and Wealands, 2004).

Based on these notions, FLOODsite (2007) identifies the following three main spheres in which risk analysis can be used in public policy:

1 *Supporting decisions on financial allocation of tax money*: comparing flood risk (in terms of annual expected flood damage) with other societal risks (such as damage due to illness, earthquakes, terrorism, etc.) provides policy-relevant information about the significance and severity of different risk factors in society. This kind of information can provide decision support on the allocation of tax money to various policy fields all aimed at reducing societal risk.

2 *Project appraisal*: information on annual expected flood damage is vital for decision-making on flood risk management measures and investments. The risk-reducing effects of different flood management measures can be estimated and compared by means of flood risk analysis.

3 *Accountability*: flood risk analysis results can be used to justify public investments and to demonstrate the appropriateness of public spending. They also provide useful insights into why some flood protection measures may be highly efficient in one basin, but not necessarily in another.

Another key use of flood risk analysis is the production of flood risk maps. Merz et al (2007) summarize several of the most important uses of flood risk maps, as listed below:
** raising awareness amongst people at risk and decision-makers;
** providing information for land-use planning and urban development, investment planning and priority-setting;
** helping to assess the feasibility of structural and non-structural control measures;
** serving as a basis for deriving flood insurance premiums;
** allowing disaster managers to prepare for emergency situations;
** developing land-use regulations, building codes and insurance.

Examples of such flood risk mapping studies include those in Austria, Italy and the Czech Republic, where maps are created by, or in association with, insurance companies in order to differentiate premiums according to the flood risk (de Moel et al, 2009). In Finland, the UK, France, Poland and Germany, legislations enforce the use of maps. The degree to which these legislations are binding differs between the countries.

4 Methodological Framework

In this section we describe the general methodological framework that is used for flood risk assessment. As stated previously, this discussion focuses mainly on direct, tangible damages. Even for direct, tangible flood damage assessment, a plethora of methodologies exist depending upon factors such as scale and data availability (Meyer and Messner, 2005). However, any flood risk analysis involves three basic facets (adapted from FLOODsite, 2007) – namely:

1 project definition and selection of appropriate approach;
2 data gathering and damage modelling; and
3 calculation and presentation of risk.

The most time- and resource-intensive phase of a flood risk assessment is often the data gathering and damage modelling (i.e. step 2), which forms the main thrust of this section. The discussion is based mainly on FLOODsite (2007), which provides more detailed explanations and guidelines for each step.

4.1 Project definition and selection of appropriate approach

Clearly, the geographical scale at which a risk assessment is to be carried out will be a key factor in choosing the approach; there are clear methodological differences between macro-, meso- and micro-scale approaches (FLOODsite, 2007). Macro-scale approaches are mainly used in investigations of large international areas, and consider aggregated damage within administrative or physical units (e.g. municipalities, homogenous stretches of coastline, river basins). Meso-scale analyses tend to be carried out for regional flood risk assessments, and consider damage for aggregated land-use units or classes, such as residential areas, industrial areas, etc. Finally, micro-scale methods are used in local assessments in which an object-oriented approach is often used (i.e. damages are calculated for single properties, such as buildings) (Hall et al, 2005; Nicholls et al, 2008; Veerbeek and Zevenbergen, 2009). However, according to Meyer and Messner (2005), this simple macro–meso–micro differentiation is not so clear cut, and object-oriented assessments of flood damage are already applied on the regional and national scale (Hall et al, 2003). Still, the level of detail generally decreases as the geographical scale of study increases.

Next to the geographical scale of the study, the approach to be used is also strongly dependent upon the objective of the study (e.g. quick and approximate overview of risk versus detailed calculations for project implementation) (Gewalt et al, 1996), the availability of resources (budget and time restrictions) and the availability of pre-existing datasets (which will affect the budget and time constraints).

Another important consideration during the project definition phase is the selection of damage categories to be assessed. There are many categories of direct, tangible damages, such as residential properties (buildings, household goods), non-residential properties (buildings, machinery and equipment), technical infrastructure (streets, railways, flood defences, water courses, etc.), vehicles, and agricultural products (livestock and crops). Ideally, a flood risk assessment would take all of these into account; but, again, due to constraints of scale, budget, time and data availability, it may be necessary to prioritize those categories most relevant for the study at hand. In any case, damage statistics from observed floods help to identify the most important damage categories in a given region.

4.2 Data-gathering and damage modelling

There are three main types of data that are required in the majority of flood risk assessments – namely, data on hazard characteristics, data on exposure characteristics and data on vulnerability characteristics. These are then combined to estimate the potential damage for a given flood event.

4.2.1 Hazard characteristics

A number of parameters can be used in damage and risk assessment to characterize the flood hazard of a given flood event, such as inundation depth (e.g. Smith, 1994; Merz et al, 2007; Middelmann-Fernandes, 2010); flow velocity (Sangrey et al, 1975; USBR, 1988; Clausen and Clark, 1990; Marco, 1994; Middelmann-Fernandes, 2010); inundation duration (Parker et al, 1987; Lekuthai and Vongvisessomjai, 2001; FEMA, 2005); and sediment or contamination load (Haehnel and Daly, 2002; Penning-Rowsell et al, 2003; Thieken et al, 2005). By far the most commonly used of these characteristics is the inundation depth (Merz et al, 2007; Apel et al, 2009). Several studies have identified inundation depth as the inundation characteristic with the largest influence on flood damage (e.g. Penning-Rowsell et al, 1994; Wind et al, 1999), and nearly all damage functions are solely depth-damage functions (see section 4.2.3).

