Disasters and climate change

Analyses and methods for projecting future losses from extreme weather

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Disasters and climate change: analyses and methods for projecting future losses from extreme weather

Rampen en klimaatverandering: analyses en methodes voor de projectie van toekomstige schade door extreem weer

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Disasters and climate change: analyses and methods for projecting future losses from extreme weather

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Summary

This thesis, titled "Disasters and climate change: analyses and methods for projecting future losses from extreme weather", examines to what extent anthropogenic climate change will result in more damage from weather-related natural disasters during the next decades, in comparison to non-climatic drivers of risk. A review is made of the scientific literature on historic disaster losses, as well as projections of future disaster losses. Also, an analysis is made of changing risks from flooding of rivers for a case study area in The Netherlands, and their climatic and socioeconomic causes. From this research I conclude the following:

Past increases in weather disaster losses are due to non-climatic drivers: Economic losses from weather disasters (including floods, windstorms, tornadoes, thunderstorms, wildfires and droughts) have undoubtedly increased, but no scientific study of loss records has identified anthropogenic changes in extreme weather as the main driver for the observed trend. The observed loss increase is caused primarily by increasing exposure and value of capital at risk. The overview of studies presented in this thesis shows that loss records that were corrected for changes (increases) in population and capital at risk show no long-term trends that can be attributed to anthropogenic climate change. That no trend has yet been found in corrected losses follows logically from the fact that anthropogenic changes have only been detected for a few weather extremes.

Projections of future weather risks need a comprehensive approach: Most studies have not sufficiently taken into account the consequences side of risk. The role of economic growth and population growth is in most instances ignored. This thesis proposes a comprehensive approach, that combines scenarios of changing exposure with a catastrophe model. The approach is aimed at quantifying the bandwidth of the possible development of future weather risks, in this case flood losses. It seems warranted to expand the efforts in projecting and analysing the role of exposure in future disaster risks.

River flood losses could increase more rapidly than windstorm losses: The future increase in losses from river flooding due to anthropogenic climate change may be higher than the increase in windstorm losses. This expectation is based on a comparison of loss projection studies. The difference in the increase in risk is due to the difference in projected changes in the river flood and windstorm hazards, that show larger increases in flood frequency compared to windstorm frequency or intensity. Also, there is more certainty that intense precipitation will become more frequent. Projections of changes in floods are somewhat more robust compared to projections of windstorms. That this effect will be found in loss records in reality is

uncertain, given that flood losses are often not well recorded. Also, differences in exposure to storms and floods, as well as risk reduction measures, may differentiate trends in both types of disaster losses.

Through an analysis of historic river discharges and time series of large scale atmospheric circulation and sea-level pressure, it is shown that variations in high river discharges in Europe in winter are caused by variations in the frequency of west atmospheric circulation. High river discharges are found to be more sensitive to these variations than the mean discharges. If anthropogenic climate change would lead to an increasing pressure gradient in the northern hemisphere, flood probability in northwest Europe could increase. The analysis in this thesis shows that some periods, in particular the 1990s, stand out in terms of high peak discharge occurrence in northwest Europe, but such periods have also occurred earlier in the record, in particular during the 1910s and 1920s.

The impact of climate change on weather losses will remain small in coming decades: For a case study on flooding of the river Meuse in The Netherlands, future impacts on river flood risk have been separated for projected climate change and exposure. It is found that anthropogenic climate change may lead to a substantial increase in potential flood losses for this case by the year 2040 (up to 201%), that is about as large as the increase in exposure due to land-use change and increasing value of capital combined (up to 172%). All published projections of future weather risks that have been assessed in this thesis show increases in losses due to anthropogenic climate change by the middle of this century. However, for the period up to 2040, the contribution from increasing exposure and value of capital at risk according to current studies is substantially (about 2-10 times) larger than the contribution from anthropogenic climate change. Given the fact that loss events are stochastic, and that their occurrence varies over time due to natural climatic variations, the relatively small signal from anthropogenic climate change until the year 2040 is likely to be lost among other causes for increasing and varying losses, at least for storms and river floods.

Implications for climate policy: Attribution of increases in disaster losses to anthropogenic climate change will remain very difficult in the decades to come. There are other impacts from climate change, apart from changed impacts of extreme weather, that should be the primary motivation for the reduction of greenhouse gas emissions. Adaptation to changing risks seems the most effective way of reducing the increasing impact from extreme weather in the short term, up to the middle of this century. Therefore efforts in climate policy and other policies should be focussed on better understanding the actual causes of risk, and on promoting adaptation also in the short term, in addition to efforts for emission reduction.

Samenvatting

Dit proefschrift, getiteld “Rampen en klimaatverandering: analyses en methodes voor de projectie van toekomstige schade door extreem weer”, onderzoekt in hoeverre antropogene klimaatverandering zal leiden tot meer schade door weergerelateerde natuurrampen in de komende decennia, in vergelijking tot niet-klimatologische oorzaken. De wetenschappelijk literatuur over historische rampschade wordt onderzocht, naast projecties van toekomstige rampschade. Ook wordt een analyse gemaakt van veranderende overstromingsrisico’s van rivieren voor een gevalstudie in Nederland, en de klimatologische en sociaaleconomische oorzaken daarvan. Op basis van dit onderzoek concludeer ik het volgende:

De stijging van weergerelateerde rampschade in het verleden is veroorzaakt door niet-klimatologische oorzaken: De economische schade van weergerelateerde rampen (waaronder overstromingen, windstormen, tornado’s, onweersbuien, bosbranden en droogtes) is ongetwijfeld gestegen, maar er is geen wetenschappelijke studie die antropogene veranderingen in extreem weer als hoofdoorzaak heeft geïdentificeerd voor de waargenomen trend. De waargenomen stijging van schade is vooral veroorzaakt door een toename in blootstelling en waarde van kapitaal. Het overzicht van studies dat in dit proefschrift wordt gepresenteerd laat zien dat schadegegevens die zijn gecorrigeerd voor veranderingen (toenames) in bevolking en kapitaal geen lange termijn trend vertonen die kan worden toegeschreven aan antropogene klimaatverandering. Dat er nog geen trend is gevonden in gecorrigeerde schades volgt logisch uit het feit dat antropogene veranderingen voor maar een aantal weersextremen zijn gedetecteerd.

Projecties van toekomstige weergerelateerde risico’s behoeven een uitgebreide aanpak: De meeste studies houden niet voldoende rekening met de gevolgenkant van risico’s. De rol van economische groei en bevolkingsgroei is in de meeste gevallen buiten beschouwing gelaten. Dit proefschrift stelt een uitgebreide aanpak voor, dat scenario’s van veranderingen in blootstelling combineert met een catastrofemodel. De aanpak heeft als doel de bandbreedte van de mogelijke ontwikkeling van toekomstige weergerelateerde risico’s van extreem weer te kwantificeren, in dit geval van overstromingsschade. Het lijkt gerechtvaardigd om inspanningen op het gebied van het projecteren en analyseren van de rol van blootstelling uit te breiden.

Rampschade door overstromingen zou sneller kunnen toenemen dan schade door windstormen: De toekomstige toename in schade van overstromingen door antropogene klimaatverandering zou hoger kunnen zijn dan de toename in schade van windstormen. Deze verwachting is gebaseerd op een vergelijking van studies naar schadeprojecties. De verschillen in toename in schaderisico wordt veroorzaakt door het verschil in geprojecteerde veranderingen in rivieroverstromingen en windstormen, die een grotere toename laten zien in overstromingsfrequentie in vergelijking met de frequentie en intensiteit van windstormen. Er is ook meer zekerheid dat intense neerslag frequenter zal voorkomen. Projecties van veranderingen in overstromingen zijn enigszins meer robuust dan projecties in stormen. Dat dit effect ook daadwerkelijk zal worden gevonden in schadegegevens is onzeker, omdat overstromingsschade vaak niet goed wordt gedocumenteerd. Ook verschillen in blootstelling aan overstromingen en stormen, en maatregelen om risico's te verminderen, kunnen leiden tot afwijkingen in de trends van beide types schade.

Met behulp van een analyse van historische rivierafvoeren en tijdseries van grootschalige atmosferische circulatie en luchtdruk is aangetoond dat variaties in hoge afvoeren van rivieren in Europa in de winter worden veroorzaakt door variaties in de frequentie van westelijke atmosferische stroming. Hoge rivierafvoeren blijken gevoeliger te zijn voor deze variaties dan de gemiddelde afvoer. Indien antropogene klimaatverandering zou leiden tot een toename in de drukgradiënt op het noordelijke halfrond, dan zou de overstromingskans in noordwest Europa kunnen toenemen. De analyse in dit proefschrift laat zien dat sommige periodes, zoals de jaren '90 opvallen in termen van het voorkomen van hoge piekafvoeren in noordwest Europa, maar dat zulke periodes ook eerder zijn voorgekomen, in het bijzonder in de jaren '10 en '20.

De gevolgen van klimaatverandering voor schade door extreem weer zal klein blijven in de komende decennia: Toekomstige gevolgen van geprojecteerde klimaatverandering en blootstelling voor overstromingsschade zijn onderscheiden voor een gevalstudie van overstromingsrisico's langs de Maas in Nederland. Hieruit blijkt dat antropogene klimaatverandering kan leiden tot een substantiële toename in het risico van overstromingsschade voor dit geval in het jaar 2040 (tot 201%), wat ongeveer even groot is als de toename in blootstelling door landgebruikveranderingen en toename in waarde van kapitaalgoederen gecombineerd (tot 172%). Alle gepubliceerde projecties van toekomstige schade door extreem weer die zijn onderzocht in dit proefschrift, laten zien dat schade door antropogene klimaatverandering toeneemt tot het midden van deze eeuw. Echter, voor de periode tot 2040 is de bijdrage van toenemende blootstelling en waarde van kapitaal volgens de studies substantieel (2 tot 10 keer) groter dan de bijdrage van antropogene klimaatverandering. Omdat schadegevallen stochastisch zijn, en hun voorkomen variabel is over de tijd door natuurlijke klimaatvariaties, is het waarschijnlijk dat het relatief kleine signaal van antropogene klimaatverandering tot het jaar 2040 verloren gaat tussen andere oorzaken van toenemende en variërende schade, ten minste voor stormen en rivieroverstromingen.

Consequenties voor klimaatbeleid: Het toeschrijven van toenames in rampschade aan antropogene klimaatverandering zal zeer moeizaam blijven in de komende decennia. Er zijn andere gevolgen van klimaatverandering, naast veranderde gevolgen van extreem weer, die de primaire reden voor het verminderen van emissies van broeikasgassen zouden moeten. Aanpassing of adaptatie aan veranderende risico's lijkt de meest effectieve manier om de toenemende gevolgen van extreem weer te verminderen op de korte termijn, tot het midden van deze eeuw. Daarom zouden inspanningen in klimaat- en overig beleid kunnen worden gericht op beter begrip van de oorzaken van risico's, en op het aanmoedigen van adaptatie ook op de korte termijn, naast inspanningen om emissies te reduceren.

Chapter 1. Introduction

1.1 Problem definition and scope

Natural disasters are regarded as the ultimate expression of the destructive forces of nature. They feature often on the evening news around the world. Many people suspect that climate change is influencing the occurrence and impact of natural disasters, mainly because the number and severity of disasters around the world has been increasing (UN-ISDR, 2009a; Munich Re, 2010). Especially the insurance sector has been concerned with this issue for some time (Dlugolecki, 1992; Vellinga and Tol, 1993; Vellinga et al., 2001). Climate change occurs because of high and low frequency natural variations, and because of atmospheric pollution through anthropogenic greenhouse gas emissions[1]. The issue has evolved over recent years to become the most important environmental issue. But do we really know how climate change is affecting weather disasters? The knowledge about the impacts of climate change on weather hazards has improved considerably during the last few years, and recent changes in temperature and rainfall that are being observed have partly been caused by greenhouse gas emissions (IPCC, 2007a). Disasters however are defined by the disruption of the functioning of society, involving widespread human, material, economic or environmental losses (UN-ISDR, 2009b), and is thus largely influenced by population and their location (Hewitt, 1997).

Traditionally, two research communities have dealt with weather disasters. One is the 'disaster risk management' community, that studies natural hazards in detail, and is mostly concerned with reliable estimation of contemporary risk, often through the application of catastrophe models (Grossi and Kunreuther, 2005). The other is the 'climate impacts' community, that is studying historic and future impacts of climate change, by use of scenarios for climate and socioeconomic development in integrated assessment models. The latter models usually omit or include losses from weather extremes in a simplified manner (Tol, 2002; Goodess et al., 2003; Smith et al., 2009). While the analysis of observations and modelling of the physics of weather has contributed to understanding future changes in extreme weather, the exposure and vulnerability to hazards matter at least just as much. There is therefore a need to also understand the role of societal change (Pielke and Sarewitz, 2005), and science should put more emphasis on the role of socio-economic development in disaster losses. The challenge is to find a bridge between the two communities, by combining exposure and climate scenarios and catastrophe models for assessing future risk. This need for combining approaches has been

[1] Throughout this thesis, 'climate change' is principally meant to refer to anthropogenic climate change. The distinction between natural and anthropogenic causes for change is however not trivial. In this thesis, natural climate change, caused by natural or non-anthropogenic external and internal forcings, is referred to as 'climate variability'.

highlighted by some scholars (e.g. Hallegatte, 2008; Mechler et al., 2010). This thesis will make use of these two approaches, and thereby contributes to an integration of methods.

The scope of this thesis includes all weather related natural disasters, with a focus on flood risks in river basins. Flooding is the most important natural hazard in many low-lying regions of the world, including the country of The Netherlands. Moreover, although uncertainties are large, the impact from climate change on flood risk in river basins has been well established, compared to impacts on other weather extremes (IPCC, 2007a; IPCC, 2007b). In this introduction chapter I will briefly discuss the relation between climate change and flooding, and the historic changes in the flood risk in The Netherlands, the country in which the case study area for this thesis is situated. The main research questions that will be addressed in the subsequent chapters of the thesis are also presented.

1.2 Climate change and flood risks

Climate change may impact on all weather phenomena. However, future changes in temperature and precipitation have been established with most certainty, while the exact impact on storms and smaller scale weather extremes, such as tornadoes and hail, remains largely unknown (IPCC, 2007a: Table SPM.2). Research has established a human imprint on precipitation trends (Zhang et al., 2007). Also, there is now evidence that with increasing temperatures, precipitation extremes above a certain temperature may increase twice as fast as predicted by the Clausius-Clapeyron relationship between temperature and atmospheric water holding capacity (Lenderink and Van Meijgaard, 2008). In addition, duration and frequency of atmospheric circulation, that determine the duration of rainfall, may shift because of climate change. The expectation that with climate change, intense and prolonged precipitation and consequently river floods may become more frequent in some locations is quite robust. Therefore, studying river floods seems relevant for informing decision makers on future risks[2].

The flood hazard is a weather related risk with wide ranging consequences. In Europe, flooding that is caused by intense rainfall events (including mass movements in mountainous areas) accounts for a share of about a quarter of the number of weather related disasters (Figure 1.1). It caused the majority of weather-related losses over the past 28 years; namely a total of 75 billion Euros. Windstorms have generally a high insurance cover, leading to more insured losses, while heat waves have caused most deaths, in particular during the heat wave in the summer of 2003. Flooding, however, constitutes the most important economic extreme weather impact in the European economy, with a share of 40% of total economic losses.

[2] Note that Chapters 2, 3 and 7 of this thesis address impacts also from other weather extremes.

This stresses the importance for studying potential changes in the future frequency and impact of flooding on losses.

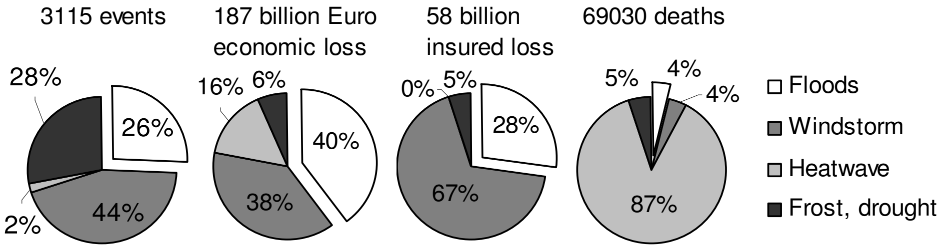

Figure 1.1. Extreme weather impacts in Europe 1980-2007 (figure after EEA, 2008; data from Munich Re).

While climate change is expected to lead to an increase in the flood hazard in particular regions, many other non-climatic factors affect river discharge and the occurrence of flooding as well, such as land-cover change, river management and training. Also, flood events are rare, and for most rivers in the world homogenous and long time series that allow for the analysis of any changes in flood hazards are lacking. No unidirectional trends have yet been found for the number of flood events around the world (IPCC 2007b: Section 1.3.2; Kundzewicz et al., 2005). At the same time, hydrological analysis of projected future climate change shows considerable changes in the frequency of peak discharges of rivers (IPCC, 2007b), which indicates future changes in risk.

1.3 The evolution of flood risk in The Netherlands

The flood prone parts of The Netherlands form an interesting case study, given their low elevation and exposure to flood hazards from the sea and the two large rivers, the Rhine and Meuse. The country also exemplifies the situation of many highly urbanised delta areas around the world. Like in other regions, much of the population and economic activity is located at or slightly below sea-level. As Chapter 2 of this thesis describes, such areas will see increasing risks from natural hazards, not only because of climate change, but also because of ongoing population growth and economic development. Detailed analyses of projected future risks in these areas however are currently lacking.

Dutch water managers have been very successful at minimising flood probabilities. This has resulted in a reduction of risk, despite an increase in population and wealth. Figure 1.2 shows how flood loss probabilities have evolved over the past 55 years in The Netherlands. A clear shift can be seen of loss exceedance probability curve toward lower probabilities over time. Flood risk, which can be defined as the annual expected loss (AEL), consists of the integral of these loss probability curves.

The annual expected loss first increased from some 120 million Euros per year in the 1950s, to 368 million Euros in the 1970s, and then declined to some 170 million Euros in 2005[3]. The successful reduction in annual expected losses in The Netherlands has been achieved by upgrading the flood defence systems, in particular by the reinforcement and heightening of dikes. This resulted in a substantial decline of the probability of flooding and consequent loss events. At the same time, the magnitude of the largest loss events with a low probability has increased, as is apparent in Figure 1.2 from a gradual uplift of the loss probability curve. This increase in the potential damage associated with large floods is a result of increasing habitation and amount of capital exposed in the low-lying areas in the west of the country, resulting in an increase in the potential losses.

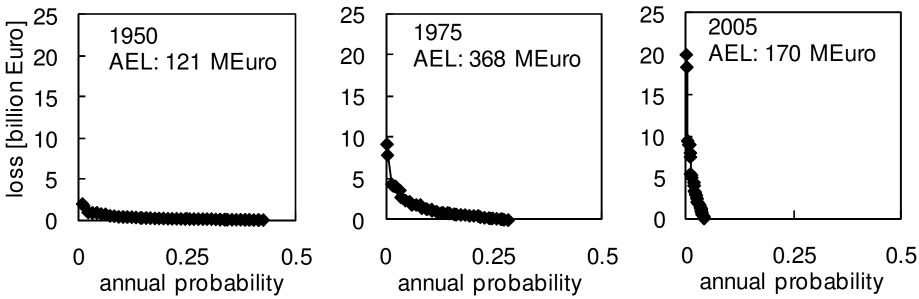

Figure 1.2. Flood loss exceedance probability curves for The Netherlands for the years 1950, 1975 and 2005, corrected for inflation only (data: Van der Klis et al., 2005).

Of course, increases in wealth play a major role, and the loss curves corrected for wealth, measured by the national gross domestic product (GDP), show a smaller, but still significant increase in the greatest loss events that can occur[4] (Figure 1.3). Some studies have found that potential losses from flooding in The Netherlands have increased to higher levels over recent decades (Vellinga, 2003; MNP, 2004; Bouwer and Vellinga, 2007), necessitating renewed flood risk management plans. Also studies that assess future flood risks show that flood risks are likely to continue to increase substantially due to socioeconomic developments (Klijn et al., 2007; Aerts et al., 2008). Such loss increases are not always counterbalanced by an increased ability to pay through rising wealth (De Moel et al., submitted).

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[3] Note that this is a very rough analysis, and only an approximation of the actual historic and current flood risk, corrected for inflation only, to 2004 prices. Most importantly, Van der Klis et al. (2005) report that the risk of very high loss events with low probabilities has been ignored in their estimates.

[4] This shift points to the fact that risk cumulation has increased, meaning an increase in potential catastrophic losses, which is known from empirical research to be less favoured by actors then increases in average expected losses (see e.g. Aerts, 2009, for a discussion).

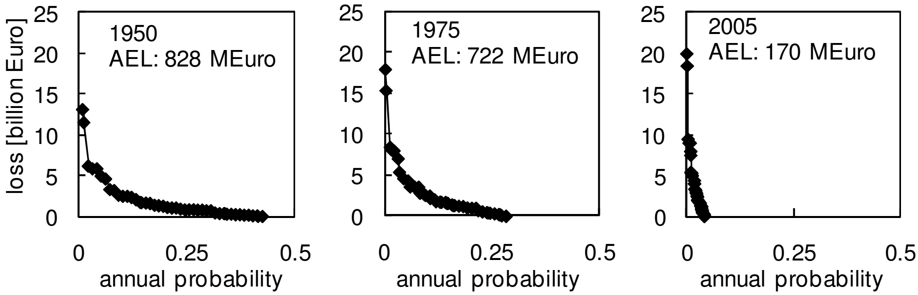

Figure 1.3. Flood loss exceedance probability curves corrected for changes in wealth (risk data from Van der Klis et al., 2005; GDP data from CBS Statline).

Although risk measured in annual expected losses has decreased, the maximum potential loss amounts have increased considerably as population and capital at risk grow. This raises the question whether in the long term risk management through the reduction of flood probabilities is sufficient. Anthropogenic climate change, through changes in extreme weather events, potentially adds to these rising risk levels. Increasing risk has potentially three causes; increasing flood probabilities, and increasing capital and people at risk, and increasing vulnerability of capital and people. Although many studies have highlighted the important role of the latter (e.g. Changnon et al., 2000), there is a need to further quantify historic and future changes. Given the difficulty to mitigate climate change, and since a certain amount of future climate change will be unavoidable because of historic greenhouse gas emissions, adaptation is gaining increasing attention around the world as a complementary strategy to the reduction of emissions (Pielke et al., 2007). Within adaptation planning, a comprehensive approach is needed that reduces both the hazard probability, and the exposure and vulnerability of the natural and human systems. In order to prepare, evaluate and plan adaptation, quantification of expected climate change impacts is needed.

1.4 This thesis

This thesis aims to examine how the impact from climate change on damage caused by weather disasters compares to other influences. This is done by analyzing current literature, and by empirical study and modelling of the links between climate change, peak discharges and losses from river flooding. The thesis is focussing on river flood risks[5], because these are relatively severe and likely to be affected by climate change. As argued earlier, an analysis of historic and future impacts from

[5] Sea-level rise and changes in storms can obviously also affect flooding probabilities along the coast, but for sake of simplicity this thesis mainly focuses on river flood risks. Some studies have also taken into account the impact of sea-level rise in The Netherlands, in an integrated approach similar to this thesis, e.g. Aerts et al. (2008) and Maaskant et al. (2009).

anthropogenic climate change cannot be performed without taking into account 'people and place'. Changes in exposure, that occur because of population and economic growth, consequent land-use change, and increasing wealth, affect the levels of risk. These processes have considerably contributed to increasing losses from natural disasters, as has been observed in the past, and will likely continue in the future.