In addition to economic damage, floods can pose a serious threat to human lives and have caused large numbers of fatalities around the world. For example, Bangladesh was hit by a cyclone in 1991, causing storm surges that left between 67,000 and 139,000 victims (Chowdhury et al, 1993), and Hurricane Katrina, which hit New Orleans in 2005, caused the death of 1118 people (Jonkman et al, 2009). The inundation characteristic most commonly used as an indicator of flood hazard in assessments of loss of lives is the inundation depth (Jonkman et al, 2008). However, risk factors to life can vary with the types of flood. For large dam-break floods, the risk to life mainly originates from the resulting flood wave. Warning time is therefore a crucial parameter to be taken into account in approaches estimating mortality from dam-break floods or flash floods (Brown and Graham, 1988; Dekay and McClelland, 1993). For coastal flooding, local water depths and the pace of rising water levels are also important parameters to be taken into account when assessing the risk to life (Jonkman et al, 2008; Maaskant et al, 2009).

In risk analysis, it is not sufficient to examine the hazard characteristics for just one particular flood event. In order to develop a damage-probability curve (see Figure 1), flood events of several return periods should be considered (Hall et al, 2005). This can either be done by using maps and records of previous flood events in the studied area, and using these as proxies for future floods, or by using models to simulate the inundation depth for given coastal flood events (e.g. Thurmerer et al, 2000; Bryan et al, 2001; Mastin and Olsen, 2002; Nicholls, 2002; Madsen and Jakobsen, 2004; Nicholls, 2004; Bates et al, 2005; Dawson et al, 2005; Nicholls et al, 2008;

Purvis et al, 2008; Gaslikova et al, 2011). In essence, all of these methods attempt to predict inundation extents and depths based on some combination of process drivers (such as meteorology, tides and flood-defence design periods) (Dawson et al, 2005). There are two main approaches: planar models and hydrodynamic models. Planar models use as input the water level of the tide and distribute this over a Digital Elevation Model (DEM) by means of some kind of flow-connectivity algorithm. For the planning and implementation of protection measures, predictions are typically obtained from hydrodynamic models; for coastal flows, two-dimensional horizontal solutions of the shallow water equations are state of the art (Madsen and Jakobsen, 2004; Bates et al, 2005). Such models require accurate topographic and bathymetric data at a high resolution and are computationally demanding. As a result, Bates et al (2005) developed a simplified two-dimensional hydraulic model with much less computational demand, following similar advances in fluvial inundation modelling (Horritt and Bates, 2002).

4.2.2 Exposure characteristics

The potential damage that may result from a flood event depends upon the flood exposure characteristics in the potentially inundated area. In flood risk assessment, these exposure characteristics can be represented by several different kinds of datasets, such as buildings and assets, land-use type, and number of people living or working in the inundated area.

For the evaluation of economic damage, the most widely used exposure characteristics are representations of the land use in the areas susceptible to flooding. In order to get an approximate economic valuation of the exposed assets, monetary values can be assigned to the different land-use types (FLOODsite, 2007). For detailed valuations of the potential damage, more precise knowledge of the assets at risk in the study area, and their values, is required. This could include, for example, the number of houses, businesses and the presence of objects such as hospitals, industrial plants or petrol stations. The amount of information and detail obtained on the assets at risk will therefore depend upon the size of the study area, the availability of the data, and its quality and content. The values of the assets vary with their types (e.g. houses or industrial buildings), the period considered (market prices vary in time) and the geographical location (Merz et al, 2010). For a specific type of asset, such as a residential home, two types of values can usually be determined: the value of the building and the value of the contents. Concerning the specific problem of evaluating the exposure of human life, relevant data on exposure characteristics include the number of people living in the affected area; the availability of flood shelters; and the warning and evacuation time (Jonkman et al, 2008).

Official statistics usually provide useful data at the national, regional or local scale, such as gross and net value of fixed assets or population statistics (FLOODsite, 2007; Merz et al, 2010). In addition, depending upon the scale and the required precision of the flood risk assessment, other databases may be needed. At the macro-scale, the values of the assets can be aggregated and an equal spatial distribution of the assets in the study area can be considered. At the meso- and micro-scale, however, the required level of detail increases, and the spatial distribution of the assets needs to be closer to the real distribution (Merz et al, 2010).

4.2.3 Vulnerability characteristics

Vulnerability can be defined as the ‘relationship between the severity of hazard and the degree of damage caused’ (UN DHA, 1993). This can be denoted by damage functions (Füssel, 2007), which are typically used to assess direct, tangible flood damages. These functions provide the level of the damage that can be expected given the respective hazard and exposure characteristics described above if an area is actually flooded. The most common damage functions are stage-damage functions (Middelmann-Fernandes, 2010), which relate stage height (i.e. inundation depth) to damage.

Hypothetical stage-damage functions are shown in Figure 2, where the expected economic damage is shown on the y-axis, the inundation depth on the x-axis, and each line on the graph represents a relationship between inundation depth and damage for a given aggregated land-use type. The figure also shows the two main kinds of damage functions (Middelmann-Fernandes, 2010) – namely, absolute damage functions (see Figure 2a) and relative damage functions (Figure 2b).

Absolute damage functions estimate the actual expected damage in monetary terms for given inundation characteristics. Relative damage functions, on the other hand, show the expected damage as a proportion of the maximum potential damage that could possibly occur. Absolute damage functions are developed for specific regions using data on the market value of assets and their susceptibility to certain inundation characteristics (e.g. inundation depth); they estimate the absolute damage per property or per unit area of land depending upon the inundation and exposure characteristics (e.g. inundation depth and land use, respectively). However, since they are developed specifically for a particular region, it can be difficult to transfer these to other regions. In theory, relative damage functions can be transferred more easily between regions since they simply describe the proportion of the maximum damage that would occur for different inundation and exposure characteristics. Hence, by using market data to estimate the maximum potential damage for each exposure class, they can be applied to any other region. Of course, in practice this transferability is less simple since the shape of the relationships is not the same in different regions due to differences in building styles or different development stages.