I apply the conceptual approach as illustrated below for river floods (Figure 1.4). The river flood hazard is determined by a chain of climatological processes, notably warming of the atmosphere through changes in its energy balance, and consequent increasing amount of precipitable water in the atmosphere, changes in atmospheric circulation, and changes in the frequency and duration of intense precipitation. Exposure and vulnerability are shaped by socioeconomic drivers. Damages occur due to a combination of hazard (flood occurrence), exposure (number of people and amount of property in at-risk areas), and vulnerability (sensitivity of people and property to harm or damage due to inundation). The main factor driving exposure is the process of increasing urbanisation of at-risk areas, due to the increase in population and changes in household composition resulting from cultural change (Changnon et al., 2000). Increasing wealth and real value of capital contribute to increasing levels of monetary exposure. Changes in vulnerability are mainly driven by economic development, and may either lead to increasing or decreasing susceptibility to damage[6] when buildings, infrastructure and assets are exposed to the same hazard.

When considering historical or future damages, these socioeconomic changes need to be accounted for. While many studies have tried to assess future risks in considerable detail, most integrated assessment models of climate change use a highly aggregated approach at a low spatial resolution. Catastrophe models have the required spatial detail and representation of physical processes, but are usually not applied for projections of losses over coming decades. This thesis therefore uses the spatial detail found in catastrophe modelling, combined with socioeconomic scenarios for exposure that are often applied in integrated assessment models. This is an innovation over previous studies, that have mostly studied the effect of climate change only.

My thesis addresses the following questions:

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[6] Note that vulnerability in a wider sense may also include other aspects, in particular the ability to cope or respond to disturbances (e.g. Klein et al., 2004; Adger, 2006; Füssel and Klein, 2006). Although the wider concept is definitely relevant for disaster risk management, I use vulnerability in a more narrow sense, that is susceptibility to harm. The wider definition is more relevant for social vulnerability than for vulnerability of capital and assets, and is more difficult to assess and extrapolate in a quantitative sense (Brouwer et al., 2007), and therefore beyond the scope of this thesis.

- What are the main historic drivers of disaster losses?
- How have flood hazards evolved over recent decades in Europe?
- What are the main drivers of disaster losses in the future; what is the role of climate change, and what are the main uncertainties in such projections?

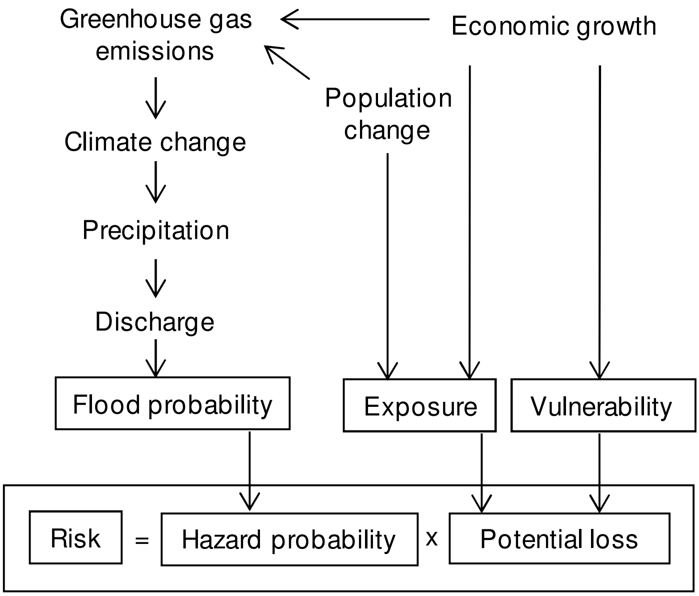

Figure 1.4. Conceptual approach of the analysis of changes in flood risk.

The remainder of this thesis is structured as follows: Chapter 2 discusses contemporary issues in weather disaster management, and the links to climate change adaptation, and builds on the results from an international workshop held in 2006. Chapter 3 discusses increases in losses caused by weather related disasters from a series of published impact studies, their causes, and in particular the role of anthropogenic climate change. Chapter 4 analyses the links between variability in atmospheric circulation and river discharges in Europe over timescales of decades. Chapter 5 introduces a method to simulate flood losses from river flooding for a case study area in The Netherlands. This case study area consists of a low-lying polder area along the river Meuse in the southeast of The Netherlands. Chapter 6 presents the results of flood loss projections under climate change and socio-economic change for this case study area. Chapter 7 presents an overview of loss projection studies of weather-related risks from the literature, and puts the results from Chapter 6 in perspective. Finally, Chapter 8 discusses the main conclusions and findings of this thesis.

Chapter 2. Weather disaster management

Abstract

Action on disaster risk reduction can support sustainable development under climate change.

2.1 Increasing weather related losses

According to data collected by Munich Re, global costs (inflation adjusted, 2006 dollars) of weather-related disasters have increased from an annual average US$8.9 billion (1977-1986) to US$45.1 billion (1997-2006). Munich Re's data comes from their NatCatSERVICE database and includes losses from designated great natural weather catastrophes. Great natural catastrophes match the criteria that an affected region's ability to help itself is distinctly overtaxed and hence interregional or international assistance is necessary. As subsidiary criteria serve substantial overall losses defined as exceeding 10^6 * 5% of per capita GDP (developed countries) or at least US$300 million (developing countries) and/or more than a thousand fatalities, and/or more than a hundred thousand people made homeless. This data set is generated to be homogenous since the 1970s, as it does not include smaller weather events that would be underreported earlier in the record. Annual losses in Munich Re's global data set are highly correlated (r^2=0.68) with annual U.S. hurricane losses from 1970-2005 (Pielke et al., 2008).

However, because of issues related to data quality, the low frequency of extreme event impacts, limited length of the time series, and various societal factors present in the disaster loss record, it is still not possible to determine the portion of the increase in damages that might be attributed to climate change brought about by greenhouse gas emissions (Höppe and Pielke, 2006). This conclusion is likely to remain unchanged in the near future (Höppe and Pielke, 2006).

Inflation-adjusted data from Munich Re indicates that the average annual losses from the period 1977-1986 to the period 1997-2006 increased at a decadal rate of about 125%. Over the same period, annual growth in real GDP was smaller, and averaged 35 to 45% between decades (OECD, 2001; IMF, 2006). The larger increase in disaster losses could reflect more rapid relative growth in vulnerable locations, changes in climate events (regardless of cause), or both. Median annual losses increased between the two periods by a decadal rate of about 55%. The increase in median losses is lower than the mean because the size of the largest losses increased by a greater amount. The largest annual loss in the most recent

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decade reached U.S.$180.9 billion (2005); during 1977-1986, it was U.S.$24.1 billion. As median loss potentials increase because of changes in population and per capita real GDP, so too will the potential for extreme losses as risk becomes increasingly more concentrated.

2.2 Attribution of loss increases

Societal change and economic development are mainly responsible for increasing losses in recent decades, as convincingly shown in analyses of long-term records of losses (Höppe and Pielke, 2006). After adjusting for societal changes, resulting time series accurately reflect documented trends (or lack thereof) and variability consistent with the observed climatological record of weather events (Pielke and Landsea, 1999; Downton et al., 2005; Höppe and Pielke, 2006;). This implies that the net result of the adjustments has to a significant degree successfully removed the signal of societal change from the loss record.

A community perspective on the relation between climate change and disaster losses was developed at an international workshop (Höppe and Pielke, 2006) in May 2006, summarised in Table 2.1. The consensus reached at that workshop can inform expectations for the immediate future and decision-making in the context of those expectations.

Table 2.1. Consensus (unanimous) statements of the Hohenkammer workshop (Höppe and Pielke, 2006).

1. Climate change is real, and has a significant human component related to greenhouse gases.
2. Direct economic losses of global disasters have increased in recent decades with particularly large increases since the 1980s.
3. The increases in disaster losses primarily result from weather related events, in particular storms and floods.
4. Climate change and variability are factors which influence trends in disasters.
5. Although there are peer reviewed papers indicating trends in storms and floods there is still scientific debate over the attribution to anthropogenic climate change or natural climate variability. There is also concern over geophysical data quality.
6. IPCC (2001) did not achieve detection and attribution of trends in extreme events at the global level.
7. High quality long-term disaster loss records exist, some of which are suitable for research purposes, such as to identify the effects of climate and/or climate change on the loss records.
8. Analyses of long-term records of disaster losses indicate that societal change and economic development are the principal factors responsible for the documented increasing losses to date.
9. The vulnerability of communities to natural disasters is determined by their economic development and other social characteristics.

10. There is evidence that changing patterns of extreme events are drivers for recent increases in global losses.
11. Because of issues related to data quality, the stochastic nature of extreme event impacts, length of time series, and various societal factors present in the disaster loss record, it is still not possible to determine the portion of the increase in damages that might be attributed to climate change due to GHG emissions
12. For future decades the IPCC (2001) expects increases in the occurrence and/or intensity of some extreme events as a result of anthropogenic climate change. Such increases will further increase losses in the absence of disaster reduction measures.
13. In the near future the quantitative link (attribution) of trends in storm and flood losses to climate changes related to GHG emissions is unlikely to be answered unequivocally.

Policy implications identified by the workshop participants:

14. Adaptation to extreme weather events should play a central role in reducing societal vulnerabilities to climate and climate change.
15. Mitigation of GHG emissions should also play a central role in response to anthropogenic climate change, though it does not have an effect for several decades on the hazard risk.
16. We recommend further research on different combinations of adaptation and mitigation policies.
17. We recommend the creation of an open-source disaster database according to agreed upon standards.
18. In addition to fundamental research on climate, research priorities should consider needs of decision makers in areas related to both adaptation and mitigation.
19. For improved understanding of loss trends, there is a need to continue to collect and improve long-term and homogenous datasets related to both climate parameters and disaster losses.

2.3 Projections of future losses

Within the next 20 years projected changes in the intensity and frequency of extreme events-depending on the time scale and hazard-remain uncertain. The most severe effects of human-caused climate change are expected in the second half of the century (IPCC 2007a, b). In coming decades, the number of people at risk from extremes will very likely grow, and extreme weather will likely increase (IPCC, 2007a; b). In the immediate future, disaster losses will increase already as a result of societal change and economic development, independent of climate change.

Growing population and capital in mega-cities exemplify loss potential increases in the near future. Most of these cities are located in vulnerable coastal areas and river plains in developing countries. The continents most prone to large numbers of fatalities in disasters-Asia, Africa, and Latin America-currently contain around 275 cities with more than a million people. This number is expected to grow to over 400 during the next decade (PWC, 2007). Table 2.2 presents the projected increase in population and economic loss potentials for the world’s 10 largest cities. The loss potentials are the percentage changes in projected real GDP (PWC, 2007), which includes United Nations population estimates (UN, 2006). In all, loss potentials of 79 of the world's 151 largest cities are expected to grow faster than 3.5% annually and 70 by more than 4.0%.

Table 2.2. Increase in mega-city disaster loss potential from 2005 to 2015. Ranking is by population at 2015. Population estimates (UN, 2006), estimated GDP (PWC, 2007).

City	Population [million]			Estimated GDP [US$ bn 2005 PPP]		
	2005	2015	Change [%]	2005	2015	Change [%]
Tokyo, Japan	35.2	35.5	0.8	1191	1452	22
Mumbai, India	18.2	21.9	20	126	226	79
Mexico City, Mexico	19.4	21.6	11	315	489	55
São Paulo, Brazil	18.3	20.5	12	225	336	49
New York, USA	18.7	19.9	6	1133	1408	24
Delhi, India	15.0	18.6	24	93	170	83
Shanghai, China	14.5	17.2	19	139	261	88
Kolkata, India	14.3	17.0	19	94	167	78
Dhaka, Bangladesh	12.4	16.8	35	52	94	81
Jakarta, Indonesia	13.2	16.8	27	98	184	88

By 2015, loss potentials among the world's 10 largest cities, most of which are in developing countries, are projected to increase from 22% (Tokyo) to 88% (Shanghai, Jakarta) (Table 2.2). A repeat of the July 2005 floods in Mumbai in 2015 could cause 80% higher losses and affect 20% more people, independent of climate change.

The relatively more rapid loss potential increase in cities helps to explain why disaster losses have increased faster than real global GDP. These data suggest that developing countries are repeating the dramatic increase in loss potentials observed in the U.S. Gulf and Atlantic coast counties. From 1950 to 2005, more than 130 of 177 coastal counties saw their loss potentials increase faster than real global GDP with increases of more than 10% annually in some counties (Pielke et al., 2008). The median annual increase was about 4% (Pielke et al., 2008), which equates to a 48% increase over a 10-year period.

2.4 Policy responses

Greenhouse gas emission reductions are of central importance, but they cannot decrease hazard risk for decades. In this context, we offer three recommendations for decision-makers.

Improve data collection

With few exceptions, records of disaster losses are of poor quality, inhomogeneous, and collected using a wide range of methods for different purposes, making research extremely challenging. Improved data could be used to evaluate disaster policies, estimate return periods, identify factors that drive loss trends and could potentially offer the prospect of an early-warning system for changes in the earth-climate system. Currently, the most comprehensive loss databases are held by insurance companies and are not publicly available. An open-source, peer-reviewed database would enable the scientific community to study worldwide disasters.

Expand the role of disaster risk reduction in adaptation

The cost-benefit ratio of disaster risk reduction ranges from 1:2 to 1:4 (Mechler, 2005), but efforts remain underfunded. In particular, inadequate pricing of costs and benefits leads to inappropriate valuation of investment and financial calculations in risk-reducing measures (Benson and Twigg, 2004). Risk reduction is not usually referred to as climate adaptation, but may be described as plant breeding and selection, flood-risk reduction, public health care, and so on. Developing countries have many opportunities to integrate climate adaptation in disaster risk-reduction efforts (Few et al., 2006). More generally, disaster aid is probably best spent on ex ante risk reduction (Linnerooth-Bayer et al., 2005).

Develop and apply innovative finance mechanisms

Industries with greatest exposure have responded to increasing losses with innovative products. Catastrophe bonds are a mechanism used to transfer peak risks to the capital markets, with the range of hazards covered continuing to expand, recently to the flood risks in the U.K. (Allianz, 2007). Previously uninsured flood risks in Belgium and the Netherlands are to be covered through public-private insurance constructions. Existing development financing within local communities, for example, investment funds for small infrastructure improvement in El Salvador, support risk reduction, and community groups in India have developed deficit rainfall insurance (Warner et al., 2007). In Colombia, microentrepreneurs offer affordable and easy to understand life and property microinsurance to the most vulnerable. The World Bank-sponsored Caribbean Catastrophe Risk Insurance Facility offers governments cover against hurricanes and earthquakes with funds available a few days after the event (Munich Re, 2007). The Munich Climate Insurance Initiative[7] brings together the World Bank, insurers, nongovernmental organisations, and the scientific community to develop finance solutions for adaptation in developing countries.

[7] Munich Climate Insurance Initiative, http://www.climate-insurance.org.

If present trends continue, global disaster losses will keep outpacing average economic growth. Therefore, disaster risk reduction must be core to climate adaptation policies. Numerous mechanisms for action exist that can contribute to the aim of sustainable development.

2.5 Acknowledgements

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Chapter 3. Have disaster losses increased due to anthropogenic climate change?

Abstract

The increasing impact of natural disasters over recent decades has been well documented, especially the direct economic losses and losses that were insured. Claims are made by some that climate change has caused more losses, but others assert that increasing exposure due to population and economic growth has been a much more important driver. Ambiguity exists today, as the causal link between climate change and disaster losses has not been addressed in a systematic manner by major scientific assessments. Here I present a review and analysis of recent quantitative studies on past increases in weather disaster losses and the role of anthropogenic climate change. Analyses show that although economic losses from weather related hazards have increased, anthropogenic climate change so far did not have a significant impact on losses from natural disasters. The observed loss increase is caused primarily by increasing exposure and value of capital at risk. This finding is of direct importance for studies on impacts from extreme weather and for disaster policy. Studies that project future losses may give a better indication of the potential impact of climate change on disaster losses and needs for adaptation, than the analysis of historical losses.

3.1 Introduction

Anthropogenic climate change leads to more damage from weather disasters. This claim is made frequently in debates on the impacts of ongoing global warming. While many other impacts and risks are associated with climate change, shifts in weather extremes is one of the most prominent anticipated impacts, and of concern to many. The Intergovernmental Panel on Climate Change (IPCC) reported that the frequency of heavy rainfall and heat waves has increased, that the area affected by drought has increased in many regions, and that tropical cyclone activity has increased in the North Atlantic Ocean (IPCC, 2007a: Table SPM.2). The recent Global Assessment Report on natural disasters of the United Nations shows that the number of natural disasters, economic losses and number of people affected are increasing at a rapid rate, and faster than risk reduction can be achieved (UN-ISDR, 2009a).

Governments are concerned about the potential economic implications of increasing

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risks, and in particular about the consequences for insurance systems for companies and households (GAO, 2007; Ward et al., 2008; Botzen et al., 2010a). There is clearly a need for analyses on the causes of increasing impacts from weather extremes, as decision-makers in government and companies plan for more frequent disasters and attempt to reduce exposure and risks. Also, better understanding of the relationship between anthropogenic climate change and disaster losses is needed to inform decisions on global climate mitigation policy that is being negotiated and developed under the United Nations Framework Convention on Climate Change (UNFCCC). The expected impacts also indicate to what extent developed countries should financially compensate developing nations for the impacts of climate change and the costs of adaptation (Bouwer and Aerts, 2006).

Some major studies on the costs of climate change have been made over the course of past years (e.g. Pearce et al., 1996; Tol, 2005; Stern, 2007). The costs from weather extremes however, are in general omitted or included in a very crude manner in the models of the costs of climate change (Tol, 2002; Hallegatte et al., 2007; Tol, 2008), and therefore hardly accounted for in cost-benefit analyses of global climate policy (Van den Bergh, 2010). This is mainly due to the fact that the complex interaction between hazards, exposure and vulnerability has so far not been approached in a uniform manner through impact studies which would allow inclusion in economic models and cost-benefit analyses.

While some authors argue that anthropogenic climate change has already led to increased loss probabilities (Bruce, 1999; Mills, 2005; Höppe and Grimm, 2009; Schmidt et al., 2009a), others assert that it is too early to find trends in disaster losses due to climate change, as increasing exposure due to population and economic growth has been a much more significant driver (Changnon et al., 2000; Pielke et al., 2005; Bouwer et al., 2007). This chapter revisits this discussion, by providing an overview of recent quantitative studies, and by assessing the role of climate change in disaster loss increases relative to other changes.

3.2 Detection and attribution of disaster impacts

The science on natural disasters and climate change is still incomplete, despite many studies. A large range of changes in biological systems, hydrology, and the cryosphere has been detected, and has partly been attributed to anthropogenic climate change (Rosenzweig et al., 2008). These impacts are mainly related to simple climate parameters, such as average or seasonal temperature and precipitation. The IPCC Fourth Assessment Report stated that "(w)here extreme weather events become more intense and/or more frequent, the economic and social costs of those events will increase" (IPCC, 2007b: p. 12). To date, attribution of anthropogenic climate change has not been established for historic losses from extreme weather events.

Changes in impacts from extreme events are relatively hard to detect and attribute, as they are rare by nature, very few observational records are available for analysis, and they are the result of the complex interplay between weather extremes, and socioeconomic processes, including adaptation. Also, natural climate variability, for instance a period of high number of landfalling hurricanes, may lead to increases in losses, which is consistent with climate change projections, but these should not be misinterpreted to be manifestations of these projections. Analyses by insurance companies of past disaster losses show that direct economic losses have increased, in particular the losses that are due to weather related hazards, such as floods, droughts, storms, and landslides (Munich Re, 2010).

Losses from disasters not related to weather, such as earthquake losses, have also increased (Vranes and Pielke, 2009), although at lower rates than many weather-related hazards. The fact that the number of events and losses from non-weather disasters has stayed stable compared to weather extremes has led some to conclude that climate change has been driving losses from weather related hazards (Bruce, 1999; Mills, 2005). There is no indication however that exposure and vulnerability to weather and non-weather disasters have evolved in the same manner, given their different natures and different spatial distributions. There is empirical evidence that the impacts from earthquakes and extreme temperature evolve differently with countries' economic development, compared to the impact from landslides, floods and windstorms. For instance, Kellenberg and Mobarak (2008) show that socioeconomic development initially increases the occurrence and level of loss of life due to landslides, floods and windstorms, while for earthquakes and extreme temperature it is reduced immediately. This suggests that location choices, such as settlement in coastal zones and flood plains have influenced exposure to flooding, landslides and windstorms. This is different from the exposure to hazards that occur more homogenous over space, such as earthquakes and extreme temperatures. An observed increase in the number of weather-related events relative to earthquakes events is therefore no good support for claiming that anthropogenic climate change is apparent in disaster records.

3.3 Normalization of loss records

Some studies have attempted to determine in detail why economic losses from weather hazards may have increased. Twenty-two studies were found through a literature search that fulfilled the following criteria (Table 3.1): they have systematically analyzed well-established records from natural hazard losses, they cover economic losses (monetary damages), they cover at least 30 years, and they are peer-reviewed. Only one study has analyzed global losses from a range of different weather types, one study is on losses from non-weather events (earthquakes), and most studies have analyzed losses in developed countries, in

Table 3.1. Normalization studies of disaster loss records.

Hazard	Location	Period	Normalization	Normalized loss	Reference
Bushfire	Australia	1925-2009	Dwellings	No trend	Crompton et al. in press
Earth-quake	USA	1900-2005	Wealth, population	No trend	Vranes and Pielke 2009
Flood	USA	1926-2000	Wealth, population	No trend	Downton et al. 2005
Flood	China	1950-2001	GDP	Increase since 1987	Fengqing et al. 2005
Flood	Europe	1970-2006	Wealth, population	No trend	Barredo 2009
Flood	Korea	1971-2005	Population	Incr.since 1971	Chang et al. 2009
Flood and landslide	Switzer-land	1972-2007	None	No trend	Hilker et al. 2009
Hail	USA	1951-2006	Property, insurance market values	Increase since 1992	Changnon 2009a
Wind-storm	USA	1952-2006	Property, insurance market values	Increase since 1952	Changnon 2009b
Wind-storm	Europe	1970-2008	Wealth, population	No trend	Barredo 2010
Thunder-storm	USA	1949-1998	Insurance coverage, population	Increase since 1974	Changnon 2001
Tornado	USA	1890-1999	Wealth	No trend	Brooks and Doswell 2001
Tornado	USA	1900-2000	None	No trend	Boruff et al. 2003
Tropical storm	Latin America	1944-1999	Wealth, population	No trend	Pielke et al. 2003
Tropical storm	India	1977-1998	Income, population	No trend	Raghavan and Rajesh 2003
Tropical storm	USA	1900-2005	Wealth, population	No trend since 1900	Pielke et al. 2008
Tropical storm	USA	1950-2005	GDP, population	Incr.since 1970 No trend since 1950	Schmidt et al. 2009a
Tropical storm	China	1983-2006	GDP	No trend	Zhang et al. 2009
Tropical storm	USA	1900-2008	GDP	Incr.since 1900	Nordhaus 2010
Weather[1]	Australia	1967-2006	Dwellings, dwelling values	No trend	Crompton and McAneney 2008
Weather[2]	USA	1951-1997	Wealth, population	No trend	Choi and Fisher 2003
Weather[3]	World	1950-2005	GDP, population	Incr.since 1970 No trend since 1950	Miller et al. 2008

Notes: [1] Flood, thunderstorms, hail, bushfires; [2] Hurricanes, floods; [3] Hail, storm, flood, wildfire

particular the USA. Economic impacts from drought are not well recorded, and no study on drought losses is available.