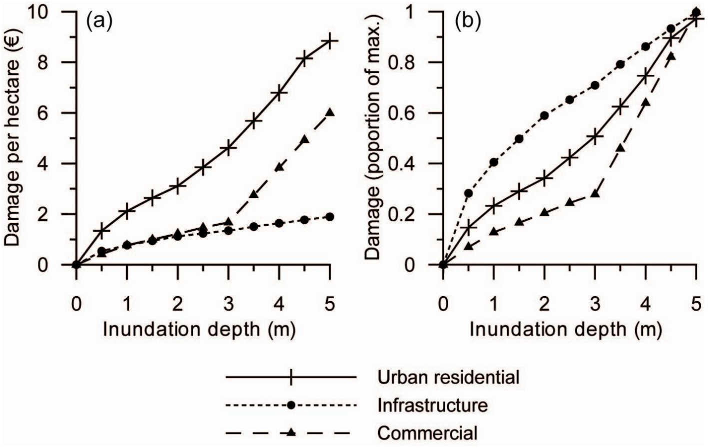

Figure 2 *Hypothetical absolute (a) and relative (b) stage-damage functions for use in flood-damage modelling*

Similar functions are also used in many assessments of loss of lives; a comprehensive overview of methods is provided by Jonkman et al (2008). A common feature of many of these methods is the use of a function that relates flood mortality to inundation characteristics. An example of such an approach is given in section 6.

4.3 Calculation and presentation of risk

As stated in section 2, flood risk is the product of hazard, exposure and vulnerability characteristics. It can be considered as the average total expected flood damage per year for all kinds of floods. Therefore, in theory, risk estimates should be based on a fully probabilistic analysis of the damages associated with floods of all return periods. However, due to time and resource constraints, flood risk assessments, in practice, simply assess damage for a small number of inundation scenarios and then interpolate the damage estimates for floods of different return periods. The average annual damage, or risk, can then be calculated as the integral of the area under a damage-probability curve, as shown in Figure 1.

Spatial representations of flood risk can also be portrayed in flood risk maps, which are useful for the reasons listed in section 0. Damage and risk mapping can be carried out relatively easily in modern Geographic Information Systems (GIS) programmes, and can be used for communication and stakeholder participation (Fuchs et al, 2009, Van Alphen et al, 2009).

5 Scenarios

Flood risk is expected to increase in many coastal regions in the future due to on-going socio-economic development in risk-prone areas, as well as due to global warming (IPCC, 2007b; Bouwer et al, 2010), In order to develop sustainable flood management strategies, to design appropriate risk mitigation measures and to optimize spatial planning, it is important to gain insights into the pace and magnitude of possible changes in flood risk over time. This is especially true because many investments in flood protection or programmes for spatial planning often take 20 to 30 years to implement (Maaskant et al, 2009). However, estimating future flood risk is no easy task because both climate change and socio-economic developments involve considerable uncertainties, making it difficult, if not impossible, to accurately estimate future flood risk.

A possible way to deal with these uncertainties is to use climate and socio-economic scenarios in flood risk assessment. Scenarios are sets of assumptions reflecting alternative and preferably contrasting future developments that are coherent, internally consistent and plausible (Kuik et al, 2008). Usually, scenarios are not assigned probabilities, but show a range of plausible outcomes. Hence, contrasting scenarios can be used to visualize the possible bandwidth of future flood risk developments and its uncertainty (Bouwer et al, 2010; Te Linde et al, 2010a). A widely used set of such scenarios derives from the *Special Report on Emission Scenarios* (SRES) provided by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2000).

In order to estimate the development of flood risk over time, information from both climate and non-climate scenarios needs to be taken into account. Climate change scenarios can be used to derive information on changes in hazard characteristics, such as sea level, waves and storm surges (IPCC, 2007a), river discharges (Belz et al, 2007) or flood probabilities (Te Linde et al, 2010a). Socio-economic scenarios can be used to determine the change in exposure and vulnerability characteristics of social systems over time, such as land use (Verburg et al, 2008) or population (Maaskant et al, 2009).

The task of gathering detailed (object-based) information on future exposure is very difficult and time consuming. As a result, the majority of methods applied to assess future development of flood risk use information on land use as an input parameter to calculate damages, loss of life and, consequently, risk due to flooding (ICPR, 2001; Aerts et al, 2008; Maaskant et al, 2009; Bouwer et al, 2010), Thus, land-use change projections have been proven to be especially relevant for studies investigating future developments in flood risk. A modelling framework that enables the development of land-use change projections on the basis of scenarios is provided by the CLUE model (Verburg and Overmars, 2009). The CLUE model can be used to translate aggregate changes in demand for different land-use types, reflecting different development scenarios, into spatially explicit land-use patterns for a given area. The (future) demand of different economic sectors in terms of land use can be taken from existing projection or economic models. Spatially explicit land-use patterns are derived from the aggregated changes by applying dynamic spatial allocation rules that can be either based on empirical analyses, user-specified decision rules, neighbourhood characteristics or a combination of these methods

(Verburg et al, 2008). The CLUE model has, for instance, been used to derive land-use change projections for four different scenarios for the EU-15 states (i.e. the member states of the European Union as of 1st January 1995) (Verburg et al, 2008). An example of how these land-use projections have been used in an analysis to estimate future development of flood risk in the Rhine Basin and its uncertainty is provided by Te Linde et al (2011) (see section 6).