The general approach taken in these studies is to correct or normalize (Pielke and Landsea, 1998) the original economic losses for inflation, and changes in exposure and vulnerability that are related to growth in population and wealth. This correction shows losses as if all disasters occurred in the same year, i.e. with same exposure assets. Table 3.1 lists the types of information for which the loss data is normalized, and whether the normalized loss record derived by the studies exhibits any trends or not. When records of insured losses are used, the records are usually corrected for change in insurance portfolio (number of policyholders), and changes in insurance conditions (cover, deductibles). Economic losses may show variations related to decadal shifts in weather extremes that occur naturally, or related to long term trends in extremes. Because climate has a high variable natural component on decadal time scales, there will be variations in losses, even after adjusting for socioeconomic changes. Anthropogenic climate change that is due to the emissions of greenhouse gasses causes changes in extremes over longer periods, for detection and attribution according to the IPCC typically longer than 30 years (IPCC, 2001: p. 702). If after normalization no long-term trend is found in the loss record, it is unlikely that anthropogenic climate change has made an impact.

Most of the twenty-two studies have not found a trend in disaster losses, after normalization for changes in population and wealth (Table 3.1). Eight studies however have identified increases:

1. The Stern Review (Stern, 2007) concluded on the basis of very limited evidence, that anthropogenic climate change is already leading to more frequent disaster losses (Pielke, 2007a). The main study supporting this (Miller et al., 2008) showed that global losses from all weather related disasters have been increasing since 1970, when corrected for wealth and population increases, but find no trend since 1950. However, the authors indicate that the trend of 2% increase per decade they found is very sensitive to the correct adjustment of these losses, which are dominated by hurricane losses in the USA in 2004 and 2005. Population and wealth increases in that country play a dominant role in the dataset (Miller et al., 2008). The study concludes that there is not sufficient support for an anthropogenic climate change signal in the global loss dataset.
2. Nordhaus (2010) asserts a significant increase in tropical cyclone (hurricane) losses in the USA since 1900 for data only corrected for national economic productivity (Gross Domestic Product, GDP).
3. Schmidt et al. (2009a) also found a significant trend in US hurricane losses, but only since 1970, and after correction for wealth and population. No trend was found for the entire record, since 1950. These findings from Schmidt et al. (2009a) are statistically indistinguishable from different sets of normalized hurricane loss data from other authors (Miller et al., 2008; Pielke et al., 2008). The approach with the longest time series of losses (1900-2005) shows no trend, which was found to be consistent with the historical record of a lack of trend in hurricane landfall frequencies and intensities (Pielke et al., 2008).

4. Chang et al. (2009) found an increase in flood damage in six Korean cities since 1971, resulting from extreme precipitation in summer and deforestation, but corrected only for changes in population and not for wealth increases.
5. Fengqing et al. (2005) show that losses from flooding in the Xinjiang autonomous region of China have increased in response to increases in extreme rainfall and flash floods since 1987. The study however notes that siltation of retention reservoirs and flood control structures also play a role in the increasing incidence of flooding. Since this effect is not quantified, it is hard to conclude whether or not losses have increased due to an increase in extreme rainfall only.
6. Changnon (2001) found an increase in normalized losses from tornadoes, hail, lightning, high wind speeds and extreme rainfall, due to thunderstorm activity in the west of the USA since about 1974. But the study concludes that normalized losses also increased in areas where thunderstorm activity decreased, indicating that socioeconomic factors cause this trend.
7. Changnon (2009a) found increases in insured losses from large hailstorms in the USA since about 1992, but notes that the expansion of urban areas has lead to increasing exposure and vulnerability to hailstorms, while changes in more frequent occurrences of major hailstorm events has not been observed.
8. Changnon (2009b) found an increase in insured losses from windstorm in the USA over the period 1952-2006, but notes that the increase in losses is concentrated in the western part of the country, and is likely related to recent increasing population and wealth.

3.4 Trends versus variability

All twenty-two studies show that increases in exposure and wealth are by the far the most important drivers for growing disaster losses. Most studies show that disaster losses have remained constant after normalization, including losses from earthquakes (see Vranes and Pielke, 2009). Studies that did find increases after normalization did not fully correct for wealth and population increases, or identified other sources of exposure increases or vulnerability changes, or changing environmental conditions. No study identified changes in extreme weather due to anthropogenic climate change as the main driver for any remaining trend. Pronounced upward signals can exist in the corrected loss record, that mirror observed large-scale climate variability (Pielke and Landsea, 1999; Lonfat et al., 2007; Crompton et al., in press), indicating that variations in climate and weather extremes do lead to fluctuations in risks and losses. Trends that are found for instance since the 1970s for hurricane losses (Schmidt et al., 2009a), thunderstorm losses (Changnon, 2001), and since the 1980s for flash flood losses (Fengqing et al., 2005), are likely related to the large natural variability shown by the weather hazards. For hurricane losses in the USA it is well established that hurricane activity was at a low point in the 1970s and was much higher in 2004 and 2005 (Pielke et al., 2008), which explains the short-term trend found by some studies.

Studies could easily misinterpret this short-term trend as a sign of anthropogenic climate change. Even when weather-related losses have grown more rapidly than economic production and population in recent years (e.g., Mills, 2005); rapid urbanization and high concentrations of population and wealth may lead to changes in losses that are larger than national GDP growth (Bouwer et al., 2007).

3.5 Losses follow geophysical change

Losses from extreme weather may begin to show increases when changes in extreme weather events become more apparent. Neither hurricane landfall activity, nor hurricane wind speeds exceed the long-term variability found in the historical record since at least 1900 (Landsea et al., 2006; Chen et al., 2009; Knutson et al., 2010). Similarly, upward trends in extreme river discharges have been found in some individual basins around the world, but no general trend towards more frequent discharge extremes or flooding (Kundzewicz et al., 2005). Consequently, using the definition of detection from the IPCC, a long-term trend in weather disaster losses has not yet been detected, and is unlikely to be found as long as the geophysical data do not show systematic trends in extremes. Increases in economic losses could be expected for weather extremes for which trends have been found with some certainty, and where the trend has been attributed to anthropogenic climate change, in particular heat waves, droughts, and heavy precipitation events (IPCC, 2007a: Table SPM.2; Stott et al., 2010).

3.6 Uncertainties and possible improvements

Considerable uncertainty remains in all the loss normalization studies, as loss data is often not accurate (Downton and Pielke, 2005; Gall et al., 2009), and most studies have focused on average losses, while changes and volatility of the greatest losses are not addressed. The scale of analysis is also an issue, as aggregating to regional or global level may have the advantage that local variability is eliminated, but one could fail to see trends due to anthropogenic climate change that may vary per location in sign and magnitude. Also, normalization procedures cannot perfectly account for the various changes in exposure and vulnerability over time. As indicated earlier, urbanization and high concentrations of population and wealth may lead to changes in losses that are larger than growth indicated by national indicators of economic and population growth. Different methods for normalization are therefore being tested and compared (Pielke et al., 2008; Schmidt et al., 2009a). When society becomes wealthier and more exposed, investments are more likely to be made, in order to prevent and protect against natural hazards. Normalization studies often fail to correct for measures that reduce vulnerability as they are harder to quantify than changes in exposure. Properly set-up studies would need to include aspects of the hazard (geophysical data), exposure (population and wealth), as well as changes in vulnerability. Some studies do take into account changing vulnerabilities. For instance the normalization study by Crompton and McAneney

(2008) corrected over time for increasing resilience of buildings to high wind speeds. A rigorous check on the potential introduction of bias from a failure to consider vulnerability reduction in normalization methods is to compare trends in geophysical variables with those in the normalized data. Normalized hurricane losses for instance match with variability in hurricane landfalls (Pielke et al., 2008). If vulnerability reduction would have resulted in a bias, it would show itself as a divergence between the geophysical and normalized loss data. In this case, the effects of vulnerability reduction apparently are not so large as to introduce a bias.

Normalization studies of historic loss data provide important insights in the role of changes in vulnerability and exposure. There is an extraordinary 'adaptation deficit' (Burton, 2004), as economic losses from weather disasters have increased five-fold over the past 30 years (Bouwer et al., 2007). This implies that society responds only slowly to the increased exposure, and would need to do more adaptation if risks were to be reduced. More insight could potentially be gained from studies that assess the impact of future anthropogenic changes in weather extremes, that are projected to be larger than the changes so far observed (IPCC, 2007b). In particular in developing countries these changing hazards will coincide with changing exposure and vulnerability. Studies of projected risks for instance using scenarios for hazard and exposure (e.g. Maaskant et al., 2009), can help inform decision makers on their needs for risk reduction and climate adaptation.

3.7 Conclusions

The analysis of twenty-two disaster loss studies shows that economic losses from various weather related natural hazards, such as storms, tropical cyclones, floods, and small-scale weather events such as wildfires and hailstorms, have increased around the globe. The studies show no trends in losses, corrected for changes (increases) in population and capital at risk, that could be attributed to anthropogenic climate change. Therefore it can be concluded that anthropogenic climate change so far has not had a significant impact on losses from natural disasters. Considerable uncertainties remain in some of these studies, as exposure and vulnerability that influence risk can only be roughly accounted for over time. In particular the potential effects of past risk reduction efforts on the loss increase are often ignored, because data that can be used to correct for these effects is not available. More insight in the relative contribution from climate change on disaster losses could potentially be gained from studies that attempt to project future losses. These studies can assess the impact of future climate change, which is projected to be much larger than the change so far observed. The discussion above shows the need to include exposure and vulnerability changes in future risk projections, which clearly contribute substantially to changing risks.

3.8 Acknowledgments

This research is part of the project 'Financial arrangements for disaster losses under climate change', supported by the Dutch National Research Programme 'Climate changes Spatial Planning' (http://www.climatechangesspatialplanning.nl). Two anonymous reviewers, Stéphane Hallegatte, Roger Pielke Jr., Pier Vellinga, Jeroen Aerts, and Wouter Botzen provided helpful comments and suggestions. All errors and opinions are my own responsibility.

Chapter 4. River discharge and climate variability in Europe

Abstract

Variability of atmospheric circulation is thought to be the most important factor causing annual and decadal variability of fresh water fluxes from the continents. Previous studies however have rarely established the sensitivity of the basins to atmospheric circulation variability. Here we present an analysis of long-term (>30 years) links between atmospheric forcing and winter (December-February) precipitation, and sensitivities of annual mean and maximum winter discharges observed at up to 608 stations across Europe. Links to four atmospheric indices are examined: the North Atlantic Oscillation (NAO) index, the Arctic Oscillation (AO) index, the frequency of west circulation (FWC) as described by the subjective Großwetterlagen classification, and the north to south sea level pressure difference across the European continent (SLPD). The results show that annual maximum discharges are more sensitive to variability of atmospheric circulation than mean discharges. Mean discharges vary on average between 8 and 44%, while peak discharges vary between 10 and 54% per unit index change. Discharges in Iberia and Scandinavia are more sensitive than those in central and northwest Europe. Discharge closely follows variability of atmospheric circulation. Compared with FWC and SLPD, the NAO and AO indices have only limited use for analyzing climate impacts in river basins in northwest Europe.

4.1 Introduction

Climate variability and climate change may modify the availability of fresh water, as well as the frequency and intensity of flood events. In particular west atmospheric circulation, consisting of zonal flow, is known to determine fluctuations in wintertime precipitation in west Europe (Hurrell, 1995). Many studies, some of which are listed below, have assessed whether river discharge in Europe is closely connected to atmospheric circulation variability. Such studies are important in order to estimate the impacts of current climate variability, impacts of anthropogenic climate change on the global water cycle (Zhang et al., 2007), and the potential impacts of future climate change as projected by general circulation models. However, previous studies have rarely established the sensitivity of river

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basin discharge to atmospheric circulation variability. This chapter aims to fill that gap by systematically studying the sensitivity of European river basins.

Variation in west atmospheric circulation is often expressed by the North Atlantic Oscillation (NAO) index. Atmospheric circulation as described by the NAO index, is linked most closely to precipitation variability in winter (Hurrell, 1995), as well as to winter river discharges (Dettinger and Diaz, 2000; Trigo et al., 2004). The NAO index and other atmospheric indicators are based on the north-south pressure gradients over the northern hemisphere of the planet. The north-south pressure gradient gives an indication of the frequency, strength and location of western atmospheric flow over the European continent. During periods with a small pressure gradient, low atmospheric pressure weather systems on the Atlantic travel in the direction of the Mediterranean causing increased rainfall, while during phases of a high pressure gradient low-pressure systems travel toward Scandinavia and precipitation in northern Europe is increased. Additionally, prolonged west circulation may substantially reduce evaporation through increased cloudiness and increased air humidity and increase soil humidity, potentially resulting in increased river discharges and increased peak flows. River discharge in Europe during the winter months (December, January and February) represents between 23 and 43% of total annual runoff in the major European river basins (Bouwer et al., 2006). Most major peak discharge and flood events have occurred in Europe during winter in response to prolonged west atmospheric circulation and associated precipitation (Caspary, 1995; Tu et al., 2005a), while during the summer season flooding may occur due to other weather patterns (Becker and Grünewald, 2003; Mudelsee et al., 2004).

Previous studies on the links between circulation and discharge appear to be limited in a number of ways. Most of the previous studies have focused on mean winter flow, rather than peak discharges; for an extensive overview see Kingston et al. (2006a). Although some studies have examined the links between the occurrence of peak discharges and atmospheric circulation in the United States (Duckstein et al., 1993; Ely et al., 1994; Bell and Janiowak, 1995), these connections have been addressed in only a handful of studies on a small number of European river basins (Jacobeit et al., 2003a; Mudelsee et al., 2004; Bárdossy and Filliz, 2005; Petrow et al., 2007). A systematic study of links between circulation and peak discharges for Europe is currently lacking.

Studies that have covered large geographical domains have sometimes used relatively short discharge records, typically in the order of 30 years (Shorthouse and Arnell, 1999; Kingston et al., 2006b), rather than the full length of the records available (Dettinger and Diaz, 2000). The use of short records may have the important drawbacks of insufficient power and may lead to incorrect conclusions regarding the impact of climate change, when short-term cycles in climate and discharge coincide (Woo et al., 2006). Moreover, many studies have looked at averaged river discharges over periods of 10 or more years (Jacobeit et al., 2003a; Rimbu et al., 2004), rather than interannual variability. Variability of atmospheric circulation may determine seasonal discharges, water availability and the occu-rrence of floods. Therefore interannual variability, including variability of extreme discharges, is at least as important for determining ecological and economic impacts as the shift in average discharge over decades.

The largest river basins in Europe, as well as a large share of population and economic activity, are located in west and central Europe. West and central Europe comprise the transition zone of the NAO influence, where consequently neither basin-average precipitation nor river discharge is strongly linked to the NAO index (Bouwer et al., 2006). Similarly, Mudelsee et al. (2004) found no significant correlation between winter flood events and the NAO index for the Elbe and Oder rivers. Qian et al. (2000) suggested that the NAO index may not be the most important pattern governing precipitation in Europe. The NAO index, which is based on pressure differences between two locations on the border of the Atlantic Ocean, may be a limited index for describing circulation patterns over Europe (Kingston et al., 2006a). This raises the concern that the NAO index may not be an appropriate index for assessing impacts of climate variability and change on the water cycle for any area in Europe. A relevant question is therefore whether other indicators are better suited to describe atmospheric forcing influences on precipitation and river discharges in west and central Europe. Other indices, based on principal component analysis (PCA) of large scale circulation variability, such as the Arctic Oscillation (AO) index, or indices based on synoptic observations, may be more closely linked to variability of European climate.

Most other studies have examined the extent of the discharge variability that can be explained by variability in atmospheric forcing. However, what is equally important for impacts studies is to determine the sensitivity of discharges to atmospheric forcing, as this may show what variability in discharge can be expected from climate variability and climate change. Only few studies have quantified discharge sensitivities to climate variability (Struglia et al., 2004; Bower et al., 2004).

This chapter presents a systematic analysis of the spatial patterns of connections between circulation patterns and precipitation, as well as connections between circulation patterns and river discharge in Europe. The analysis helps to understand historic variability and predict changes in future river discharges. The chapter provides year-to-year correlations between four atmospheric forcing indices and precipitation, as well as between these four indices and mean and peak river discharges in winter. This is done for entire river discharge records that are readily available. Additionally, we quantify the sensitivity of the river discharges to atmospheric forcing. The forcing indicators that are assessed are the NAO index; the Arctic Oscillation (AO) index, the frequency of west circulation (FWC) as described by the subjective Großwetterlagen classification system, and the normalized north to south sea level pressure difference (SLPD) over Europe, which is an objective measure of west atmospheric flow across the European continent.

4.2 Data and methods

We have collected data on daily river discharges for 586 gauging stations across Europe, complemented by monthly discharge records for 49 of these stations that comprised longer periods, and 22 separate monthly records. The discharge data were obtained from the Global Runoff Data Centre (GRDC) in Koblenz, Germany. These records include many of the longest discharge records for the major rivers in Europe. The monthly and daily data were combined in order to arrive at a dataset of 608 seasonal mean discharge records and 586 records for annual maximum discharge series for individual stations. Figure 4.1 displays the location of the gauging stations, and the length of the records. It is clear that there is a bias of long datasets towards locations in northern European countries. For these countries also more discharge records are available, often at different locations along the same river, or its tributaries.

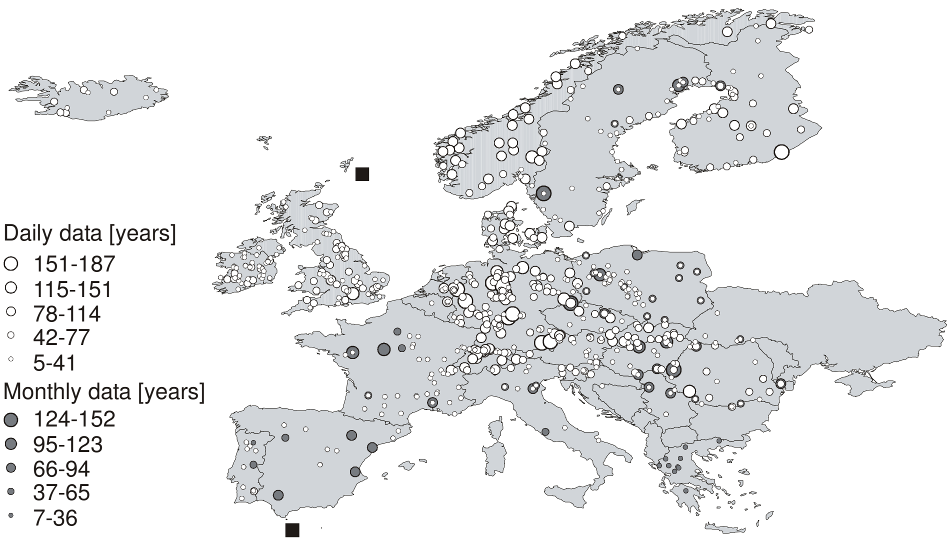

Figure 4.1. Length of the daily and monthly discharge records of the 608 European stations. The two black boxes indicate the locations of the two grid cells for which the SLPD index was constructed.

Data on monthly precipitation were collected from the CRU TS 2.0 gridded dataset (Mitchell and Jones, 2005). From these data the total winter precipitation was derived for December-February over the period 1901-1999 on a 0.5 by 0.5˚ grid.

The NAO index has been constructed by Hurrell (1995), consisting of the difference of normalized sea level pressures anomalies between Ponta Delgada in the Azores and Stykkisholmur/Reykjavik in Iceland. The data on the Arctic Oscillation (AO) index is based on the normalized principal component values for the period December-March for the Northern Hemisphere (20-90˚N). Data on the NAO (1864-2002) index for December-February and the AO (1898-2005) index for December-March were retrieved from the website http://www.cgd.ucar.edu/cas/jhurrell/-indices.html.

The German Großwetterlagen classification system provides information on the daily type of atmospheric circulation over Europe. This subjective classification system is based on the locations of high and low pressures and ridges and troughs at the 500 hPa level. From Bouwer et al. (2006) it follows that winter river discharge in many large basins in Europe is significantly correlated to the frequency of west circulation as described by this classification. Data for the period 1881-2004 was collected from the catalogue produced by Gerstengarbe and Werner (2005), updated with data from the German Weather Service up to 2005. A dataset of the annual frequency (number of days) of west circulation in winter was constructed, using the classes west anti-cyclonic (WA), west cyclonic (WZ), southwest (WS) and angular west (WW).

From this annual frequency, a normalized index was constructed in a similar way as the NAO index, using:

$$FWC=(f_i-\overline{f})/\sigma \qquad \text{(Equation 4.1)}$$

where f_i is the annual frequency (days in the winter season) of west circulation in year i as defined by the Großwetterlagen classification system, $\overline{f}$ is the average frequency of west circulation, and σ is the standard deviation of the frequency of west circulation.

An index of normalized sea level pressure differences (SLPD) between the points at 60˚N, 0˚E, and 35˚N, 5˚W for the period 1850-2006 was constructed from the data compiled by Allan and Ansell (2006). Data for two grid cells centered on these two points for the period 1850-2006 was retrieved from the website http://climexp.knmi.nl. The location of these two grid points is shown in Figure 4.1. The construction of the normalized SLPD index on the basis of the sea level pressure data is similar to the construction of the NAO index:

$$SLPD=(p_1-\overline{p}_1)/\sigma_1-(p_2-\overline{p}_2)/\sigma_2 \qquad \text{(Equation 4.2)}$$

where p_1 and p_2 are the sea level pressure in the two locations, $\overline{p}_1$ and $\overline{p}_2$ are the average sea level pressures in the two locations, and σ_1 and σ_2 are the standard deviations of the sea level pressure in the two locations.

The sensitivity of mean and peak river discharges to atmospheric forcing is estimated using the simple linear least squares regression function:

$$ln(q_i)=\beta_0+\beta_1 a_i+\varepsilon_i \qquad \text{(Equation 4.3)}$$

where q_i is the observed peak or mean discharge in year i, a_i is the atmospheric forcing parameter, β_0 and β_1 are coefficients, and ε_i is the error term.

In this formulation, the value of β_1 represents the sensitivity of the particular basin to atmospheric forcing, as a percentage change in discharge per unit change in atmospheric forcing. From this formula it follows that β_1*100 represents the percentage increase of discharge (q_i) per unit increase in the atmospheric forcing parameter (a_i). Only stations with a correlation significant at the 5% level were selected for basin areas of at least 1000 km^2 in order to arrive at relations that have a considerable impact on local and regional hydrology. The regression coefficients shown in this chapter are based on discharge records that contain at least 30 years of data, in order to retrieve coefficients that are robust at least at average climatic timescales. The spatial patterns observed in these sensitivities across Europe help to clarify in which regions river discharges variability are related to particular atmospheric circulation changes.

Because we are only interested in detecting a climate signal in the discharge records, we have not taken into account the influence of land-use change and other non-climatic impacts on river discharges. In particular land-use change, regulation and deforestation may lead to monotonic change or trends in discharge. But climate impacts on inter-annual discharge variations can be determined, as it is assumed that climate plays as a major role in determining discharge as other factors, at least at the basin scale (Blöschl et al., 2007). Also, in areas where flood reducing and engineering measures have been taken, signals of regional atmospheric variability can still be found, for instance in flood frequency records (Florsheim and Dettinger, 2007).