6 Examples of Flood Risk Assessment Applications

In this section, we provide brief overviews of several studies that examine flood damages and risk at different scales, using the classifications of macro-, meso- and micro-scale as introduced in section 0. Where possible, examples of flood risk assessments in coastal areas are provided. Furthermore, an example is given of how the future risk of flooding has been examined in terms of loss of life in South Holland, The Netherlands.

6.1 Macro-scale: Global exposure in port cities

The most comprehensive study of flood damage exposure at the global level is that of Nicholls et al (2008), which examined exposure to flood damage due to storm surge in 136 global port cities (with populations of over 1 million). The assessment investigates how climate change is likely to affect each port city's exposure to coastal flooding by the 2070s, alongside subsidence, population growth and urbanization. The analysis focuses on the *exposure* of population and assets (economic assets in cities in the form of buildings, transport infrastructure, utility infrastructure and other long-lived assets) to a 100-year surge-induced flood event (assuming no defences), rather than the risk of coastal flooding. Flood protection is not included explicitly as it is difficult to ascertain accurate and comprehensive data on flood protection in many, if not most, of the cities under study.

The following scenarios were used to examine changes in exposure to a 1/100-year water-level event:
** *current city (C):* situation in 2005;
** *future city, no environmental change (FNC):* current environmental situation with the 2070s economy and population scenario;
** *current city, climate change (CCC):* current socio-economic situation with the 2070s climate change and natural subsidence/uplift;
** *current city, all changes (CAC):* current socio-economic situation with the 2070s climate change, natural subsidence/uplift and human-induced subsidence;
** *future city, climate change (FCC):* future socio-economic situation with 2070s climate change and natural subsidence/uplift;
** *future city, all changes (FAC):* future socio-economic situation with 2070s climate change and natural subsidence/uplift and human-induced subsidence.

In order to demonstrate the land area and population exposed to inundation, the investigation took the form of an elevation-based GIS analysis, after McGranahan et al (2007). Current extreme water levels were taken from the database of the Dynamic Interactive Vulnerability Assessment model (DIVA) (DINAS-COAST Consortium, 2006; available at http://www.civil.soton.ac.uk/). The water levels for each future scenario and each city were calculated by combining the appropriate relative sea-level rise, the 100-year return period extreme water level, a storm enhancement factor, and, where appropriate, natural and anthropogenic subsidence. The calculated water levels were used with the population distributions to estimate the exposed population and the value of exposed infrastructure assets at an elevation below the 100-year extreme water level (i.e. those that would be affected by a 100-year event in the absence of any flood defences). Population data were taken from Landscan 2002 and constrained using city extents from postcode data. For each city, the population distribution data were mapped onto the relevant DEM, giving a horizontal map of geographical cells with defined population and elevation. From this, the total populations within 1m vertical bands were extracted. The population 'exposed' below the contour defined by the extreme water level was estimated, thus corresponding to the 100-year event for each scenario. The calculation of exposed assets was based on national per capita Gross Domestic Product (GDP) purchasing power parity (PPP) for 2005, obtained from the International Monetary Fund (IMF) database (see www.imf.org). The assets exposed and at risk were calculated directly from the population measures using a simple relationship between exposed population, GDP per capita and exposed assets.

In total, 136 cities were ranked, with 38 per cent of the cities located in Asia; these cities represent 65 per cent of the global exposed population. The largest share of the economic exposure is in the cities of North America, closely followed by Asia. The total value of exposed assets in all of the cities studied was estimated at approximately US$3000 billion under current conditions. By 2070, the value of these exposed assets could increase up to US$35,000 billion as a result of both climate change and socio-economic growth.

6.2 Meso-scale

6.2.1 Flood risk in the Rhine Delta

An example of a flood risk analysis on a meso-scale is provided by Te Linde et al (2011) for the Rhine Basin, including a part of the Dutch delta area in The Netherlands. Current flood risk is assessed using a simple damage model based on the two input parameters of inundation depth and land use. Calculated damages are combined with estimations of flood return periods for different sections along the Rhine to evaluate flood risk.

The impact of projected climate change and socio-economic developments upon future flood risk is assessed by using two climate change and two socio-economic scenarios. The latter are represented by land-use change projections for 2030 and are derived from a land-use model called the Land-Use Scanner (Loonen and Koomen, 2009). The two (contrasting) socio-economic scenarios used as input for the land-use model are based on the scenarios developed within the EUruralis project (Verburg et al, 2008; Verburg and Overmars, 2009). By combining a low climate change scenario with a low socio-economic scenario, as well as a high climate change scenario with a high socio-economic scenario, the possible bandwidth of future flood risk developments and the associated uncertainties are exemplified. Results indicate that future basin-wide flood risk might increase between 54 and 230 per cent between 2000 and 2030 due to future climate change and on-going socio-economic development in risk-prone areas. The use of both climate and socio-economic scenarios also allows one to separately assess the contribution of each driving factor on future flood risk. Flood risk, for example, has been found to increase by 43 to 160 per cent due to the effect of climate change on flood probabilities, while socio-economic developments contribute to an increase in risk of between 6.5 and 27 per cent.