In addition to the OLS regressions, we apply principal component analysis in order to construct broad signals of discharge variability. Previous analysis showed that PCA may conveniently capture the influence of atmospheric variability on discharges over large areas of Europe, by correlating the leading signals in a given set of discharge records to atmospheric indices (Bouwer et al., 2006). Moreover, PCA allows assembling the observation of rare peak discharge events that would be randomly distributed across river basins.

4.3 Results

The time series of the four atmospheric indicators are all significantly and positively correlated among each other (Figure 4.2, Table 4.1), although to a variable extent. Therefore atmospheric flow as described by these four indices is similar in all cases. They all describe a north to south atmospheric pressure difference that results in west atmospheric flow. The NAO and AO indices put more emphasis on north to south atmospheric pressure differences over the Atlantic Ocean, while the SLPD and FWC indices show the north to south atmospheric pressure difference and the actual frequency of west atmospheric flow over the European continent. All indices exhibit similar patterns of inter-decadal variability; that is generally high index values in the 1910s and 1930s, as well as in the 1990s, and a decline during the 2000s.

The increase in the frequency of west circulation since the 1970s until the late 1990s, as apparent from all four atmospheric indicators (Figure 4.2), has been detected by various studies of the FWC dataset (Bárdossy and Caspary, 1990; Werner et al., 2000; Kyselý and Domonkos, 2006), as well as in sea level pressure datasets (Jacobeit et al., 2003b; Trenberth et al., 2007). However, it remains unclear whether this increase is part of a systematic trend, or part of natural variability. Notably, Jacobeit et al. (2003b) made a construction of circulation variations since the mid-seventeenth century, and conclude that the current high frequency is part of a natural low-frequency cycle, and that the current high frequency in west circulation may well remain during coming decades. It has also been found that intensity of westerly flow has increased over recent decades, which, together with increasing vorticity may determine the occurrence of major discharge events (Jacobeit et al., 2006). The recent increase in sea level pressure gradients in the northern hemisphere has been attributed to anthropogenic climate change (Gillet et al., 2003); as recently reiterated by the Intergovernmental Panel on Climate Change (Trenberth et al., 2007: p. 280).

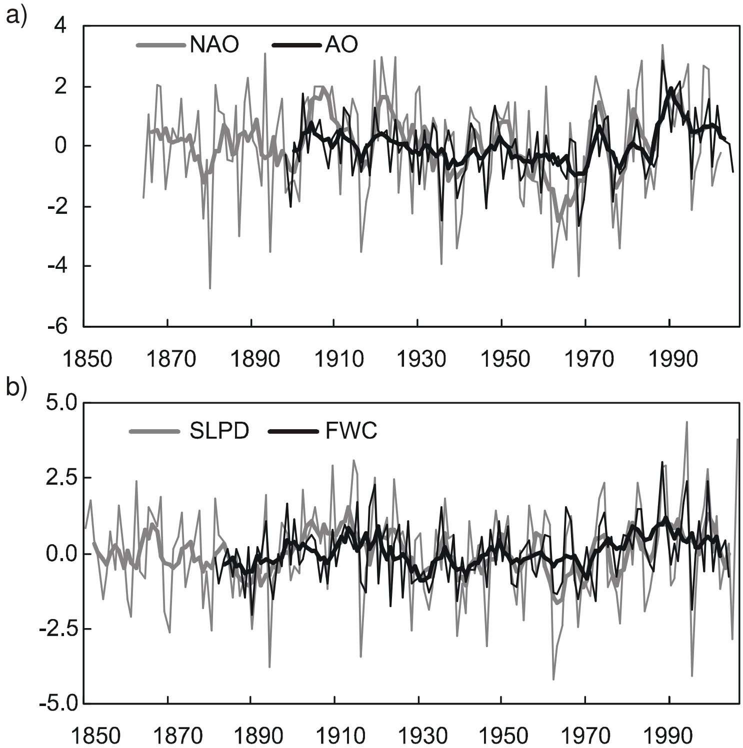

Figure 4.2. Atmospheric circulation indices NAO (1864-2002), AO (1866-2000) (a), and FWC (1881-2004) and SLPD (1864-2006) (b), and their 5-year running mean.

Table 4.1. Coefficients of determination (r^2) and coefficients of regressions (β_1, standard error) between different atmospheric forcing parameters, all $p<0.001$.

	NAO		AO		FWC	
	r^2	β_1	r^2	β_1	r^2	β_1
NAO	-	-				
AO	0.44	0.37±0.04	-	-		
FWC	0.10	0.17±0.05	0.09	0.31±0.09	-	-
SLPD	0.53	0.65±0.05	0.27	0.85±0.14	0.42	1.04±0.11

Linear correlations between wintertime precipitation in Europe and the four atmospheric circulation indices suggest that the amount of precipitation is largely determined by west atmospheric flow (Figure 4.3). During the positive phase of the NAO and AO indices, west circulation and precipitation over northern Europe are enhanced. During the negative phase, the same happens over southern Europe. The NAO and AO indices mainly identify Atlantic circulation variability that influences wintertime precipitation in coastal European countries (Iceland, UK), parts of Scandinavia, Iberia (Spain, Portugal), and southeast Europe (Italy, Balkan area, Greece). West circulation over the European continent as described by the FWC and SLPD indices, shows similar links to precipitation in these regions but they relate much stronger to precipitation in west and northern Europe. The FWC and SLPD patterns of links to precipitation are very similar, while more differences exist between the NAO and AO patterns. An analysis of correlations between basin-average precipitation and seasonal discharge in Europe is provided in Bouwer et al. (2006).

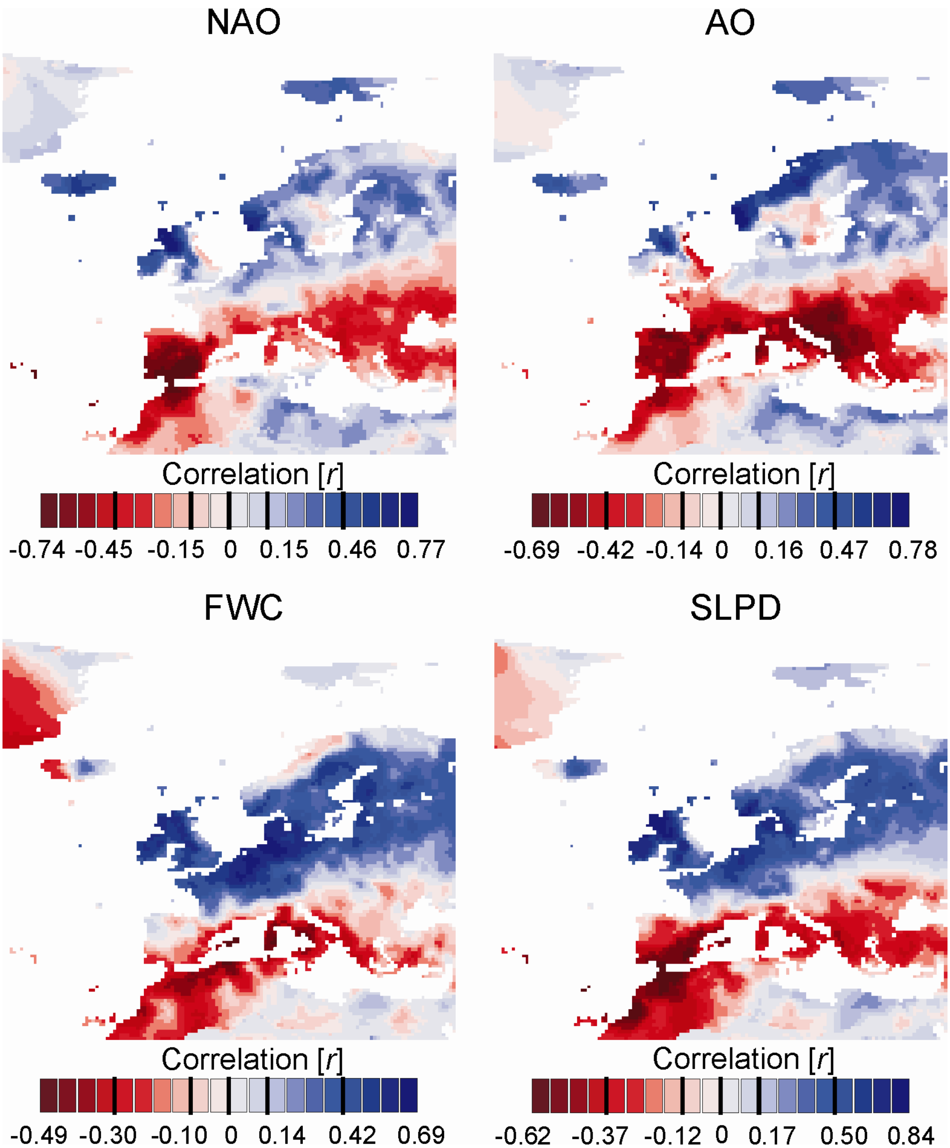

Figure 4.3. Correlations between atmospheric circulation indices and winter (DJF) precipitation.

Mean discharges are linked to west atmospheric circulation variability all across Europe (Figure 4.4). Observed sensitivities are greatest for NAO and AO indices in Iberia (up to 50%) and Scandinavia (up to 25%). Note that the sign of the β_1 coefficients varies, depending on the location of west atmospheric flow as described by the indices. Variability described by NAO and AO indices have little impact on mean discharges in northwest Europe, as shown by the few stations that show significant sensitivities, in areas such as Germany and the UK (Figures 4.4a and b). This confirms our earlier analysis (Bouwer et al., 2006). Circulation variability as described by the FWC and SLPD indices affects discharges all across northwest Europe (up to 30%), some parts of central Europe, and to a smaller extent in Scandinavia and south Europe in the case of the SLPD index (40%).

Peak discharges are linked to the NAO and AO indices for fewer stations, but they are slightly more sensitive to circulation variability than the mean discharges (Figure 4.5). As peak discharges are more variable than seasonal discharges, finding significant correlations requires relatively long records, which are not available for all regions and locations. The same spatial pattern can be found as for mean discharges: relatively high sensitivities in Scandinavia, Iberia and southeast Europe, and less in northwest Europe. Peak discharges in northwest Europe and some areas in central Europe are sensitive to circulation variability as described by the FWC and SLPD indices, though less than discharge in other areas. Again, peak discharges appear more sensitive to circulation variability than the mean discharges. The average frequency of west circulation in winter as described by the FWC index is 27 days. Peak discharges are particularly sensitive to prolonged precipitation, in the order of 10 days in some river basins in northwest Europe (Tu et al., 2005b; De Wit and Buishand, 2007). But we found that the persistence of west circulation (12 days on average in winter) correlates less to peak discharges than total wintertime frequency of west circulation. Therefore variability in seasonal circulation frequency seems more important for peak discharges than persistence.

Overall, peak discharges appear slightly more sensitive to atmospheric circulation variability than mean discharges (Table 4.2; nine out of the twelve cases). This is particularly the case for Iberian rivers, where AO-index sensitivities differ as much as 10%. This implies that the daily peak discharges volume here can vary as much as 50% per unit index change in circulation, even if the total seasonal volume changes by only 40%.

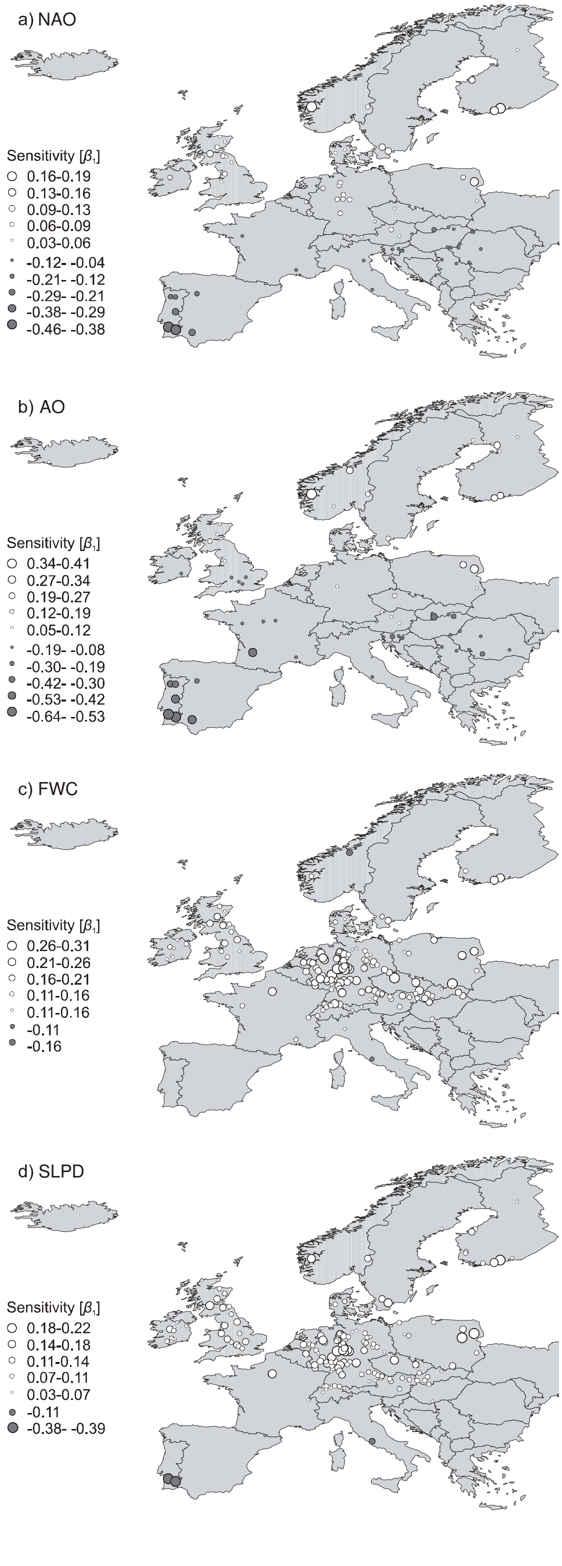

Figure 4.4. Sensitivity ($\beta 1$) of mean discharges to atmospheric circulation, all $p<0.05$, catchments >1000 km^2, correlations >30 years; a) NAO, b) AO, c) FWC, d) SLPD.

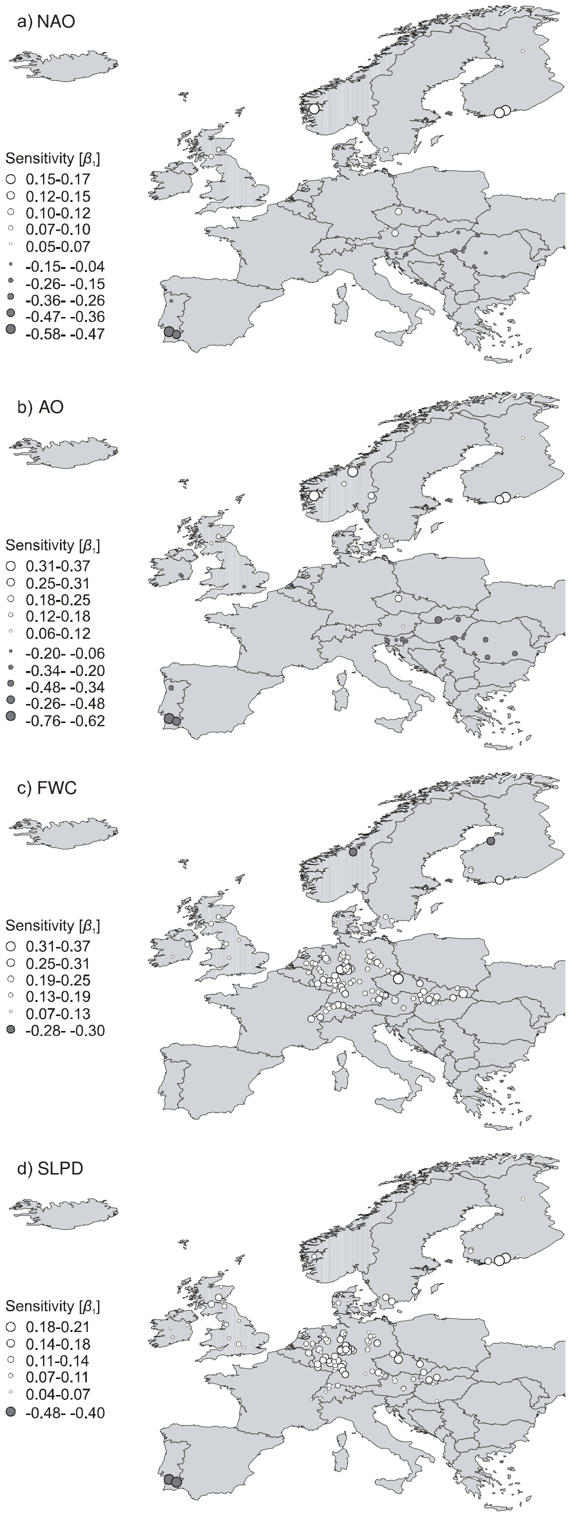

Figure 4.5. Sensitivity (β1) of peak discharges to atmospheric circulation, all p<0.05, catchments >1000 km^2, correlations >30 years; a) NAO, b) AO, c) FWC, d) SLPD.

Table 4.2. Average sensitivities (β_1) of mean and peak discharges and their standard deviations, correlation coefficients (r) and their standard deviations, and number of stations (n); all correlations p<0.05.

	Mean discharges			Peak discharges		
	β_1	r	n	β_1	r	n
NAO						
UK, East Europe and Scandinavia	0.08 ±0.04	0.37 ±0.11	39	0.10 ±0.04	0.36 ±0.07	12
Southeast Europe, Italy, France	-0.09 ±0.03	-0.34 ±0.08	22	-0.11 ±0.04	-0.34 ±0.06	15
Iberia	-0.26 ±0.13	-0.48 ±0.09	7	-0.37 ±0.23	-0.48 ±0.10	3
AO						
North UK, East Europe and Scandinavia	0.14 ±0.08	0.37 ±0.10	29	0.17 ±0.10	0.33 ±0.06	20
Southeast Europe, Italy	-0.18 ±0.05	-0.40 ±0.10	18	-0.20 ±0.08	-0.36 ±0.07	16
Iberia	-0.44 ±0.12	-0.42 ±0.06	7	-0.54 ±0.26	-0.39 ±0.04	3
South UK, France	-0.16 ±0.04	-0.33 ±0.06	10	-0.13 ±0.05	-0.37 ±0.14	3
FWC						
North and central Europe	0.16 ±0.05	0.42 ±0.09	140	0.17 ±0.05	0.35 ±0.06	109
UK	0.13 ±0.04	0.46 ±0.12	20	0.12 ±0.04	0.39 ±0.09	8
North Scandinavia	-0.16	-0.27	1	-0.29 ±0.01	-0.29 ±0.01	2
South UK, France	-0.11	-0.26	1			
SLPD						
North and central Europe	0.10 ±0.04	0.42 ±0.12	162	0.10 ±0.03	0.35 ±0.08	109
Iberia	-0.29 ±0.16	-0.45 ±0.03	3	-0.44 ±0.01	-0.44 ±0.06	2

From the sensitivities it is possible to construct the variability of mean and peak discharges for different regions based on the relative frequencies of circulation index values. The upper and lower 5% frequencies of occurrence of circulation indices were established for each index, over the total record length (Figure 4.6). Table 4.3 shows that estimated impact of upper and lower 5% observed circulation frequencies on peak discharges in different regions in Europe. In north and central

Europe, the 5% circulation frequencies are associated with an approximate 30% increase or decrease in winter peak discharges in northwest and central Europe. Scandinavian peak discharges are somewhat more sensitive to circulation variability. Iberian peak discharges are very sensitive to circulation index variability, and may vary between 71 and 80%, depending on the index applied. It must be noted that these estimates are somewhat uncertain, as they only take account of variability of atmospheric circulation, and not of other peak discharge generating mechanisms. However, a climate signal could be found in the discharge data, which would explain an important part of the peak discharge variability caused by climate variability.

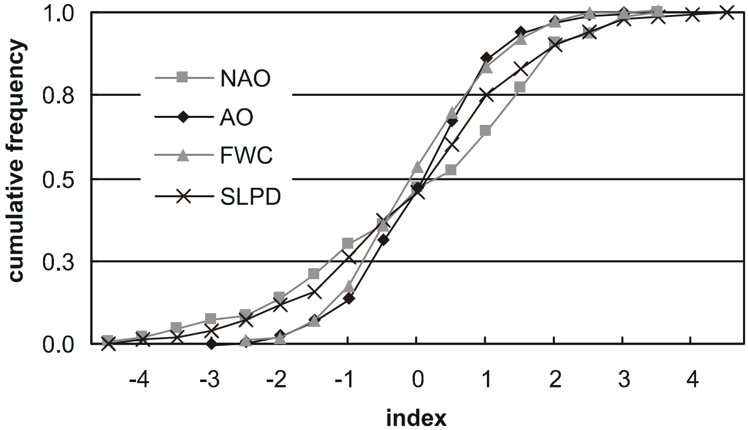

Figure 4.6. Cumulative frequencies of the atmospheric circulation indices.

Table 4.3. Average impact of upper and lower 5% observed circulation index on peak discharges.

	NAO		AO		FWC		SLPD	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
North and Central Europe					30%	-28%	27%	28%
(North) UK, East Europe, Scandinavia	29%	-38%	28%	-32%				
North Scandinavia					-43%	41%		
UK					21%	-19%		
South UK			-20%	23%				
Southeast Europe, Italy, south France	-26%	32%	-30%	33%				
Iberia	-72%	80%	-71%	75%			-78%	79%

For deriving signals of mean and peak discharge variability for different regions, we performed a principal component analysis (PCA) on the longest discharge records available for some of the major river basins in Europe. From the sensitivity analysis and links to circulation variability described by the four different indices presented earlier, a number of distinct regions can be recognized on the basis of similar sign and size of sensitivities recognized in Figures 4.4 and 4.5. These regions are northwest Europe, Scandinavia (including Finland), southeast Europe, and Iberia; indicated by alternating black and white basin areas in Figure 4.7.

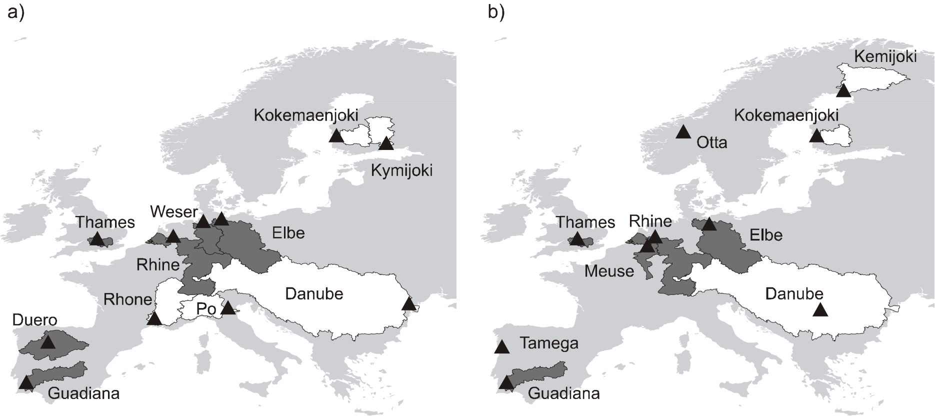

Figure 4.7. Basins used for the principal component analysis of mean (a) and peak (b) discharges.

For mean discharges, variability as described by the first principal component for the four regions is shown in Figure 4.8, with a 5-year running mean. The first principal component for northwest Europe is constructed on the basis of discharges of four rivers (Elbe, Rhine, Thames, and Weser), and this component is positively linked to variability of west circulation as described by index FWC and SLPD index, as shown by year-to-year correlations (Table 4.4). Variability of mean discharge in Finland (Kokemeanjoki and Kymijoki) is positively linked to the SLPD index. Mean discharge variability in southeast Europe (Danube, Po, and Rhone) is negatively linked to the AO index, and to a lesser extent to the NAO index. In Iberia (Duero and Guadiana) mean discharges are negatively linked to the NAO index and to a lesser extent to the AO index. Also, signals of variability of the north-south pressure difference over the European continent as described by SLPD index are seen in the first component of this area.

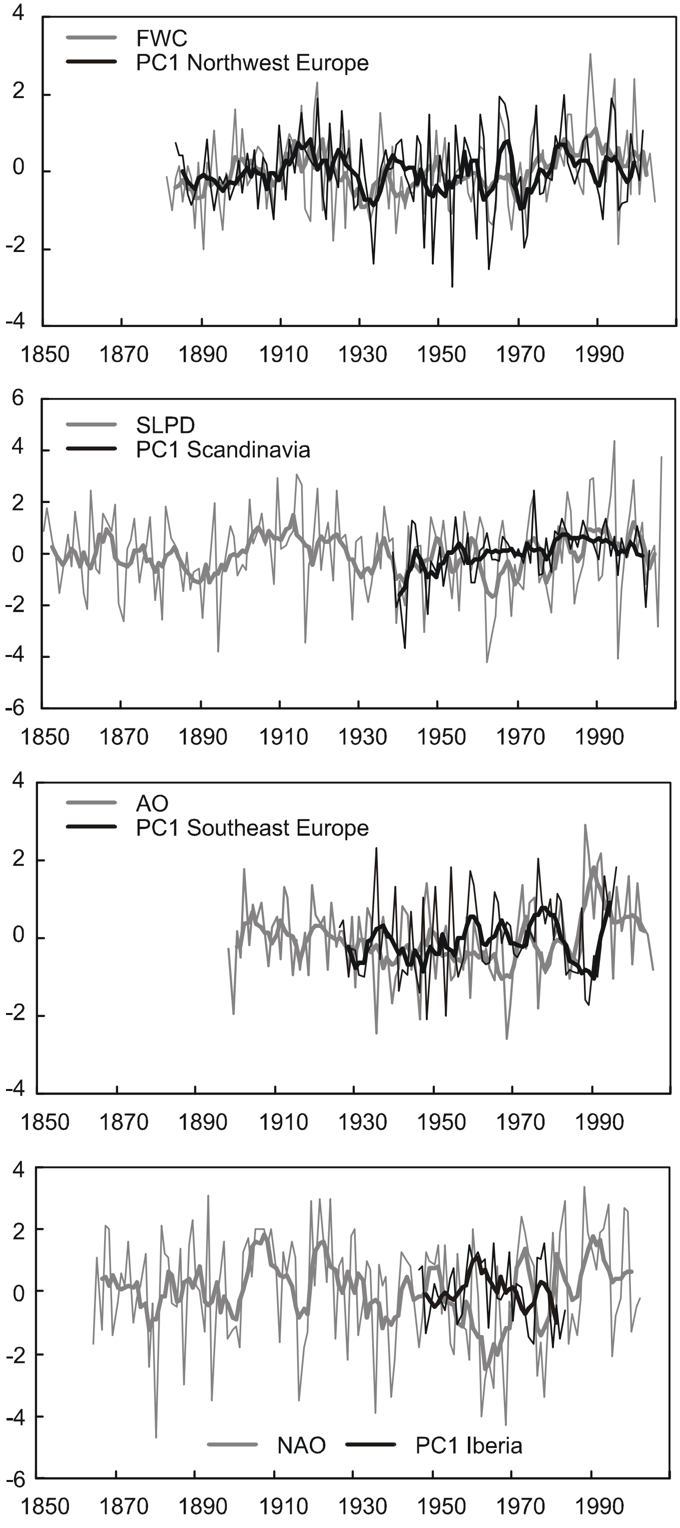

Figure 4.8. First principal components for mean discharges and 5-year running mean.

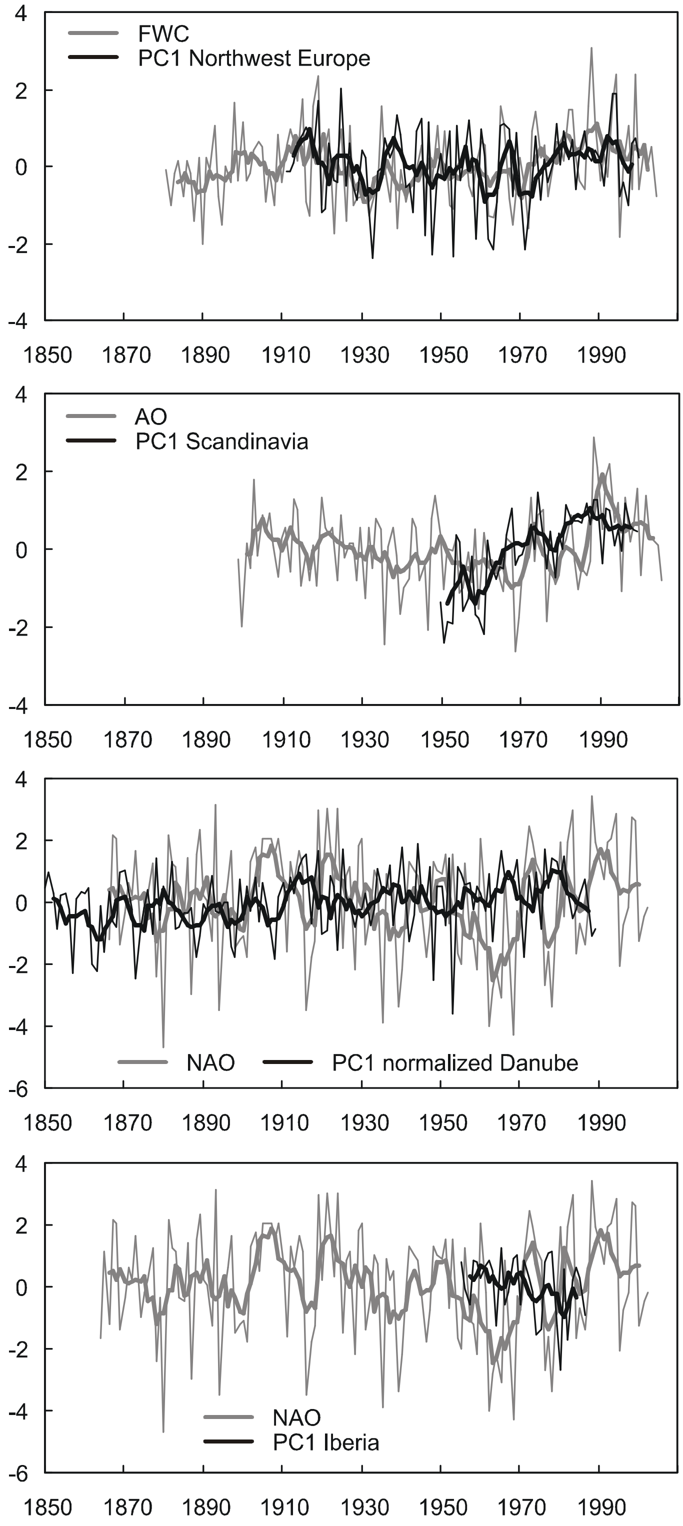

Figure 4.9. First principal components for peak discharges and 5-year running mean.

Table 4.4. Correlation coefficients (r) of OLS regressions between principal components of mean discharges and atmospheric circulation indices for different European regions.

Region	PC1	NAO		AO		FWC		SLPD	
		r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
NWE[1]	66%	0.09	0.34	0.03	0.78	0.41	0.00	0.43	0.00
Scan[2]	94%	0.22	0.07	0.23	0.06	0.18	0.15	0.30	0.01
SEE[3]	58%	-0.27	0.02	-0.31	0.01	0.23	0.06	0.07	0.55
Iberia[4]	91%	-0.57	0.00	-0.50	0.00	-0.20	0.23	-0.39	0.01

Notes: [1] Northwest Europe; Rhine, Elbe, Weser, Thames; 1883-2001
[2] Scandinavia; Kymijoki, Kokemaenjoki; 1938-2003
[3] Southeast Europe; Danube, Rhone, Po; 1926-1996
[4] Iberia; Guadiana, Duero; 1946-1983

Peak discharges exhibit more variability than mean discharges (Figure 4.9 and Table 4.5), as was also clear from the sensitivity analysis presented in Tables 4.2 and 4.3. As less daily data were available for the analysis of peak discharges, slightly different sets of rivers were selected for this analysis for northwest Europe (Elbe, Rhine, Meuse, and Thames), Finland and Norway (Kemijoki, Kokemeanjoki, and Otta), southeast Europe (Danube), and Iberia (Guadiana and Tamega). The Scandinavian region exhibits a large increase in peak discharges since the 1950s in response to the positive phase of the AO index since that time.

Table 4.5. Correlation coefficients (r) of OLS regressions between principal components of peak discharges and atmospheric circulation indices for different European regions.

Region	PC1	NAO		AO		FWC		SLPD	
		r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
NWE[1]	60%	0.08	0.47	0.01	0.96	0.44	0.00	0.44	0.00
Scan[2]	56%	0.25	0.08	0.44	0.00	0.21	0.15	0.20	0.15
SEE[3]	-	-0.34	0.00	-0.32	0.00	0.12	0.20	-0.07	0.38
Iberia[4]	87%	-0.50	0.00	-0.43	0.01	-0.31	0.09	-0.42	0.02

Notes: [1] Northwest Europe; Rhine, Elbe, Meuse, Thames; 1911-2000
[2] Scandinavia; Kemijoki, Kokemaenjoki, Otta; 1949-1999
[3] Southeast Europe; normalised Danube discharge data; 1850-1989
[4] Iberia; Guadiana, Tamega; 1955-1986

4.4 Summary and conclusions

Significant correlation is found between atmospheric circulation variability, described by the NAO, AO, FWC and SLPD indices, and peak and mean river discharges. West circulation over Europe is causing increased discharges in most basins. River basins have different sensitivities to atmospheric circulation variability across Europe, depending on position on the continent, local climate, vegetation and other basin conditions. Annual maximum discharges appear to be more sensitive to variability of atmospheric circulation that mean discharges, as the regression coefficients (*β1*) are higher per unit change of the atmospheric circulation indices (for nine out of twelve cases). We had only limited access to long-term data series from south Europe, leading to gaps in our analysis of sensitivities for this area. Compared with FWC and SLPD, the NAO and AO indices have only limited use for analyzing climate impacts in river basins in northwest Europe.

Over time, there is great variability of mean and peak discharges, as shown by the analysis of principal components of river discharges for different regions. Although some periods, in particular the 1990s, stand out in terms of high mean and peak discharge occurrence in northwest Europe (Figures 4.8 and 4.9), there are not necessarily trends towards higher discharges, as periods of high discharge have also occurred earlier in the record, in particular during the 1910s and 1920s. Discharges follow closely the variability of atmospheric circulation. This underscores the difficulty to determine trends in discharge records, as the findings will depend on the time span that is being studied (Woo et al., 2006), the river basins that are selected (Milly et al., 2002), and as flood events may be clustered in certain years and decades (Blöschl et al., 2007). The most comprehensive trend analysis available, which used some of the longest series in the GRDC dataset, detected both upward and downward trends for annual maximum discharges across Europe, and found no systematic trends towards more extreme discharges (Kundzewicz et al., 2005). Mudelsee et al. (2003) found a decrease in recent extreme discharges for extended discharge records for the Elbe and Oder rivers in northwest Europe.

Our research indicates that a sustained or increased strength and frequency of positive phases of the NAO and AO indices and west atmospheric circulation (FWC and SLPD) over northwest Europe implies considerable increases in peak discharges in northern Europe and declines in water availability in south Europe in winter. The estimation of future impacts on discharge variability and change will depend on the ability of general circulation models (GCMs) to capture such circulation variability. Analysis of GCM output suggests that winters in Europe may see more frequent west circulation and increased precipitation (Van Ulden et al., 2007). James (2006) showed that it is also possible to link the output of GCMs to the subjective Großwetterlagen classification system, in order to estimate such changes. But it appears that there are systematic problems with the simulation of historic circulation changes, as current GCMs are not able to capture the recent tendency toward more frequent west circulation (Gillett, 2005). Indeed, atmospheric circulation biases may be great with particular large impacts on precipitation, and responses vary between GCMs, especially in summer (Van Ulden and Oldenborgh, 2006). There is clearly a need to improve the skill of the circulation models to accurately capture the variability of atmospheric circulation, as this skill will improve our understanding of potential atmospheric impacts on river discharges and flood events.

4.5 Acknowledgements

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Chapter 5. Evaluation of potential flood damage in a polder area

Abstract

We present an approach for flood damage simulations through the creation of a comparatively large number of inundation scenarios for a polder area, using a high-resolution digital elevation model. In particular, the method could be used for detailed scenario studies of the impact of future socioeconomic and climatic developments on flood risks. The approach is applied to a case-study area in the south of The Netherlands along the river Meuse. The advantage of our approach is that a large number of potential flood events can be created relatively fast without hydrodynamical calculations, and that it can be applied to high-resolution elevation models and for large areas. The large number of flood scenarios and the high horizontal resolution reduces at least part of the uncertainties encountered in flood loss modelling. The approach with a low horizontal-resolution (100-metre) for loss modelling results in an overestimation of losses by up to 22% for high density urban areas, and underestimation of 100% for infrastructure, compared to the high-resolution (25-metre). Loss modelling at 5-metre horizontal resolution shows that aggregate losses may be overestimated by some 4.3%, compared to the 25-metre resolution. The generation of a large variety of inundation scenarios provides a basis for constructing loss probability curves. The calculated range and expected values of damages compare reasonably well with earlier independent estimates.

5.1 Introduction

Flat polder areas protected by dikes exist in many places around the globe, especially in low-lying river deltas. These areas are particularly vulnerable in the event of dike breaches during high water levels and because of high concentrations of people and capital (Smith and Ward, 1998). For decisions and investments in flood risk management reliable estimates of potential damages are needed (e.g. Vrijling et al., 1998). Because of the low probability nature of extreme floods and therefore the limited availability, or even complete absence, of historical loss data, simulation of loss events using catastrophe models is needed in order to arrive at a realistic range of potential damages. This is particularly the case in The Netherlands, where flood events due to dike breaches with extensive impacts are very rare. Loss events that have been well documented only comprise a major storm surge event in 1953 (Van Dantzig, 1956; Gerritsen, 2005). More recently, river

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flood events in 1993 and 1995 involved considerable economic losses, but were limited to relatively small-scale inundations and no dike breaches occurred (Wind et al., 1999). By applying modelling approaches that use loss-inundation relationships based on flood events in other regions of the world, it is possible to estimate potential flood risks for extreme flood events.

While river basins in valleys mainly face different inundation levels during flooding, low lying polder areas face a multitude of flood events that can take place in different locations, with very different consequences. The location of flooding in polders depends on the unpredictable failure of flood defences, which poses a particular problem for the accurate assessment of potential flood risks. This is usually solved by the creation of different flood scenarios. In particular maximum inundation depths from flood scenarios are used to calculate damages (Messner et al., 2007; Rijkswaterstaat, 2005a). Two-dimensional hydrodynamic modelling has commonly been used to create estimates of possible flood extents and inundation depths for specific floods (Van der Most and Wehrung, 2005; Rijkswaterstaat, 2006a; Jonkman et al., 2008a). However, the relatively small number of scenarios that can be reasonably produced in this manner, and the relatively coarse horizontal resolution of the flood scenarios limit the usefulness of these models for high spatial resolution loss estimates for large areas. There is usually a trade-off between the physical detail of the model, and the spatial scale and size of the study area (Hunter et al., 2007). Particularly, the construction of loss probability curves requires a large set of potential damage estimates (Messner et al., 2007). Such loss probability curves are needed, since they provide important information for decision-making on flood risk management policies, as they can show the range of possible losses. Loss probability curves allow the evaluation of the integral of the loss curve, including extreme values. Assessments based on probabilistic risk estimates can help to support decisions on the allocation of public finances for risk reduction, the appraisal of flood management projects, and to demonstrate the appropriateness of spending of public budgets (Vrijling, 2001; MNP, 2004; Messner et al., 2007; De Bruijn and Klijn, 2009). Additionally, the potential introduction of private insurance in The Netherlands for flood losses due to dike breaches requires accurate evaluation of losses and their probabilities (Botzen and Van den Bergh, 2008).

The relatively small number of flooding scenarios currently available from hydrodynamic modelling in The Netherlands may not sufficiently allow to take into account the variation in quantities of inundating water, the uncertainties associated with the potential failure of secondary flood defences, and the different potential locations of dike breaches and associated losses. Additionally, the spatial resolution of inundation scenarios determines to a large extent the accuracy of estimates made using depth-damage functions, and therefore the accuracy of potential losses. Hydrodynamic modelling, depending on type of model involved, is typically limited to a coarse resolution, or a limited area of investigation, due to high computational power demand and time. Current estimates of flood risk in The Netherlands are typically constrained to 100-metre resolution. For a large study area, the estimated inundation level relative to the actual ground level elevation (vertical accuracy), and exact location of the boundaries of different loss categories (horizontal accuracy) are only roughly approximated, leading to uncertainty in the estimation of potential losses. Obviously, an infinitely fine resolution would be ideal, but there is a limit to any analysis. Here we demonstrate the usefulness of a considerable increase in inundation resolution, by using an elevation model at 5-metre horizontal resolution. The Dutch project 'Flood risks and safety in the Netherlands' (Floris) is to provide benchmark estimates for flood risks on which national policies will be based that are related to evacuation, flood protection, and risk reduction (Rijkswaterstaat, 2005b; Van der Most and Wehrung, 2005). The project provides a detailed flood risk analysis for the case study area, using scenarios from hydrodynamic modelling on a 100-metre resolution. This set of flooding scenarios however comprises only 13 scenarios at present (Rijkswaterstaat, 2006a).

We present an alternative approach for creating a larger number of flood scenarios in an area protected by one main dike, using a high-resolution digital elevation model. This number of scenarios is larger compared to the current hydrodynamic scenarios that are available. Our approach in many cases will be easier and quicker carried out for a more extensive study area. It compliments more detailed hydrodynamic approaches, by providing a risk assessment with sufficient accuracy, but at a larger geographic scale. It also compliments the first approximate national scale risk assessments that have recently been made of current and future flood risks (e.g. MNP, 2004; Rijkswaterstaat, 2005a; Klijn et al. 2007; Aerts et al., 2008), but that do not consider the various different flood events that could occur in individual polders.

Our method is mostly aimed at providing a platform for giving more detail to dynamic estimates of risk over time, due to land-use change and climate change. The approach is applied to a study area along the river Meuse in the south of The Netherlands. Potential losses are then calculated with a simple loss model using depth-damage curves. The approach involves the identification of 23 individual sub-basins that can potentially be submerged and consequently the creation of flood scenarios consisting of different combinations of flooded sub-basins. The damage module that we apply can incorporate a small set of parameters that describe current and future land-use, as well as the fraction of losses based on estimated inundation depths. Subsequent research will apply a range of land-use and climate change scenarios in order to estimate the impact of socioeconomic and climatic changes on potential future flood losses. In Chapter 6 (Bouwer et al., 2010) we provide a scenario analysis for the year 2040, based on the scenario and loss modelling approach presented here. Such projections of future risk are useful for the estimation of low probability events that could occur over the next tens of years, and that determine the benefit of investment decisions over these timescales. Such assessments require methods that are sufficiently detailed but simple and feasible to carry out (Klijn et al., 2007; Aerts et al., 2008).

Our approach assumes that individual basins within the main dike ring area are filled up to the level of the lowest basin boundary. The approach ignores the fact that floods have a dynamic nature and assumes only losses from inundation. This is an acceptable simplification, considering the relatively flat topography of polder areas, and the fact that high flow velocities generally occur only locally, close to the dike breach. The method mimics approaches applied for valley flooding that use linear interpolation of flood water levels and their intersection with models of surface elevation (Apel et al., 2009). Although these methods perform less well then more detailed hydrodynamic modelling, the choice of flood loss model generally is of more concern then the hazard model (Apel et al., 2009). The main advantage of our approach is that a large range of potential flood events can be created with relatively little effort. For our case study area we apply an elevation model with 5-metre horizontal resolution. Both the large range of the flood scenarios and the high horizontal resolution would reduce at least part of the uncertainties encountered in flood loss modelling. The estimated flood losses resulting from our approach are compared to the loss estimates from the Floris project (Rijkswaterstaat, 2006a).

5.2 Study area, methods and data

The study area comprises dike ring area 36, called Land van Heusden/de Maaskant in the south of The Netherlands (Figure 5.1). A dike ring area is an area enclosed by a single primary flood defence (dikes), and in some areas also by higher grounds. Dike ring area 36 consists of a polder area of 740 km^2, and is bounded by the river Meuse to the north and east, and is protected by dikes along these stretches. The flooding hazard in the area consist of high river discharges on the river Meuse, that mainly occur in winter time, and that can lead to high water levels and consequent failure of stretches of dikes. Approximately 79% of the area is occupied by agriculture, nature, and recreation, and another 20% by urban areas. The major cities located in this area are Den Bosch (136,000 inhabitants) and Oss (76,000 inhabitants). Some major infrastructure features such as highways, roads, dikes and canals dissect the area.

The study area is relevant for studying flood risks for two reasons. First, it is representative for The Netherlands, as it comprises both high density urban areas, in particular the cities of Den Bosch and Oss, and extensive agricultural areas, in particular grassland. Secondly, it has been found that the area, in contrast to some

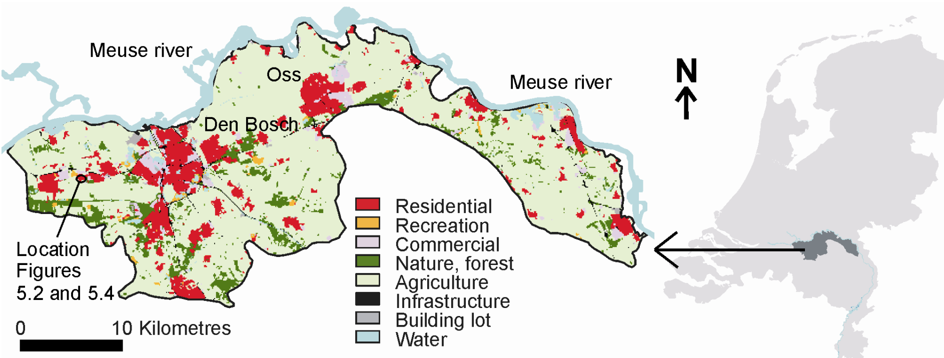

Figure 5.1. Land-use map of the study area, dike ring area 36 Land van Heusen/de Maaskant (source: Land-use Scanner).

smaller dike ring areas, is unlikely to flood completely in the event of a dike breach (Rijkswaterstaat, 2005a: page 24). Therefore, modelling approaches are needed that take into account the various possible inundation events that affect different parts of the study area and that could occur in the event of dike failures. All areas in The Netherlands protected by dikes have been assigned different protection levels under the Flood Defence Act of 1996, according to the potential severity of flooding and the number of people and amount of capital at risk (Van der Most and Wehrung, 2005; Bouwer and Vellinga, 2007). According to this Act, our case study area is to be protected by dikes that can withstand a river water level with a recurrence interval of 1,250 years. Note that this recurrence interval is different from flooding probabilities for the dike ring area, as a dike failure in one place would not lead to immediate flooding of the entire area. Moreover, dike failure can also occur at water levels with a frequency higher than once in 1,250 years (Vrijling, 2001). Actual failure probabilities of individual stretches of dikes and other elements of the flood protection system have been calculated for this dike ring and other parts of the Netherlands by the Floris project (Rijkswaterstaat, 2005c).