6.2.2 Flood risk in England and Wales

In order to assess future flood risk in England and Wales, Hall et al (2005) used data on the location, the Standard of Protection (SOP) and conditions of the 34,000km English and Welsh flood defences, as well as on floodplain extent, topography, occupancy and assets values. So-called impact zones were determined using land-use data and 'impact information' (i.e. depth-damage curves and population data). For each impact zone, the probability of failure of the defences, and the water depth at which it would occur (y), were calculated. The resulting economic damage, or expected annual damage (R), was defined as a function of the damage and the probability density function for flood depths y in the impact zone studied. The total expected annual damage (T) in England and Wales was evaluated by summing the expected annual damage R obtained for each impact zone. The social damage was evaluated using the Social Flood Vulnerability Indices, which were developed by Tapsell et al (2002) in order to measure the impact that floods can have upon communities at risk. To calculate the total flood risk, the probability of flooding was estimated as the probability of failure of the flood defences evaluated using the SOP (an assessment of the return period at which the defences will be overtopped) and was combined with the total expected annual damage, also called annual average damage. In order to estimate the future flood risk, emissions and socio-economic scenarios were used.

6.3 Micro-scale

6.3.1 Flood damage model for the city of Dordrecht, The Netherlands

The case study area of the flood damage model developed by Veerbeek and Zevenbergen (2009) for Dordrecht represents 2096ha and includes over 5600 individual buildings. The objective of this damage model was to estimate detailed damages of a potential flood event at the urban scale by taking the density and heterogeneity of the city into consideration. In order to do so, a high level of detail was needed. Specific stage-damage functions were developed using data from the Dutch building sector. To incorporate the influence of flow velocity and flood duration on expected damages, damage functions using flow velocity and flood duration as input parameters were used. The flood damage model resulted in a map representing, for a defined flood event, the number of flooded buildings and the expected aggregated damage per damage cluster. In order to provide usable data for the management of the city, flood damages were also aggregated per administrative neighbourhood and represented with damage curves per neighbourhood. These curves combined the damage and the likelihood of flooding. In order to evaluate and visualize the evolution of future flood damage that the city can expect, the authors used climate change scenarios to estimate changes in sea level and river discharges for flood events with different probabilities (return periods) in 2050 and 2100. The results predicted an increase of the flood damage in Dordrecht in the coming century.

6.3.2 Flood risk on the Perth Metropolitan Area, Australia

Middelmann-Fernandes (2010) carried out an assessment of flood damage on the Swan River system in Perth, and made several interesting findings regarding the use of stage-damage functions. Although the method examines fluvial flooding from the Swan River, the methodology and findings are relevant for both fluvial and coastal flooding in coastal cities. The study estimates the direct tangible damage for residential structures and contents using two different damage functions: one is based on inundation depth only; the second is based on both inundation depth and flow velocity. The study found that the residential damages were underestimated compared to actual insured losses, when either the stage-damage functions or the velocity stage-damage functions were used in isolation. The velocity stage-damage function only identifies those buildings that fail by moving off their foundations, and therefore buildings with only partial damage are not accounted for in the damage calculation. On the other hand, the stage-damage function does not consider that buildings may fail and therefore leads to an underestimation of damage. The study finds that the use of these two methods in combination may provide more accurate information on residential flood risk.

6.4 Case study on the loss of human lives

Maaskant et al (2009) assess the potential loss of life as a result of flooding for the province of South Holland, The Netherlands. This is a densely populated delta area comprising large cities such as Amsterdam, Rotterdam and The Hague, and is largely located below sea level. This study has been selected because it not only assesses potential loss of life at present, but also the spatial and temporal change in flood mortality projected due to future climate change and socio-economic development. Furthermore, the study also provides information on the so-called societal risk level by multiplying flood probabilities with the number of potential fatalities (i.e. average fatalities per year, or risk), and constructs a loss-probability curve. Thus, it provides a good example of how the risk-based approach (see section 2) and the use of climate and socio-economic scenarios (see section 5) can be applied in the context of loss of life due to flooding in coastal areas.

An estimation of potential flood casualties for a given flood event is provided by combining information on inundation characteristics, the population exposed and an estimate of the mortality amongst the exposed population. Flood mortality is thereby defined as the number of fatalities divided by the number of exposed people. A flood mortality function is applied that relates mortality to flood depth. The mortality function applied by Maaskant et al (2009), as well as the 5 to 95 per cent uncertainty bounds, is given in Figure 3.

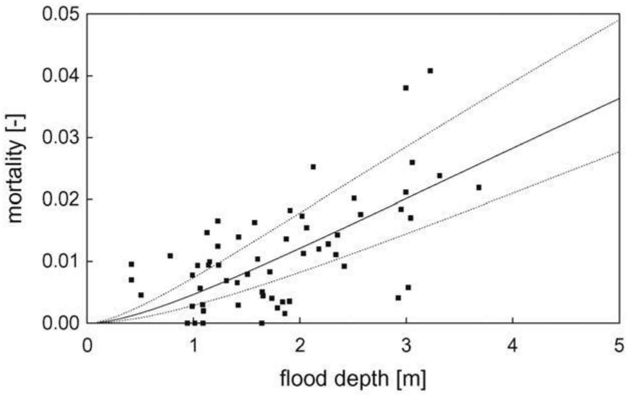

Figure 3 *Mortality function and 5 to 95 per cent uncertainty bounds*
Source: Maaskant et al (2009)

In order to examine changes in flood mortality over time, information from both climate change and socio-economic scenarios are integrated within the modelling approach. Information on the future number, distribution and density of the population is derived from land-use projections for 2040. These projections of future land use for The Netherlands are available from a land-use model referred to as Land-Use Scanner (Schotten et al, 2001; Loonen and Koomen, 2009). The land-use change projections thereby reflect the *Welvaart en Leefomgeving* (WLO) scenarios. The effects of climate change on certain flood characteristics and, consequently, flood mortality are derived from Dutch climate change scenarios (Van den Hurk et al, 2006). Due to a projected rise in sea level and a change in river discharge, flood depths are assumed to increase and flood probabilities are projected to decrease. Taking these developments into account, Maaskant et al (2009) assess the effects of climate change and population growth on flood mortality, both separately and combined. Evaluating the effects of both of these changes on flood mortality is of interest because it allows for the estimation of the independent contribution of each driving factor.