Surface elevation data

A high-resolution elevation model is available from the Ministry of Transport, Public Works and Water Management for the Netherlands, called the 'Actueel Hoogtebestand Nederland' (AHN; Current Elevation database Netherlands). Point measurements for this model have been derived using airborne laser altimetry at an original point density of 1 measurement per 16 m^2 (Huising and Pereira, 1998). A number of different raster products were made from these measurements, one of which is a gridded elevation model at a horizontal resolution of 5 metres, which was created using inverse distance weighting interpolation. The vertical accuracy of the elevation data is estimated to be some 10-15 cm for flat terrain (Huising and Pereira, 1998). The companies that collected the data filtered this grid for heights resulting from buildings and vegetation in non-urban areas. However, the grid still contains heights distorted by buildings and vegetation in the urban areas, and also contains some ‘no-data’ gaps, in particular over water areas. Slight differences in elevation can result in considerable inaccuracies in the estimation of potential damages using depth-damage curves. Especially in urban areas it is essential to filter out values that do not reflect the ground level, as urban areas usually account for the largest share of damages (e.g. Rijkswaterstaat, 2006a).

For the assessment of inundation depths to which buildings and other valuable objects are exposed, it thus is crucial to have an accurate estimate of the actual (vertical) surface elevation, as well as actual (horizontal) location of these inundation depths as they relate to the actual location of people and capital at risk. This can be achieved by a high-resolution elevation model. The surface level is what is usually referred to as the ‘bare earth’; i.e. the surface free from vegetation, buildings and other man-made structures (NRC, 2007). In order to derive this bare earth elevation, a correction is needed for high features such as trees and houses in urban areas. We applied a minimum filter to the 5-metre grid which moves a rectangular search window over the grid and assigns the lowest value found in every search window to the centre cell.

Because of the different sizes of the objects in these areas, three different filters were applied for industrial, residential and rural areas. The three categories were defined on the basis of CBS land-use statistics data (CBS, 2000). For industrial areas, where the elevation of relatively large building complexes needs to be corrected, a large search window of 18 grid cells wide (equal to 8100 m^2) was chosen. For residential areas a smaller search window of 10 grid cells wide (equal to 2500 m^2) was chosen, as most residential buildings are smaller and occupy less space than buildings in industrial areas. For rural areas, where only minor distortions need to be corrected, a search window of only two grid cells wide (equal to 100 m^2) was applied. Within this area it is assumed that the lowest cell value represents the actual local elevation. Some man-made structures, in particular impermeable sediment bodies that carry roads, railway-lines, dikes and other infrastructure features were exempted from the minimum filter, as they form important secondary barriers to flooding. They therefore have maintained their original elevation. Within the Floris project, minimum filters have been applied as well to produce elevation data for the flood risk estimates (Rijkswaterstaat, 2005a). The advantage of the applied procedure for the correction of elevation values is that it does not require extensive secondary information sources, for example datasets that describe the exact location of buildings. Additionally, the method is capable of correcting other high features, and filling most of the ‘no-data’ gaps in the raster, which occur mainly over water areas. Note that the reconstruction of actual elevation over water surfaces is not important for our purpose, as no flood damages are calculated for areas occupied by water.

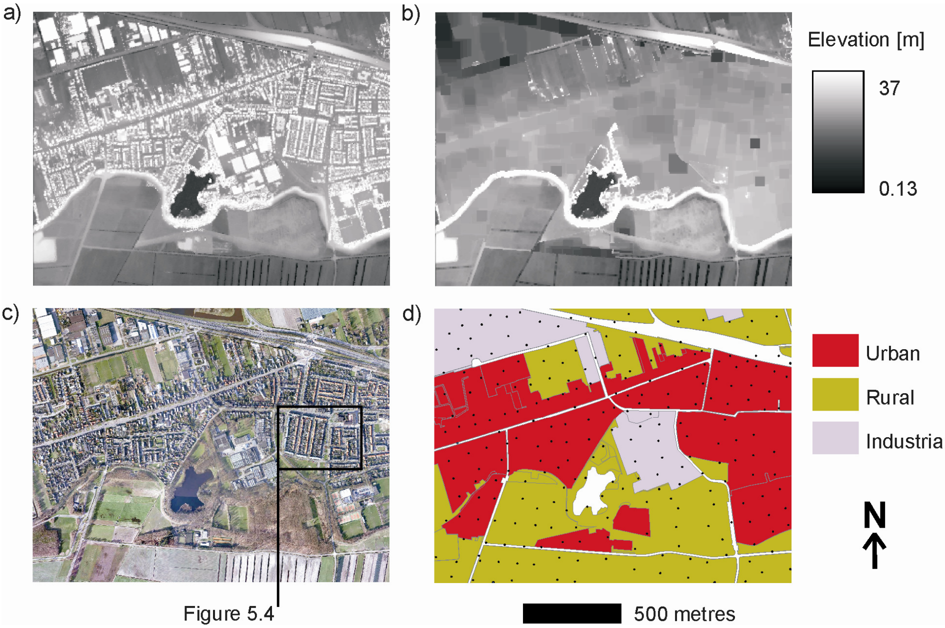

Figure 5.2. Original 5 metre elevation model (a) and after minimum filter application (b), aerial photograph of the same area in the year 2007 (c), and point ground level field measurements and land-cover classes (d), for location see Figure 5.1.

A visual assessment of a part of the corrected elevation model (Figure 5.2b) and a comparison with an aerial photograph (Figure 5.2c) shows that the filtering technique is successful in removing elevations resulting from buildings, trees and other high structures from urban areas, while leaving intact the relative higher elevation of old city centres. Waterways and ditches, however, are slightly widened.

In addition to the visual inspection, we performed a validation of the vertical elevation values, by comparing the grid elevation to the surface elevation as measured on the ground by topographical surveys. These data were collected during the 1950s and 1960s, and are part of the TOP10 vector dataset for The Netherlands. Field measurements are no longer made, as the AHN dataset has superseded the TOP10 elevations. For the case-study area depicted in Figure 5.2, a total of 216 individual point measurements from the year 1954 were collected from this dataset (Figure 5.2d), and compared against the corrected and uncorrected DEM on the basis of the AHN data. The comparison of data was split for urban and industrial areas on the one hand, and rural areas on the other (Figure 5.2d), in order to attribute offsets to land-use type. What is clear is that the greatest offset in the uncorrected DEM occurs for urban and industrial areas (Figure 5.3a), which is about +52% on average. After correction, the average difference is only 7.4% And except for a few outliers, which concern high elevations on a dike in a rural area, where trees result in large deviations of the DEM, the elevation for the urban and industrial areas that comprise the largest loss categories approaches the actual measured elevations very well (Figure 5.3b). For rural areas, the correction leads to a slight reduction in the deviation between the AHN data and the field measurements (3.0% and 0.3% difference, respectively for the uncorrected and corrected DEM).

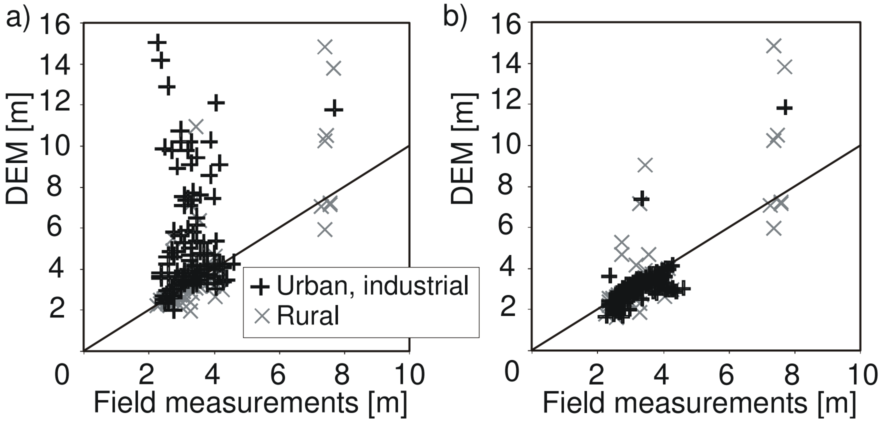

Figure 5.3. Comparison of digital elevation model (DEM) values with elevation field measurements for the uncorrected (a) and corrected DEM (b).

It should be noted, however, that this analysis captures only part of the effect of the filtering technique. Only a few point measurements coincide with grid cells of the DEM that reflect the height of houses. Thus, effect of correction is shown only for these few locations. In fact, a much larger number of grid cells representing building heights is corrected by applying the filter technique. We therefore also include a comparison between the difference of the original elevation model and the filtered elevation model with the actual location of houses (Figure 5.4a). The effect of the filtering in urban areas shows again that high obstacles (including vegetation and vehicles between the buildings) are accurately removed. The location of buildings was taken from the TOP10 vector dataset for The Netherlands. The aerial photo in Figure 5.4b provides further evidence that the disturbance from buildings and other objects has been removed from the elevation data.

Development of inundation scenarios

Several hydrological factors affect the extent of damage, including inundation depth, flow velocity, the duration of inundation, and pollution. However, inundation depth is usually the main parameter from which the fraction of damages is calculated (Messner et al., 2007). Generally, damage due to high flow velocities only occurs in a small area near the dike breach. This especially holds true for polder areas, due to their flat topography, causing flow velocities to be relatively low in most areas. Moreover, research has found that high flow velocity has a considerable influence on damages to roads, but is of minor importance for other loss categories (Kreibich et al., 2009). In the present study therefore the main interest is to determine what maximum inundation depth can occur in different segments of the polder in the study area. The inundation estimate can thus be reduced to a static situation of maximum inundation over an area, as opposed to a dynamic approach that attempts to simulate actual flow of water and inundation depths for different locations over time. The impact of high flow velocities is therefore ignored in this study.

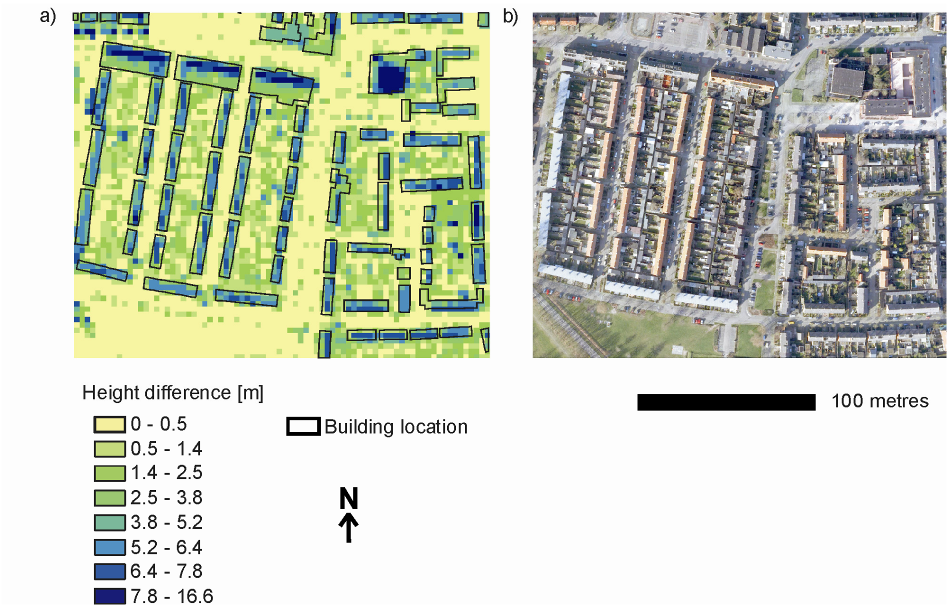

Figure 5.4. Difference map between original and filtered elevation model for urban area (a), and aerial photograph of the same area in the year 2007 (b), for location see Figure 5.2.

The topography of a polder area that is delineated by a single dike is not completely flat however, and can be subdivided into a number of individual ‘drainage’ areas. Using a Geographic Information System (GIS) these basins were identified in an automated fashion (ESRI, 2009). This analysis is the basis for delineating the individual basins. The minimum size of the basins is determined by the main linear obstacles that can be recognized in the case study area. The basins are of sufficient size to accommodate large volumes of water, as we show later. Using the automated approach, a total of 23 sub-basins were found to describe the major individual compartments that are present in the elevation model for the area, recognizing the importance of major boundaries created by dikes and other sediment bodies that carry main infrastructure, such as roads and railway lines (Figure 5.5). By combining different sets of basins, we arrive at 42 different inundation scenarios that span both very small and large inundation events.

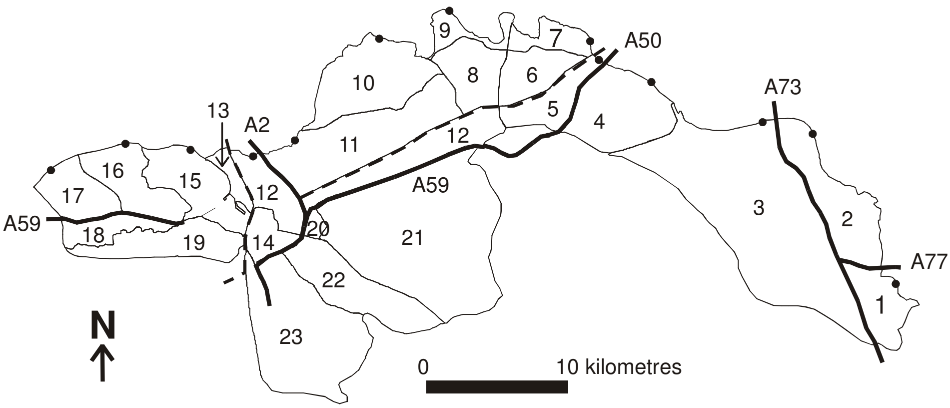

Figure 5.5. Identified basins in the study area and some major highways (bold lines) and railway lines (dotted lines), the 13 breach locations are indicated by dots.

The water level for each scenario is determined by the elevation of the lowest part of the basin boundary, which was found by analysing the linear features in the original (unfiltered) elevation data. With boundary elevation, we mean the elevation of the boundary of the individual sub-basin that we derived from the elevation model. This boundary can either consist of a dike section, or a high obstacle within the area, such as elevated sediment bodies that support highways and railway lines. The reason for using this lowest elevation is because we assume that the maximum inundation height that can be reached in an area is equal to the lowest obstacle enclosing this area. As soon as the inundation level reaches this point the water will flow over into the next sub-basin. A similar approach was also taken by the Floris study, which arrived at a general estimate of flood damage by simulating the effect of maximum inundation levels for all dike ring areas in The Netherlands up to the level of the minimum dike levels around those areas (Rijkswaterstaat, 2005a). After establishing the maximum water level (relative to the national ordnance datum), inundation depths are calculated for every grid cell in the inundation scenario that has an elevation level below this water level. As the definition of the lowest part of the basin boundary undoubtedly introduces uncertainties about the maximum possible inundation depth, we also carry out a sensitivity analysis. The average inundation depth for each scenario is derived and subsequently reduced by 10%. The effect of this reduction on the calculated damages is reported separately.

Probabilities for the inundation scenarios were taken from scenarios developed in the Floris project (Rijkswaterstaat, 2006a). These probability estimates include different failure modes of the dike segments and other elements such as barrages, sluice doors, etc. Probabilities have been established from detailed research for 13 stretches of flood defences (Rijkswaterstaat, 2005c; 2006a). The main and most likely failure mode for these dike segments is piping, which consists of water flowing underneath the dike body causing erosion and consequent collapse (see Vrijling, 2001). For the 42 scenarios, the breach location and the failure probability were taken from the Floris Project (Rijkswaterstaat, 2006a), which established the probability of failure, which combines loading and properties of the protective structure at the locations which are the weakest points in the 13 dikes segments adjacent to the inundated area. These 13 breach locations are shown in Figure 5.5. The total probability of failure in any dike segment was kept at the same level as in the Floris project (probability of 3.56×10^{-2} per year). Note that this return period is a (very) conservative estimate (Rijkswaterstaat, 2006a). It is assumed that a breach with low inundation volume is equally likely as an inundation event with a large volume of water emanating from the failure of the dike at the same location. Flooding volumes follow from the number of basins and the area that is flooded (i.e. the capacity of the area limits the volume of inflowing water). The volumes associated with the 13 scenarios from the Floris project will later in the chapter be compared to the volumes from the scenarios generated in this chapter. Probability p_i of a scenario i is therefore determined by

$$p_i=(p_1/n_1)+(p_2/n_2)+...(p_j/n_j) \qquad \text{(Equation 5.1)}$$

where $p_1...p_j$ are the probabilities of failure of the different breach locations j of the basins that are inundated, and $n_1...n_j$ are the number of inundation scenarios that occur due to failure of the particular dike segment. As in the Floris project, it is assumed that the dike fails in only one location, as a breach will alleviate the river water loading along the other dike segments (Rijkswaterstaat, 2006a), although the exact effect of this phenomenon at present remains unknown and cannot be accurately quantified (Van Mierlo et al., 2008).

Damage estimations

The ‘Damage Scanner’ model (Klijn et al., 2007) is used to calculate direct physical damages from flooding based on a series of depth-damage functions for 13 different land-use types. This Damage Scanner model is a simplification of the HIS-SSM model (Kok et al., 2005), and has been applied in the Floris project. The HIS-SSM model is the most comprehensive flood damage model available in The Netherlands, and has been described and evaluated in Messner et al. (2007). The direct damages generated by the model include damages for different loss categories, such as buildings, infrastructure, crops, and building content, as well as losses due to business interruption. The losses from business interruption consist of loss of turnover of businesses outside the flooded area, not assuming substitution effects (Kok et al., 2005). In addition to the direct damages, the HIS-SSM model also generates on average 5% indirect damage for all loss categories. The estimates resulting from the Damage Scanner model that we present here therefore already include this share of indirect damage. Simplification is necessary as the large amount of detailed information required for the HIS-SSM model is not available for future land-use change projections, and exposed people and assets, which cannot be estimated for all the loss categories included in the HIS-SSM model. The damages in the Damage Scanner model are calculated on the basis of depth-damage functions, and consider inundation depth only. In the HIS-SSM model, for which the Damage Scanner model is a simplification, depth-damage functions were estimated using a combination of empirical data on flood losses and inundation depths, as well as expert judgement (Messner et al., 2007).

It should be noted that the direct damages calculated here using the Damage Scanner model comprise only a part of all tangible priced direct damages associated with flooding. Priced direct damages also include loss of vehicles, business interruption, evacuation and rescue operations, clean-up costs, and reconstruction and rehabilitation, but these are not taken into account here. In addition, there are also intangible unpriced direct damages (e.g. fatalities and injuries), as well as tangible priced (e.g. losses for companies outside the inundated area) and intangible unpriced indirect damages (e.g. societal disruption and psychological traumas) (Jonkman et al., 2008a). However, direct damages generally make up a large part of the total costs, and are estimated for actual recent disastrous events to amount for between 50 and some 90% of total damage (RebelGroup, 2007). In addition, they are the most easily calculated, and are considered an important indicator of the severity of natural disasters.

Depth-damage functions relate the fraction of maximum losses to water depths (Figure 5.6) and have been established for different land-use types (Klijn et al., 2007). Table 5.1 lists the different land-use categories and their maximum damage amounts, which represent a countrywide average and are assumed to be valid for all dike ring areas in The Netherlands. These averages hold true for dike ring 36, as a comparison between the Damage Scanner model and the detailed HIS-SSM model showed only a slight bias of about 0-2% (Klijn et al., 2007).

The formula for total direct damages D reads (Jonkman et al., 2008a):

$$D = \sum_{i}^{m} \sum_{r}^{n} \alpha_i \left(h_r \right) D_{\max,i} \qquad \text{(Equation 5.2)}$$

where i is the land-use category, r is the location in the flooded area, m is the number of land-use categories, n is the number of locations in the flooded area,

$\alpha_i(h_r)$ is the depth-damage function depending on inundation depth h_r, and $D_{max,i}$ is the maximum damage amount for land use category *i*.

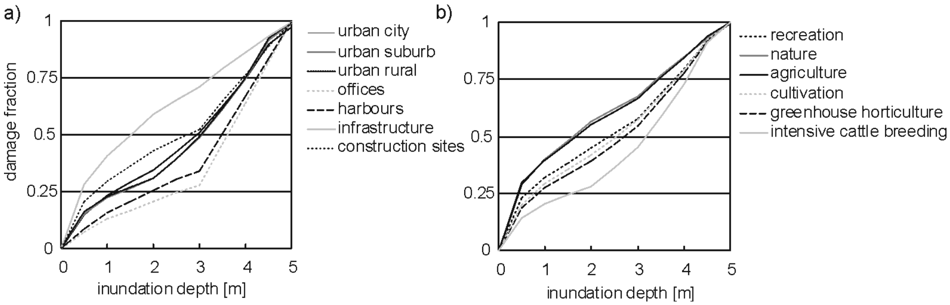

Figure 5.6. Depth-damage functions for different land-use categories in the urban (a) and agricultural classes (b) (after Klijn et al., 2007).

Table 5.1. Different land-use classes and maximum damage amounts (price level year 2000).

ID	Land-use class	Maximum damage [MEuro ha^{-1}]
0	Urban high density	9.1
1	Urban low density	4.0
2	Urban rural	3.8
3	Recreation	0.3
4	Commercial	6.0
5	Harbors	5.0
6	Nature	0.2
7	Arable land	0.2
8	Grassland	0.1
9	Greenhouses	0.7
10	Livestock	0.8
11	Infrastructure	1.9
12	Building lot	1.3

Land-use patterns

Land-use patterns for the current situation are derived from the base map of the Land-use Scanner model (Schotten et al., 2001). This model also provides future projections of simulated land-use change for the year 2040, based on spatial claims and suitability maps for different land-use types. The impact of land-use projections under different scenarios of socioeconomic development on estimated flood damage is assessed in subsequent research (Bouwer et al., 2010/Chapter 6). Here we apply the baseline land-use pattern from the model for the year 2000, which is also the reference year of the damage model. The land-use pattern in the case study area for this baseline situation is shown in Figure 5.1. The Land-use Scanner data for the baseline situation is provided at a horizontal spatial resolution of 25 metres and 100 metres. The 100 metre resolution is used for projections of future land-use change.

In order to estimate the effect of loss calculations on a high resolution compared to a coarser resolution, we calculate losses for resolutions of 5 metre (the original DEM resolution), 25 metre, and 100 metre. For this purpose, the 25-metre land-use grid has been downscaled to a 5-metre resolution. It is known that the 100-metre land-use grid slightly overestimates the total area covered by residential and agricultural areas (both on average by 4%) and considerably underestimates the total area covered by infrastructure (on average by 64%), compared to the 25-metre grid (Loonen and Koomen, 2008). The inundation scenarios were aggregated from a 5-metre grid to 25 and 100-metre grids, using the mean of the input cells.