Maaskant et al (2009) find that the share of flood victims per 1000 inhabitants increases by 29 per cent due to population growth in low-lying areas, by 15 per cent due to sea-level rise (and, consequently, higher water depths) and by 47 per cent if both effects are combined. They also show that the societal risk (i.e. the expected number of fatalities per year) increases by more than a factor 4 from 0.37 fatalities per year in 2000 to 1.46 fatalities per year in 2040. This considerable increase is attributed to the increase in the population exposed, as well as the decrease in flood probabilities and the rise in water depths.

7 Uncertainty Assessment

In section 5 we discussed how uncertainties regarding future developments can be addressed by the use of socio-economic and climate scenarios. In addition, uncertainties linked to flood risk assessments can originate from the data or the methods used. As such, uncertainties can arise from the damage functions, the generalization and categorization of land-use data, the use of aggregated data, or faults and inaccuracies in the basic data or in the methods used to estimate the data (USACE, 1996). In order to validate a flood risk analysis as part of a decision support tool, it is important to indicate the uncertainties of the analysis. The reliability of the results can be an important parameter for policy-makers to take into consideration before making a decision (Merz and Thieken, 2009). Ideally, a flood risk analysis should therefore contain the calculated risk results and their uncertainty bounds.

In scientific studies, uncertainty is commonly divided into two broad categories – namely, aleatory uncertainty and epistemic uncertainty. Oberkampf et al (2004) describe aleatory uncertainty as the 'inherent variation associated with the physical system or the environment under consideration'. It is sometimes referred to as variability, irreducible uncertainty and stochastic uncertainty. They state that epistemic uncertainty derives 'from some level of ignorance, or incomplete information, of the system or the surrounding environment'. This is also referred to as reducible uncertainty, subjective uncertainty and model form uncertainty. In their study on flood risk uncertainties in Cologne (Germany), for example, Merz and Thieken (2009) identify sources of aleatory uncertainty as factors, such as the variability of maximum runoff of a catchment in sequential years, while epistemic uncertainty is represented by factors such as a lack of runoff data when defining a probability density function of a river discharge. By increasing the amount and quality of available data, the epistemic uncertainties can be decreased; this is not the case for aleatory uncertainties. Therefore, Merz and Thieken (2009) decided for their study to analyse the two categories of uncertainties separately.

Different approaches can be used to evaluate the uncertainties of an analysis. USACE (1996) describes some approaches: the *Multi-Coloured Manual* gives examples of the integration of uncertainty parameters in damage valuation in England. Merz et al (2004) researched the uncertainties surrounding the relation between depth and damage. This analysis used empirical data and showed that only a small part of the flood depth data explained the resulting damage. De Moel and Aerts (2009) studied uncertainties related to inundation depths, land-use data and stage-damage functions for polder areas in the Dutch delta by varying the values of all of these parameters. They showed that a high proportion of the uncertainties are linked to the inundation depths and the stage-damage functions chosen. In addition, the authors also calculated absolute and proportional changes in flood damage for different land use and different stage-damage functions. The results showed that absolute changes in damage vary between a factor of 1.20 and 4.15, while proportional changes in damage vary between a factor of 1.04 and 1.20. Proportional estimations of the change in damage are therefore more robust than absolute estimations.

8 A Full Chain Example: Storm Surge Risks for the North Sea Region – Assessing Impacts upon Losses and Associated Uncertainties

In the study by Gaslikova et al (2011), the potential impact of changing climate upon coastal flood damage and the associated potential losses were assessed for a number of North Sea neighbouring countries. This was achieved by combining the climate and hydrodynamic models with the loss model from the Swiss Reinsurance Company (Swiss Re). The climate and hydrodynamic models provided the necessary climate change signal relevant for the inland flood assessments (i.e. water levels offshore). The inundation characteristics, in this case inland water depth, were determined by utilizing information about contemporary coastal protection and land elevation maps (90m resolution). To simulate the inland propagation, a planar approach was applied to the data (i.e. any water level above mean sea level in front of the coast could cause inland flooding). Coastal protection was parameterized by an empirical model employing a standard of protection and crest elevation for the coastal dykes, where protection failure probabilities were connected to the water levels near the coast. As the amount of water is limited, the inundated water level was assumed to linearly decrease with increasing distance from the flood source. Local flood depths were aggregated for the postal code areas. The exposure characteristics were presented by the potentially insurable property distribution (according to today's values). Corresponding vulnerabilities were assigned based on Swiss Re's loss experience record. Flood-related losses were estimated for five countries in the North Sea Basin (Denmark, Germany, The Netherlands, Belgium and the UK).

According to the loss model methodology, a representative set of hazardous storm surge events should be considered in order to create a wide spectrum of flooding scenarios, which can further be aggregated to the statistical quantities like annual expected losses. Observations and historic records of storms and associated high water events do not provide a sufficient database for such a loss assessment. First, the spatial coverage is fragmentary and limited to the tide-gauge locations. Second, only events that actually happened in the past are recorded, whereas the equally potential but not realized events are skipped. Moreover, an additional method is necessary to project the historical climatology into the future in order to consider the potential effects of a changing climate. To omit these difficulties, a set of multi-decadal simulations based on historical (reanalysis of the past) as well as scenario (potential future) climate conditions (Weisse et al, 2009) was used for the loss assessments. They provided storm surge water levels, which were obtained by combining an atmospheric climate model, providing wind and atmospheric pressure, with a hydrodynamic model to estimate water levels. This model chain delivered the residual of total water level and tidal cycle. To assess a future climate, two IPCC SRES scenarios A2 and B2 were considered (Bindoff et al, 2007). Additionally, two sea-level rise (SLR) scenarios, the moderate 0.5m and the extreme 1m according to IPCC estimates, were linearly added to the storm surge elevations.

For an adequate assessment of losses and their probabilities, a so-called hazard set or a set of events representative for each climate scenario (present day and future) was constructed. The hazard set included real (dynamically modelled) water levels, as well as equally probable but not

simulated water levels. For the hourly storm surge time series along the coasts of the North Sea, a total of 200 locations were analysed to select the high water events. Several requirements had to be fulfilled:
** retention of spatial patterns of water levels for each storm;
** independence of the events; and
** exceeding a certain threshold by water levels at least in some locations to select only potentially hazardous events.

Each time series was divided into equal time intervals (120 hours) and water-level maxima were identified for each location. If the maxima for at least ten locations exceeded the corresponding thresholds (here, mean annual 99.99 percentile), which was equivalent to the high water event along at least 100km of the coastline, the entire time interval was considered as a storm event and the maxima for all locations were included in the event set. The resulting set of water levels was found to follow a normal distribution.

A set of random events based on the fitted normal distribution parameters and correlation of event sets from different locations was generated. In total, the sets of 20,000 events each were constructed to reflect the historical conditions associated with the period of 1958 to 2002 (hindcast), present-day scenario conditions for 1961 to 1990 (control); and two future development scenarios for 2071 to 2100 (A2 and B2). In combination with the SLR scenarios, these built an ensemble of present-day and future possible high water-level events at the coastline and their probabilities.

It is often the case for recent global and regional atmospheric models that extreme conditions were underrated (e.g. wind speeds were underestimated and sea-level pressure overestimated) for control simulations with respect to the reanalysis (e.g. Woth et al, 2006). Together with differences in the hydrodynamic models and model setups for the reanalysis and scenarios, this lead to an underestimation of storm surge levels for the control simulation and, presumably, for the future scenarios. To give an example, the control and future simulation suffer from the fact that external surges generated beyond the model area (i.e. the North Atlantic) are not included in the simulations. However, as the absolute values (e.g. storm surge heights) were crucial for this study, and not only the differences between future and present-day values, it was important to calibrate the control dataset to the reanalysed dataset and to change the scenarios correspondingly. The method based on the use of cumulative distribution function (CDF) was applied – namely, the CDF of control water levels for each location was linearly fitted to the corresponding CDF from the hindcast. Under the assumption of the stationary relationship, the same transformation coefficients were applied to the scenario CDFs, so the possible deficiencies of the model were treated equally for control and future scenarios.

The results of the study indicated the general increase of losses for all future scenarios and all countries, although the rate of changes varied significantly between countries, but also between climate change scenarios. Furthermore, the model uncertainty spanned the range of expected losses. The mean damage ratio (expected loss divided by total value) presented as a function of return period is called a loss frequency curve. Figure 4 shows the loss frequency curves for Germany estimated for present-day (control) and future scenarios considering only changes in the storm surge climatology, as well as both with additional 0.5m SLR. All future estimated losses differ significantly from present-day ones. However, the uncertainty due to different future scenarios is rather high (shaded areas). Losses only due to changes in surge frequency are comparable with those associated with 0.5m SLR superimposed upon the present-day climate. A combination of both (changed storm surge and SLR) almost doubles the effect. Figure 5 shows the increase in annual expected losses (in percentage) for the A2 scenario and different SLR with respect to the present-day situation for each country and all countries together. The uncertainty associated with the model parameterizations, particularly coastal protection, is shown as error bars. The rate of change of expected losses for the same scenario varies between the countries (e.g. the losses for Denmark are expected to experience a several times larger increase than for The Netherlands). For The Netherlands, the changes associated only with the storm surge climate are very small, whereas the SLR has a more pronounced impact upon the annual expected losses. A possible reason could be that an intensification of storms for these scenarios was mainly found for winds from the south-west direction: these do not cause high surge along the Dutch coast (Sterl et al, 2009). The loss changes are estimated between 15 (no SLR) and 313 per cent (1m SLR) with respect to present-day conditions. For other countries, storm surges alone start to be important. Enhanced by the SLR, they can cause a significant increase of flood losses in the entire region.

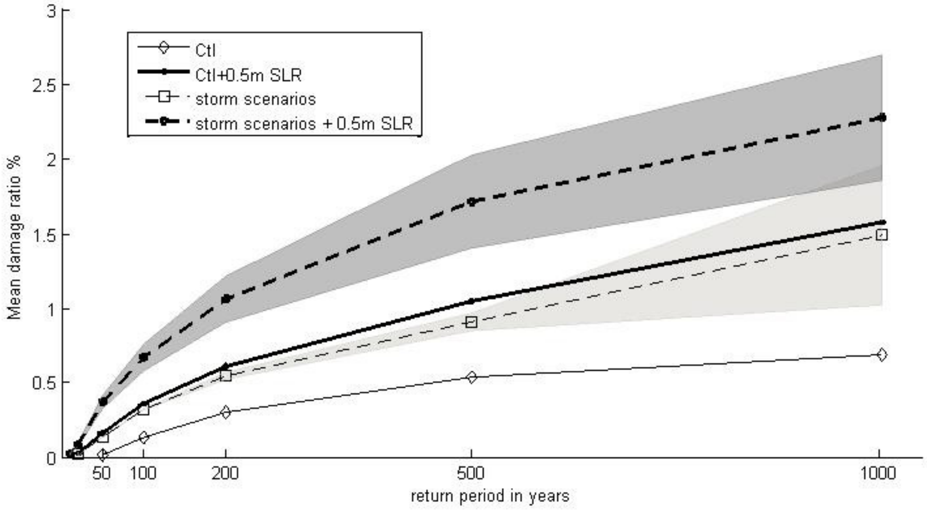

Figure 4 *Mean damage ratio with respect to the total values used for modelling for Germany*
Note: Shading indicates the variance due to storm surge climate associated with different future development scenarios (A2 and B2). Light grey = only storm surges; dark grey = storm surges with 0.5m sea-level rise.
Source: Gaslikova et al (2011)