5.3 Results

The 42 inundation scenarios consist of inundation depth maps at a horizontal resolution of 5, 25 and 100 metres. Scenarios were based on the inundation of a single basin, or a combination of several basins. A series of scenarios, developed for a single possible breach location is constructed as follows: the minimum scenario for a breach in the dike along basin 16 (Figure 5.5) concerns flooding only in basin 16, this is scenario number 6 (Table 5.2). If the adjacent basin 17 is affected, scenario 2 occurs. More basins can be inundated (basins 15, 16, 17, 18 and 19, in scenario 5), until the railway line to the east is overflowed (Figure 5.5), which gives rise to scenario 18, and so on. Table 5.2 lists the individual scenarios and the basins they comprise. The inundated surface areas found for the different scenarios range from 5-374 km^2, with an average of 81 km^2. This range is comparable with the range of inundated areas, resulting from hydrodynamic modelling for this study area, that range from 7-303 km^2, and cover on average 98 km^2 (Rijkswaterstaat, 2006a).

The resulting loss maps for the two inundation scenarios with the lowest and highest aggregate losses (Figure 5.7) show that losses are low in the rural areas (scenario 9 and 24), and highest in urban areas, in particular in the city of Den Bosch (scenario 24). What is clear from the map for scenario 24, is that within the city of Den Bosch relatively low losses occur in the old city centre in the middle of the town (compare Figure 5.1), due to its slightly higher elevation compared to other parts of the city. The highest losses occur in comparatively new areas with factories and business at the northeast side of the city of Den Bosch, and north of the city of Oss.

Table 5.2. Inundation scenarios.

No.	Basins inundated	Area [km^2]	Average depth [m]	Volume [10^6 m^3]
1	17	17	0.64	11
2	17, 16	39	2.53	98
3	17, 16, 18	50	2,23	111
4	17, 16, 18, 15	71	1.97	140
5	17, 16, 18, 15, 19	95	2.38	225
6	16	22	2.17	47
7	15, 19	44	1.15	51
8	16, 17	30	0.60	18
9	10	21	0.50	11
10	10, 11	41	0.42	17
11	10, 11, 12	111	2.03	225
12	13, 15	26	1.57	40
13	13, 12, 10, 11	115	2.05	235
14	13, 14, 15	32	1.49	47
15	14, 13, 10, 11, 12	121	2.01	243
16	15, 14, 13, 10, 11, 12	142	1.91	272
17	19, 15, 14, 13, 10, 11, 12	165	1.78	293
18	19, 16, 17, 15,14, 13, 12, 11,10	205	2.20	451
19	13, 15, 19	48	1.29	62
20	8, 9, 10, 11, 12	149	1.85	276
21	7, 6, 8, 11	71	0.33	23
22	7, 6, 8, 10	72	0.44	32
23	7, 6, 8, 9, 10, 11	98	0.40	39
24	All basins	374	1.70	635
25	20, 21, 23, 22, 13, 15, 19, 14	158	1.07	169
26	13, 14, 15, 19	72	1.26	91
27	8, 9, 10, 11, 12, 14	155	1.82	282
28	9, 8, 10, 11	61	0.42	25
29	7, 6, 8, 9, 10, 11, 12, 13, 15, 14	205	1.80	369
30	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	120	0.52	62
31	7, 6, 8, 9, 10, 11, 12	150	1.75	263
32	3, 4, 5, 6, 7, 8, 10,11	103	0.49	51
33	4, 5, 6, 7, 8	57	0.56	32
34	3, 4, 5, 6, 7	49	0.57	28
35	4	18	0.68	12
36	3, 4	23	0.59	13
37	2, 3, 4	29	0.65	19
38	1, 2, 3, 4	34	0.64	22
39	3	5	0.24	1
40	2, 3	11	0.58	7
41	1, 2, 3	7	0.59	4
42	2	7	0.95	6

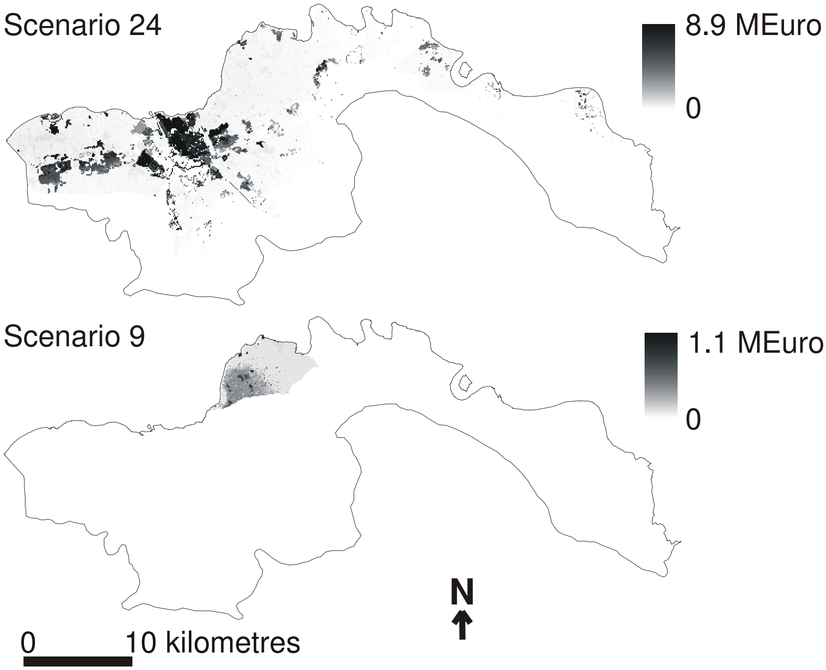

Figure 5.7. Flood damage estimates for scenarios 24 and 9.

Estimated losses aggregated for all land-use types range between 49 million Euros for scenario 9 and 11 billion Euros for scenario 24 (Table 5.3). The Floris project reports losses between 66 million and 7.0 billion Euros based on their 13 different inundation scenarios. Expected damages per year are calculated by aggregating the damage estimates for each scenario multiplied by the probabilities for each scenario. The average expected damage is 26.2 million Euros per year in the current study, while the Floris project reports an expected damage of 33 million Euros per year (Rijkswaterstaat, 2006a). The main reason for this difference, apart from different loss models being used, is that our approach considers that some of the inundation scenarios cover only a relatively small geographic area and have limited inundation depths. This reduces the average loss amounts associated with the inundation scenarios.

The accurate estimate of heights of dikes and infrastructure elements affects our results, as the maximum possible depth of inundation in the individual basins is determined by these features. We believe that the most important elements, such as highways and dikes that are between ~10-30 metres wide are accurately reflected in the data. Likely, other sources of uncertainty, such as the estimated dike failure probabilities and uncertainties in the depth-damage curves will affect the loss estimates more than the height of infrastructure elements and resulting inundation

Table 5.3. Scenario damages and probabilities.

Number	Damage [MEuro]		Probability
	25 m resolution	100 m resolution	
1	64	70	2.0E-04
2	901	939	3.4E-04
3	1488	1504	3.4E-04
4	2151	2268	6.1E-04
5	3230	3241	6.1E-04
6	645	685	1.4E-04
7	824	923	2.7E-04
8	119	163	2.0E-04
9	51	49	1.9E-04
10	143	249	2.0E-04
11	4651	5014	2.3E-04
12	806	953	2.9E-04
13	4800	5222	2.3E-04
14	1010	1405	2.9E-04
15	5004	5657	2.3E-04
16	5657	6366	5.0E-04
17	5817	6512	5.0E-04
18	7425	8079	5.0E-04
19	966	1098	2.2E-05
20	4887	5313	2.5E-04
21	338	533	8.9E-05
22	297	384	8.9E-05
23	417	615	8.9E-05
24	9663	10681	1.7E-04
25	2237	2890	2.2E-05
26	1299	1701	2.2E-05
27	5082	5749	2.2E-05
28	246	418	2.2E-05
29	6422	7103	1.1E-04
30	717	1053	1.3E-05
31	4793	5209	8.9E-05
32	513	737	1.7E-04
33	346	441	3.1E-03
34	297	364	1.7E-04
35	128	150	2.8E-03
36	152	200	1.7E-04
37	264	393	7.2E-06
38	328	482	1.3E-05
39	23	51	1.7E-04
40	136	244	7.2E-06
41	200	333	1.3E-05
42	112	193	7.2E-06

depths. We performed a sensitivity analysis of the effect of the estimated maximum inundation level on losses. A reduction of 10% in the inundation level of the scenarios (see Section 2.2), results in an average reduction of 10.9% in aggregate losses (maximum -14.6%, minimum -7.4%). We believe that the actual uncertainty in the estimation of the level of the basin boundaries in our method is an order of magnitude smaller, leading to lower uncertainties in both the inundation levels and aggregate loss estimates.

Loss-probability curves are created by calculating the cumulative probability of damage events, and plotting these according to their damage size. The curves thus indicate the probability that a particular loss is equalled or exceeded. The large quantity of inundation scenarios that we created, allows the construction of a loss-probability curve, which includes relatively small events, as well as large loss events (Figure 5.8). The curves for both the 25 and 100-metre resolution land-use maps are shown.

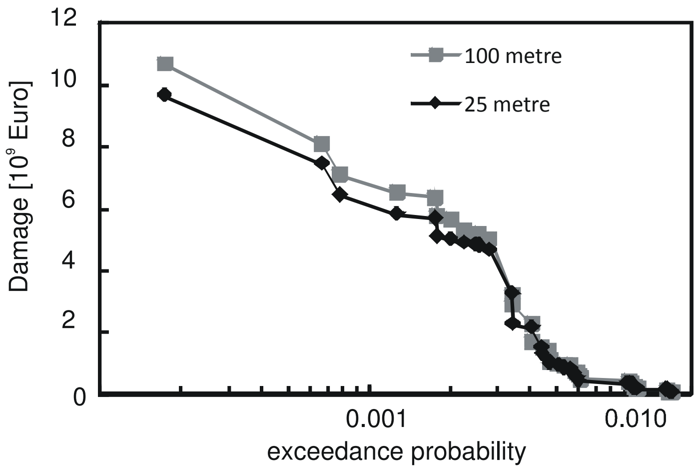

Figure 5.8. Loss probability curve estimates, using the 25 and 100 metre resolution land-use maps.

The loss shares for different land-use types differ considerably from those found in the Floris project for this dikering area (Table 5.4), but are of similar magnitude. For instance, urban areas account for the majority of losses according to our estimates (66-70%), while Floris also reports the majority of losses in this category, albeit considerably smaller (45%). According to our calculations, losses to agriculture and commercial land-uses come in second and third place (11 and 11-12%, respectively), like the Floris calculations (25 and 24%, respectively). The main reason for the differences is the difference in loss calculations. The Floris project uses a large series of loss-categories (Kok et al., 2005). Therefore, some differences are likely due to the differences in the loss models. The HIS-SSM loss model used in the Floris project is superior in terms of the number of loss categories, and the detail in the way losses are calculated. However, the reason for developing a simple approach lies in the application of future land-use scenarios in subsequent research, for which the simple loss model is better suited.

Table 5.4. Comparison of share of damage per land use category in this study with the results from the Floris project (Rijkswaterstaat, 2006a).

Land-use category	This study [% of total damage]		Floris study [% of total damage]
	25 m resolution	100 m resolution	
Agriculture	11	11	45
Infrastructure	8	4	24
Urban	66	70	6
Commercial	11	12	25
Other	3	3	0.2

The extent to which the grid resolution of the loss calculations influences the damage estimates was also investigated. Losses were calculated separately for the 25-metre and 100-metre inundation maps and 25-metre and 100-metre land-use maps. We find some differences in estimated damages between the 25 and 100-metre inundation grids. Compared to the loss estimates based on the 25-metre inundation dataset, aggregate loss estimates per scenario using the 100 metre dataset are up to 54% higher for scenarios with losses less than 4 billion Euros, and up to 12% higher for scenarios with total losses of 4 billion Euros and higher. However, overall losses are of the same order of magnitude: total expected damages amount to 23.6 million Euros per year for the 25-metre grid, and to 26.2 million Euros per year for the 100-metre grid. More striking differences are found for the different land-use categories. Estimates for the category "infrastructure" add up to 3.9% of the total damage based on the 100-metre grid, but to 8.0% for the 25-metre grid (Table 5.5). As we reported earlier in Section 2.4 on land-use patterns, the 100-metre resolution land-use grid considerably underestimates the extent of infrastructure elements (railways and roads), owing to their narrow shapes. The extent of urban areas in turn is in general overestimated using the 100-metre grid. This results in the overestimation of urban areas affected by flooding, and therefore the total loss. Expected damages in high-density urban areas differ by as much as 1.8 million Euros (Table 5.5), implying a 22% overestimation for the 100-metre grid relative to the 25-metre grid. High-density urban areas in reality account for only small extents, but are overrepresented in the 100-metre grid. These findings imply that using information with a coarse horizontal resolution can lead to considerable over and under estimates of damages for certain land-use categories. In particular, in a coarse resolution the total losses tend to be overestimated for the scenarios in which large extents of urban area are inundated.

In order to further estimate the sensitivity of the damage estimates to grid resolution, we calculated damages using the 5-metre inundation grid and a resampled land-use map for scenario 24, which covers all potential inundated sub-basins in the area (Figure 5.7). We find that using the 5-metre inundation grid, total losses equal 9,246 million Euro for scenario 24. This is about 4.3% less than the estimate using the 25-metre inundation grid (9,663 million Euro total damage), and about 13% less than the estimate using the 100-metre inundation grid (10,681 million Euro total damage). This implies that using even higher resolution inundation maps, loss estimates in general will decline, and the estimates for some land-use categories such as infrastructure may increase.

Table 5.5. Expected damage for different land-use categories using 25 and 100 meter resolution land-use maps.

ID	Land-use class	Expected damage [10^6 Euro/year]		Expected damage [%]	
		25 m	100 m	25 m	100 m
0	Urban high density	8.1	9.9	34.4	37.7
1	Urban low density	7.0	7.9	29.6	30.1
2	Urban rural	0.6	0.6	2.5	2.4
3	Recreation	0.0	0.1	0.2	0.2
4	Commercial	2.6	3.2	11.2	12.1
6	Nature	0.2	0.3	0.9	1.0
7	Arable land	0.7	0.8	3.1	2.9
8	Grassland	1.7	1.9	7.4	7.2
9	Greenhouses	0.1	0.1	0.4	0.3
10	Livestock	0.1	0.1	0.4	0.3
11	Infrastructure	1.9	1.0	8.0	3.9
12	Building lot	0.5	0.5	2.0	1.9
	Sum	23.6	26.2	100	100

5.4 Discussion and conclusions

The aim of this study was to develop a method that is able to simulate inundation in polder areas, and calculate associated flood losses. In particular, the method could be used for detailed scenario studies of the impact of future socioeconomic and climatic developments on flood risks. The relatively small number of scenarios that can be reasonably produced by hydrodynamical modelling, and their relatively coarse horizontal resolution, limit the usefulness of these models for high spatial resolution loss estimates for large areas. The method compliments more detailed hydrodynamic approaches, by providing a risk assessment with sufficient accuracy, but at a larger geographic scale. This chapter has demonstrated that the present approach allows simulation of flood events for a number of dike breach locations, based on a high-resolution elevation model. A wide range of variations in the volume of inundating water is taken into account. In addition, the uncertainty related to different amounts of inundating water volumes and the potential collapse of linear obstacles can be taken into account, as the scenarios include versions with and without inundation of adjacent basins that are protected by linear landscape elements.

The method was applied to a polder area in the south of The Netherlands, at risk from flooding of the river Meuse. The effort for developing the current range of scenarios is considerably less than the effort involved in hydrodynamic modelling. Our scenarios and consequent flood losses were constructed to illustrate the potential range of flood losses, and to assess the relative impact of land-use and socioeconomic changes in subsequent research. The generation of a large variety of inundation scenarios provides a good basis for constructing loss probability curves. Such curves are important in risk analysis as well as in the development and evaluation of flood management policies. These curves allow an estimate of the maximum losses, as well as the expected annual average losses. The calculated range and expected values of damages compare reasonably well with earlier calculations from the Floris study (Rijkswaterstaat, 2006a), which estimated flood losses on the basis of hydrodynamic flood simulations and a more detailed loss model. Yet, there are some important differences between the losses estimated in our study and those found in the Floris study, that mainly result from the different loss modelling approaches.

We also showed that the resolution of loss modelling has a considerable influence on losses calculated with the same loss model. Our study showed that damage estimates based on coarse inundation maps, errors can amount to 22% overestimates and 100% underestimates for the categories of high density urban areas and infrastructure, respectively. This has important implications for the proper evaluation of flood risks using coarse resolution inundation scenarios that are applied in flood risk modelling. Losses from urban areas and infrastructure are important, because they comprise the largest share in the total aggregate losses. The estimation of the effectiveness of mitigation measures in the urban environment and infrastructure needs to take account of the actual risks. The damages estimated using the high resolution inundation grids are expected to be closer to the actual potential losses, as inundation depths are more accurately estimated, and their position is more accurate compared to the land-use classes. We estimate the maximum damage to be 9.2 billion Euros using the high resolution (5-metre), while the Floris project estimates the maximum damage at 7.5 billion Euros (Rijkswaterstaat, 2006a) using a more detailed loss model. Other studies have estimated these maximum losses for this dike ring to be 17.7 billion Euros (Rijkswaterstaat, 2005a) and 10.3 billion Euros (Klijn et al., 2007).

It is important to stress that major uncertainties also occur in the loss modelling part, and not just in the inundation depth assessment. In particular, the relation between inundation depth and damage fraction is generally quite uncertain. The actual form of the depth-damage curves is unknown, and is a major source of uncertainty in flood risk estimates (Merz et al., 2004; Merz et al., 2008). Also the maximum damage amounts used here (Table 5.1) are just estimates for average asset values for the entire country, and not the actual objects values in the case study area.

5.5 Acknowledgments

We thank Karin de Bruijn (Deltares) for her help in applying the Damagescanner model that she developed, and for her comments on this chapter. Rijkswaterstaat (Dutch Ministry of Transport, Public Works and Water Management) kindly provided the AHN elevation data, and the ground level observation point data. Slagboom en Peeters Luchtfotografie BV, Teuge, The Netherlands, provided the aerial imagery used in Figures 5.2 and 5.4. The comments and suggestions from Dapeng Yu and an anonymous referee greatly helped to improve this chapter. Finally, we thank our colleagues Hans de Moel, Oleg Sheremet, and Wouter Botzen for their comments. This research is part of the project 'Financial arrangements for disaster losses under climate change', supported by the Dutch National Research Programme 'Climate changes Spatial Planning' (http://www.climatechanges-spatialplanning.nl). All errors and opinions remain ours.

Chapter 6. Changes in future flood risk in a Dutch polder area

Abstract

Damages from weather related disasters are projected to increase, due to a combination of increasing exposure of people and assets, and expected changes in the global climate. Only few studies have assessed in detail the potential range of losses in the future and the factors contributing to the projected increase. Here we estimate future potential damage from river flooding, and analyse the relative role of land-use, asset value increase and climate change on these losses, for a case study area in The Netherlands. Projections of future socioeconomic change (land-use change and increase in the value of assets) are used in combination with flood scenarios, projections of flooding probabilities, and a simple damage model. It is found that due to socioeconomic change, annual expected losses may increase by between 35 and 172% by the year 2040, compared to the baseline situation in the year 2000. If no additional measures are taken to reduce flood probabilities or consequences, climate change may lead to an increase in expected losses of between 46 and 201%. A combination of climate and socioeconomic change may increase expected losses by between 96 and 719%. Asset value increase has a large role, as it may lead to a doubling of losses. The use of single loss estimates may lead to underestimation of the impact of extremely high losses. We therefore also present loss probability curves for future risks, in order to assess the increase of the most extreme potential loss events. Our approach thus allows a more detailed and comprehensive assessment than previous studies that could also be applied in other study areas to generate flood risk projections. Adaptation through flood prevention measures according to currently planned strategies would counterbalance the increase in expected annual losses due to climate change under all scenarios.

6.1 Introduction

Climate change has been suggested to be a cause for increasing losses from extreme weather events (IPCC, 2007b). However, population growth, increases in asset values, and accumulation of assets in areas at risk from natural hazards have been found to be the main underlying reasons up to now for increasing losses from natural disasters (Changnon et al., 2000; Crompton and McAneney, 2008; Pielke et al., 2008). The expectation is therefore that under ongoing socioeconomic change, natural hazard risk is likely to increase independent from climate change (Bouwer

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et al., 2007/Chapter 2; Feyen et al., 2009). In general, losses from natural disasters around the world have been increasing more rapidly than general economic growth, owing to the rapid development of population and assets in large urban areas in at-risk areas (Bouwer et al., 2007/Chapter 2). Still, ongoing and future climate change is expected to affect disaster losses, as the Intergovernmental Panel on Climate Change (IPCC) states that: "(w)here extreme weather events become more intense and/or more frequent, the economic and social costs of those events will increase" (IPCC, 2007b: p. 12). In particular flood risks are anticipated to increase due to climate change.

The assessment of current flood risk is often used to estimate the long-term benefits of any flood risk management strategy (e.g. Ten Brinke et al., 2008). But actual benefits will consist of avoided future flood risks, and therefore studies are needed that quantify these future risks and their uncertainties. Such quantifications also show the potential consequences of unmitigated impacts, as well as the benefits of adaptation measures. Current studies on the economic impacts of climate change, however, poorly take into account the impact from extreme weather events (Hallegatte, 2008).

A number of studies have evaluated the conditions and time by which impacts of climate change on flood probabilities would become apparent, by analysing climate change scenarios (e.g. Wilby, 2006). Only few studies however have attempted to combine projections of changes in climate hazard and socioeconomic trends and exposure, e.g. for hurricane losses in the USA (Pielke, 2007b). Other studies have used integrated scenarios for climatic and socioeconomic change to project potential flood losses for the UK and Europe (Hall et al., 2005; Mokrech et al., 2008; Dawson et al., 2009; Feyen et al., 2009).

In The Netherlands two recent studies have assessed how the risk of flooding might evolve over time (Klijn et al., 2007; Aerts et al., 2008), in particular taking into account the impacts from economic development, climate and land-use change. These two studies however have applied only single flooding probabilities for estimating future risks, and have not taken into account a full set of potential flood events. In addition, the analysis by Van Schrojenstein Lantman (2007) estimated future losses for a selected area in The Netherlands, using a small set of flood scenarios. For analyses that aim to evaluate the full range of changes in risk (i.e. probabilities and outcomes) it is important to use land-use projections in combination with a probabilistic approach, taking into account different potential flood events and their probabilities. For the flood risk in The Netherlands, a probabilistic approach is currently undertaken in the Floris project (Rijkswaterstaat, 2005b; Van der Most and Wehrung, 2005). This probabilistic approach allows the assessment of the likelihood of current flood damages, in particular the likelihood of extreme loss events. However, the Floris study does not consider future changes in risk.

Assessing river flood risk is not a simple task, because of the complex nature of flood generation that is generally caused by a combination of precipitation and soil saturation, and river basin characteristics (Disse and Engel, 2001). Particularly with regard to flooding, it has been shown that the exact location of people and assets matters tremendously for the accurate evaluation of the risks involved. Therefore detailed modelling is required and usually applied to reliably estimate the impact of flood events (Munich Re, 1997; Messner et al., 2007). As has been shown for potential flood casualties, exposure increases disproportionately compared to average population growth trends, when more detailed analyses are made of the actual location of the exposed population (Maaskant et al., 2009). In addition, much uncertainty exists around the probability of extreme loss events. Therefore, studies that support policy need to take account of the full range of potential losses, rather than the average annual expected losses. This is often achieved through the construction of loss-probability curves on the basis of analysing small and large flood events. Most existing studies on developments in flood risk have two important shortcomings; they lack high spatial resolution that has shown to be very important, or they do not take explicit account of the shift in probabilities of both small and large loss events.