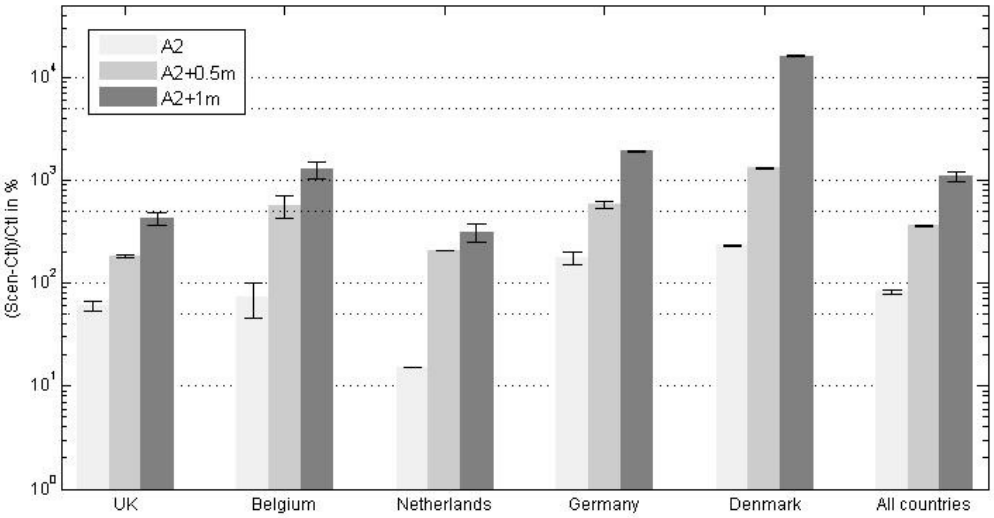

Figure 5 *Increase in annual expected losses from the current to the future climate represented by the A2 scenario (in percentage)*
Notes: Error bars represent uncertainty due to variation in the coastal protection parameter. Currently, the annual expected loss burden from surge events in the study area is approximately 0.6 billion Euros.
Source: Gaslikova et al (2011)

In summary, the general demand is that global studies resolve more details and processes (e.g. protection and more complex inland flood incorporation, more detailed property distribution maps, etc.), whereas more accurate but very local studies provide well validated and tested methodology and generalize results for larger areas without losing accuracy. Gaslikova et al (2011) made an attempt to merge regional coverage (e.g. insurance or country-wise economic loss assessment) with local features. Although no socio-economic scenarios were explicitly included within the model, significantly different results were obtained for various countries. These can be attributed to non-uniform changes in storm surge climate for different parts of the North Sea, as well as diverse exposure due to both geographical properties and the characteristics of coastal protection.

9 Conclusions

In this report we describe important concepts in flood risk assessment and modelling, where flood risk is defined as the probability of flooding multiplied by the potential consequences of a flood. Flood risk assessment is useful since it allows us to estimate current risk, as well as the change in risk that can be expected in the future; to assess the effectiveness of adaptation measures in reducing flood risk; and to create flood risk maps to raise public risk awareness. Flood risk assessments require data on both the flood hazard (e.g. inundation depth, flow velocity, etc.) and the consequences of flooding (e.g. economic damage and loss of life). Flood damage includes damage such as physical, economic, psychological or environmental damage. These damages are divided between direct and indirect damages, and between tangible and intangible damages. Flood risk is usually assessed in flood damage models, which combine information on flood hazard characteristics, such as inundation depth, with data on exposure and vulnerability characteristics. Flood damage is calculated for flood events of several return periods, from which a damage-probability curve can be derived. Flood risk can then be considered as the average total expected flood damage per year, represented by the integral of the area under the damage-probability curve. In order to evaluate the evolution of risk over time, climate change and socio-economic scenarios can be used. Climate change scenarios enable us to obtain information on changes in hazard characteristics, while socio-economic scenarios provide data to determine the changes in exposure and vulnerability characteristics. Different case studies are described in this report in order to show how different researchers approach risk analysis in practice. An important facet of risk analysis concerns the identification and quantification of uncertainties. In fact, the methods used to collect and evaluate the data, and the quality and availability of the input data themselves, lead to uncertainties in the results. If flood risk assessments are to be used in flood management decision-support and awareness-raising campaigns, it is important to recognize and analyse the uncertainties related to the processes, and to quantify the reliability of the risk analysis. The report ends with the description of an assessment of the impacts of climate change in the North Sea region, which is provided in order to give an example of the assessment of the impacts of flooding and the associated uncertainties using scenarios.

To conclude, even though flood risk and flood damage assessments have received growing attention during recent years, the scientific field of flood risk assessment still lags behind the better developed fields of hydrology and hydraulics (Büchele et al, 2006; Merz et al, 2010). Given the importance of information on flood damage and risk for developing and supporting sound flood management strategies and adaptation planning, further advances seem necessary. Aspects that are repeatedly mentioned in this respect are the lack of (publicly available) flood damage data, as well as missing information on data quality.

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