This chapter aims to identify the main factors that affect potential river flood risks in the future, and combines estimates of these factors with an assessment of the losses resulting from a large set of inundation scenarios. Our approach allows for a more comprehensive evaluation and solves some of the issues mentioned above, as it includes a detailed assessment of the factors that affect both exposure and flood probabilities, it is more detailed in spatial resolution and takes a probabilistic approach. It is the first study that provides loss-probability curves for the present and projected future situations in The Netherlands. We show for a case study area in The Netherlands the factors that contribute to increasing loss potentials between the years 2000 and 2040. We use a simple damage model, in combination with a large number of flood scenarios, and two sets of land-use change scenarios for the year 2040. This enables an estimation of the range of potential shifts in the loss probability curve in 2040, compared with the baseline loss curve for the year 2000. The main drivers of changes in potential losses that will be studied are socioeconomic development that is reflected in changes in land-use and assets at risk, as well as changes in the flood probability due to climate change. In addition, we assess whether measures for additional flood prevention that are currently planned in the case-study area, are sufficient to mitigate the additional increase in risk due to climate and socioeconomic changes. This allows an assessment of the effectiveness of the planned measures, as well as an indication of residual risk.

6.2 Methods, case study area and data

We estimate future potential flood losses by combining scenarios for socioeconomic development with climate change projections (Figure 6.1). By choosing a wide range of scenarios for physical and socioeconomic changes, we assume that we capture some of the inherent uncertainty related to future projections. Damage for a series of potential loss events is calculated with a damage model, using scenarios for inundation (flooding). The loss model calculates losses, based on land use type and inundation depth. This approach is applied to a case study area that is at risk from river flooding, located in the south of The Netherlands. This location is chosen for three reasons: a) it is a region that is at risk from only one major flood hazard (riverine flooding), which makes the approach more simple compared to areas at risk from sea and river floods, b) it has some major urban areas that are at risk which is exemplary for many urban areas at risk around the world, c) and the area is reasonably large, so that risk varies across the area, which makes it necessary to estimate a loss distribution rather than a single number. Future expected losses are calculated on the basis of changed exposure due to changes in land-use in the year 2040. This time horizon is chosen because for up until this year a series of socioeconomic and land-use projections are available, that span a range of possible future developments. Moreover, other studies in The Netherlands have used this time horizon as well. These changes in land-use are taken from a land-use model that calculates projected land-use patterns according to two scenarios for socioeconomic change. Two different factors for changes in wealth, and consequent changes in asset values are estimated on the basis of the same two socioeconomic scenarios. Additionally, factors for changes in flood probabilities are derived from two climate change scenarios. The remainder of this section describes the case study area, methods and data sources, as well as the scenarios used.

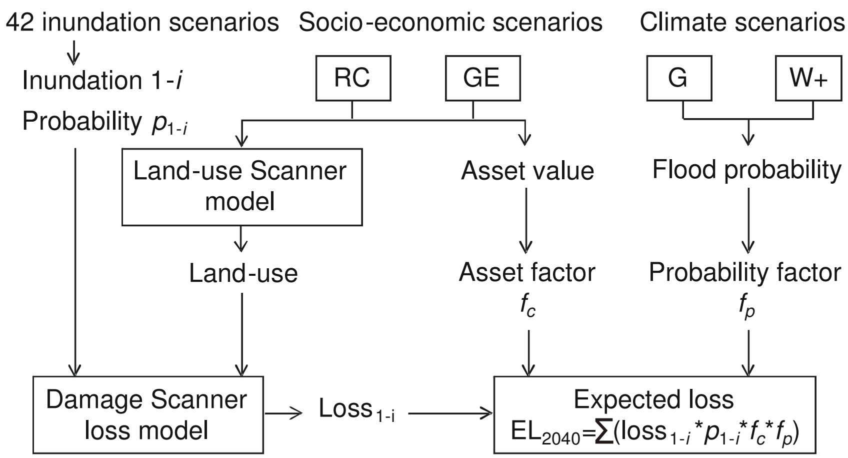

Figure 6.1. Approach for estimating future flood risks.

Case study area

The study area is dike ring area 36 (Land van Heusden/de Maaskant) located in The Netherlands and has a surface area of 740 km^2. The area is at risk from flooding due to potential failure of dikes during high discharges on the river Meuse, which flows along the northern and eastern boundary of the area. Agricultural use is the dominant land-use pattern next to recreation, and two cities (Den Bosch and Oss) are located in the area (Figure 6.2). The safety standard for the study area requires that the dikes can withstand a water level of the Meuse river that occurs once every 1,250 years. This water level has been derived from extrapolation of the observed river discharges. Flooding occurs only when parts of the dikes that protect the area are breached or overtopped. The probability of flooding for any given place in the study area is therefore different than the recurrence interval of high water levels of the river Meuse.

Projections of land-use change

Land-use change projections are derived from the 'Land-use Scanner', which is part of a model platform, used in scientific and policy studies for spatial and environmental decision making and planning (http://www.lumos.info; Schotten et al., 2001). The model is capable of simulating future land use and has been applied in a number of policy related research projects focusing on The Netherlands and several other European countries (Wagtendonk et al., 2001; Dekkers and Koomen, 2007), and the resulting land-use patterns have recently been used in flood risk research supporting the Dutch Delta Committee (Aerts et al., 2008). Using socioeconomic scenarios, the model projects future land-use patterns on the basis of spatial claims and suitability maps for different land-use types. The land-use patterns depend on individual choice behaviour, based on microeconomic theory. Using the Land-use Scanner model, projections of land-use for 2040 were generated according to the Global Economy (GE) and the Regional Communities (RC) socioeconomic scenarios. These two scenarios are part of a set of four socioeconomic scenarios until the year 2040, which were developed for economic and environmental policy studies (WLO, 2006). The RC and GE scenarios are comparable to the B2 and A1 scenarios, respectively, developed by the Inter-governmental Panel in Climate Change (IPCC, 2000). The GE scenario assumes a relatively rapid economic growth of 2.6% per year, and a continuing growth of the population in The Netherlands of 0.5% per year. The RC scenario assumes lower economic growth (0.7%), and no population growth (0%). Under the GE scenario, population and assets are projected to accumulate rapidly, and can therefore be regarded as a 'high' scenario. The RC scenario on the other hand, has the lowest economic growth of the four socioeconomic scenarios and a stable population. By using these two socioeconomic scenarios, we explore the lower and upper end of the impacts of population and economic growth on flood loss potentials.

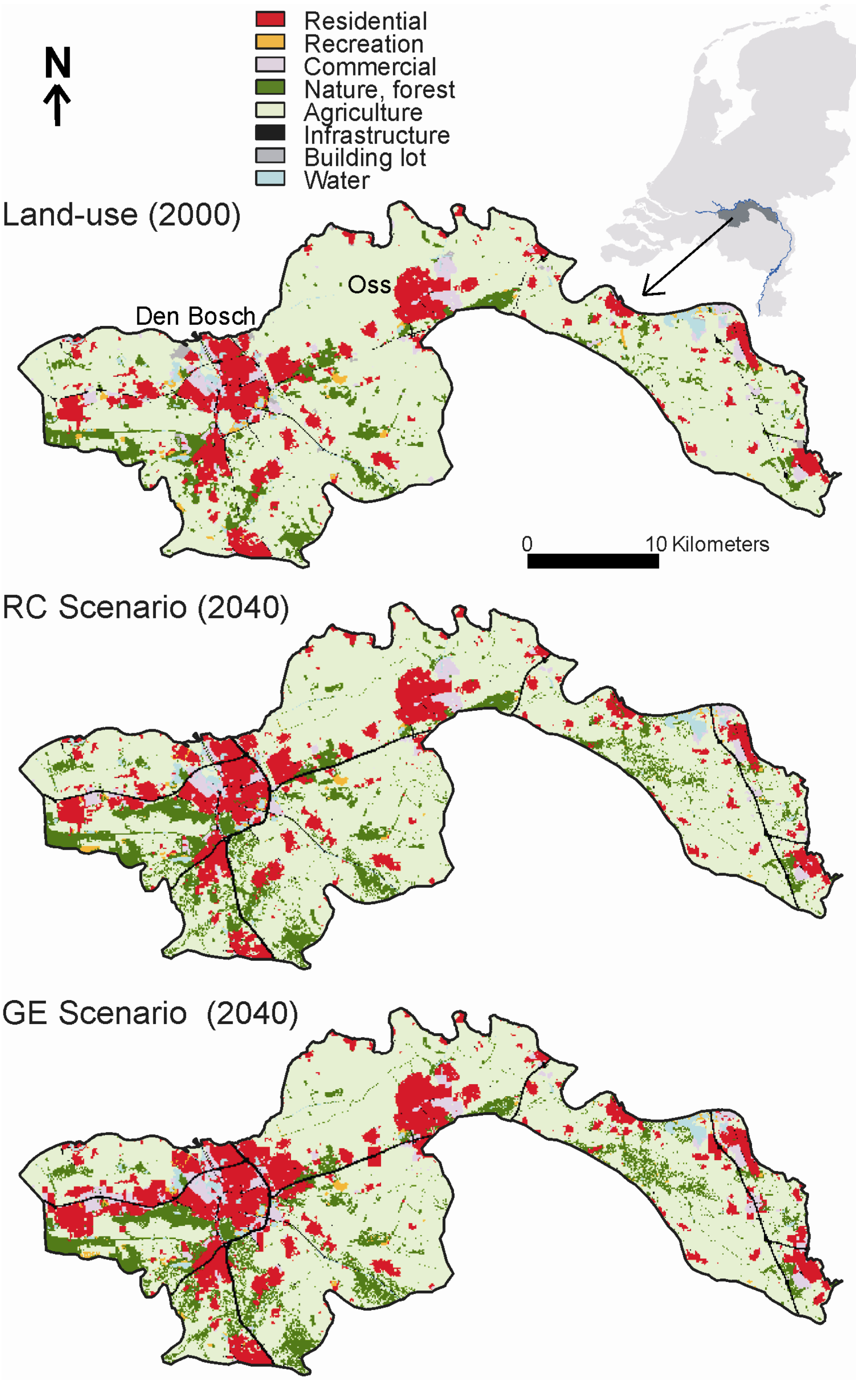

Figure 6.2. Land-use map of the study area, dike ring 36 Land van Heusen/de Maaskant, for the years 2000, and 2040 under the RC and GE socioeconomic scenarios (source: Land-use Scanner).

Potential flood damages under future land-use scenarios are calculated by using these land-use projections as input for the 'Damage Scanner' model. In general, urban areas are projected to expand in response to population growth, household size (number of persons) is projected to decline, and there is a growing preference for more dwelling space per household. This expansion results in increasing losses. The expansion of surface area per housing unit is only slightly less pronounced in the RC scenario compared to the GE scenario (average 248 and 252 m^2 respectively in 2050, with 241 m^2 in 2002) (WLO, 2006). However, in some locations, losses may decrease, as land-use classes with lower maximum damages may replace land-use classes with higher maximum damages in the future. For instance low vulnerable recreation area replaces highly vulnerable greenhouse horticulture, in some areas. The latter may in particular be the case in the RC scenario.

Projections of increasing asset value

Changes in land use reflect only a part of the projected socioeconomic development. Additionally, economic growth is likely to lead to an absolute increase in the value at risk, and therefore to an increase in potential losses. To capture the entire extent of changes, a factor that reflects the average estimate of the increase in value per surface area unit is to be applied to the projected damages (Figure 6.1). This factor is constructed from the average index of change in real gross domestic product (GDP) for The Netherlands until 2040. The values for the indices are taken from the WLO scenario descriptions (WLO, 2006). As GDP also reflects the absolute accumulation of assets, we correct the GDP index for changes in surface area allocated to housing, factories and offices, in order to single out the value increases per unit area. A similar method was applied in the study by Klijn et al. (2007). The factor f_c that reflects the change in value of a unit of assets at risk is calculated as:

$$f_c=(I_{gdp}/((I_h+I_i+I_o)/3))^t \quad \text{(Equation 6.1)}$$

where I_{gdp} is the index for annual change in GDP, I_h is the annual index for change in the number of households, I_i is the index for the surface area occupied by industry, I_o is the index for the surface area occupied by offices, and t is the number of years for which the factor is calculated.

The calculation results in annual increases in value of a unit of assets of 0.7% and 1.7% for the RC and GE scenarios, respectively. The factors f_c are 1.31 and 1.89 up to the year 2040 for the two scenarios. These factors are applied to all land-use categories. This is a simplification, as not all classes (for instance forest, grassland and recreation) will see value increases to the same extent, and changes in losses for these classes may therefore be overestimated. The land-use categories to which the factors apply represent 88% of the losses in the total damage amounts; which are urban areas and other capital intense land-use classes including commercial, harbours, greenhouses, and infrastructure. And given the small differences in the indices for housing, industry, and offices, the introduced inaccuracies are likely to be minor.

Impact of climate change on flooding probabilities

Flood probabilities in the study area are projected to change due to climate change. We assess the impacts of climate change on flood damages by estimating changes in river discharge probabilities of the river Meuse. River discharge probabilities fundamentally determine the likelihood of failure of flood defences along the case study area. A number of studies have assessed how climate change and other changes in the river basin may affect the likelihood of peak discharges. It has become clear that periods with frequent peak discharges occur in cycles over time, and that during certain decades (the 1920s and the 1990s) high discharges were particularly frequent (Bouwer et al., 2008/Chapter 4). Estimates of peak discharge probabilities for the river Meuse for the current situation have been developed for the design of flood protection. The protection level for this dike ring is set at a water level that coincides with a river discharge that is estimated to occur on average once in 1,250 years, according to statistical extrapolation of the observational record.

For the long-term flood risk management policy in The Netherlands, estimates have been made of potential shifts in this so-called design discharge. Given the close relation between the occurrence of prolonged precipitation and peak discharges in the Meuse basin (Tu et al., 2005b), the assumption has been made that future changes in extreme discharges will be very similar to those changes that are projected for 10-day precipitation sums (Kors et al., 2000). This approach was recently reaffirmed by De Wit et al. (2007), who provide estimates on the basis of projected changes in precipitation from a set of four national climate change scenarios. Usually, climate model output for local changes in extremes show large variations for hydrological changes (e.g. Dankers and Feyen, 2009). These KNMI'06 scenarios, however are based on an extensive assessment of global and regional climate projections from general circulation models in order to capture some of this scenario and climate model uncertainty (Van den Hurk et al., 2006; Lenderink et al., 2007), and they are applied in all current scientific and policy studies.

The estimates for changes in Meuse river discharges are quite uncertain, as they are not based on hydrological theory and have not been established using hydrological and/or hydrodynamic models. A range of recent studies has assessed shifts in peak discharge probability in the Meuse basin through the coupling of general circulation model (GCM) and hydrological models (Leander et al., 2008; Ward et al., in press), but they have not produced more robust estimates of future extreme discharges. Although approaches and tools exist that can aid the development of more reliable estimates of low probability discharge events (De Wit and Buishand, 2007; Te Linde, 2007; Te Linde et al., 2010), these have yet to be applied for the Meuse river.

Given the lack of robust hydrological estimates, we therefore chose to apply estimates of shifts in flood probabilities that are based on the original assumption of changes in 10-day precipitation sums. We assume that the change in failure probability of the flood defences is of equal magnitude as the change in future discharges. The four current scenarios for the Meuse (De Wit et al., 2007) only provide discharge estimates for the Meuse upstream at the village of Borgharen. Given the lack of projections for the lower part of the Meuse, we assume that changes in extreme discharges at our case study site are equal to changes at the location of Borgharen. It is further assumed that flood patterns within the study area would not substantially change over time, nor that probabilities of dike failure will change due to strengthening of these flood defences. The latter would seem unrealistic, as climate change and ongoing development in polders will likely urge policymakers to implement flood defence reinforcements. But keeping probabilities of dike failure constant allows singling out an estimate of the impact of socioeconomic development and climate change on potential losses, without adaptation. In addition, we estimate the effect of adaptation through dike reinforcements, on flood probabilities.

As the scenarios currently available for The Netherlands provide only estimates for changes in the discharge with a return period of once in 1,250 years, we calculated the future (2040) return period T_{dd} of the current (2001) estimated design discharge D of 3800 $m^3\ s^{-1}$ at Borgharen, using:

$$T_{dd}=\exp((D-b)/a) \qquad \text{(Equation 6.2)}$$

where a and b are parameters found through a logarithmic fit for extreme discharges, values for these two parameters for the WB21 scenario and the KNMI'06 scenarios were derived from the report by Rijkswaterstaat (2007).

Since the climate scenarios provide estimates for the year 2050, assuming linear change over the 50 years implies that extreme discharges in 2040 have increased by 4/5 of their value projected for 2050. Table 6.1 shows the return periods of the design discharge in 2040, and the associated factor f_p change in flood probabilities, calculated as $1250/T_{dd}$.

For comparison, we also include the central estimate for an older climate change projection, the WB21 mid scenario (Kors et al., 2000), which is currently the accepted basis for flood protection policy in the Meuse basin. Flood reduction measures are currently underway to meet the subsequent design discharge (Rijkswaterstaat, 2006b), which is estimated to be 4200 m^3 s^{-1} in 2040. We also assess the impact of the four climate scenarios in a situation where such adaptation has been successfully implemented. These measures include dike improvement but also improvement of the discharge capacity through widening and deepening of the river bed, creation of additional channels, and relocation of dike segments. The lower part in Table 6.1 shows the effect of these measures up to the level of the WB21 mid scenario. The numbers show that with currently planned protection policies, the impact of climate change is likely to be mostly offset by 2040. Note that we ignore the small but potentially significant effect that occurs when dike heights are increased, and inundation depths would consequently increase.

Table 6.1. Scenarios for changes of the design discharge in the year 2040 (scenario sources: Kors et al., 2000; De Wit et al., 2007).

Scenario	Return period [T_{dd}]	Probability change factor [f_p]
Assuming no adaptation		
Baseline (2000)	1250	1.00
G (2040)	859	1.45
G+ (2040)	713	1.75
W (2040)	594	2.10
W+ (2040)	416	3.01
WB21 mid (2040)	481	2.60
Assuming adaptation to WB21 mid climate change scenario		
G (2040)	2223	0.56
G+ (2040)	1854	0.67
W (2040)	1543	0.81
W+ (2040)	1080	1.16

For the current study, we assume a low impact scenario consisting of a combination of the RC socioeconomic scenario for land-use change and asset value increase (Figure 6.1) and the G climate scenario (Table 6.1), and a high impact scenario, comprising the GE socioeconomic scenario and the W+ climate scenario. This is usually a consistent approach (Carter et al., 1999). It is important to note however, that the climate scenarios reflect mostly differences in climate modelling uncertainties and not greenhouse gas emissions, so that the W+ climate scenario may well become reality in combination with the RC socioeconomic scenario, and the G climate scenario with the GE socioeconomic scenario. But in order to investigate the extreme flood risk outcomes, we chose to combine the extreme low and extreme high impact scenarios.

Inundation scenarios

A series of 42 flood scenarios describe the extent and depth of inundation and these were developed separately from the current research (Bouwer et al., 2009/Chapter 5). As the exact dike breach location during high river discharges is unknown, and dike breaches at different locations can cause very different damages, we capture part of this uncertainty using this large number of scenarios. The scenarios are based on potential failure of 13 separate stretches of dike, and the consequent inundation of parts of the area, depending on different volumes of inflowing water. For each scenario, one probability was calculated, based on the assessments made by the Dutch Ministry of Transport, Public Works and Water Management for this particular area (Rijkswaterstaat, 2006a).

Flood damage model

For future situations, not much is known about exposure and vulnerability, apart from land-use patterns. Therefore, direct physical damages due to flooding are calculated using the 'Damage scanner' model, which was developed and applied by Klijn et al. (2007). This model comprises depth-damage functions for 13 different land-use categories that relate the fraction of maximum losses per hectare for each land-use type to inundation depth (Klijn et al., 2007). The model allows for the calculation of losses for future situations, since the loss fractions in the model are calculated on the basis of only two parameters; land use and inundation depth. More complex models for flood loss calculation are available (Rijkswaterstaat, 2006a), but these are not able to project future damages without the generation of extensive additional data and information (Van Schrojenstein Lantman, 2007). We only address direct physical flood damages to buildings and their contents, infrastructure, agriculture and nature. Please note that the Damage Scanner model actually also includes a negligible share of 5% indirect damage. Indirect losses, due to interruption of business and services, as well as intangible losses are not taken into account, but it should be noted that these can be considerable as well (see Jonkman et al., 2008a, for a discussion). An application of the model for the baseline risk in the year 2000 using the 42 inundation scenarios is available from Bouwer et al. (2009/Chapter 5).

6.3 Results

Using the land-use projections generated for the RC and the GE scenarios, estimates can be made of the changes in exposure under future conditions. Table 6.2 shows the changes in area extent of different land-use types lying in the flood prone area for the year 2040, using the two socioeconomic scenarios. Considerable changes are projected for urban areas, with increases of 7% to 42% under the RC and GE scenarios, respectively. A major increase is projected for nature areas, which would double in size. Note that Table 6.2 shows that infrastructure extent is also projected to double, but the extent for the baseline (2000) is underrepresented, while the location and extent of infrastructure for the future is imposed on the Land-use Scanner model, and is equal for both the RC and GE scenarios. Agricultural areas on the other hand are projected to decline by some 10%, due to a drop in grassland, which is not compensated for by the expansion of arable land. At the same time, the area occupied by greenhouses would increase four-fold under the GE scenario.

Table 6.2. Average surface area percentages of different land-use types in the year 2000 and 2040 in the area that is at risk from flooding under the RC and GE scenarios.

ID	Land-use class	Baseline (2000) area share [%]	RC (2040) area share [%]	GE (2040) area share [%]	RC (2040) area change [%]	GE (2040) area change [%]
0	Urban high density	4.0	2.8	5.3	-31	33
1	Urban low density	8.8	9.0	12.4	2	42
2	Urban rural	0.8	2.8	1.6	229	89
3	Recreation	0.9	0.7	0.7	-27	-23
4	Commercial	3.4	3.1	4.2	-7	23
5	Harbours	0.0	0.0	0.0	-	-
6	Nature	5.3	9.9	10.0	86	89
7	Arable land	13.5	32.4	21.2	140	57
8	Grassland	59.9	35.3	39.2	-41	-35
9	Greenhouses	0.2	0.0	1.0	-100	429
10	Livestock	0.8	0.9	1.2	7	40
11	Infrastructure	1.4	3.2	3.2	127	127
12	Building lot	1.0	0.0	0.0	-100	-100

Expected losses for the future scenarios are first calculated using the estimated losses under land-use change, corrected for increases in asset value, and changes in flood probabilities due to climate change (see Figure 6.1). Table 6.3 shows in the first column the estimated expected losses for the baseline situation, in the year 2000. Expected losses are calculated by multiplying the probability of an individual potential flood event with its consequences, in this case the direct damages. Clearly, the densely urbanised areas cause the major share of flood damage. The sum of the three categories of urban areas accounts for 69% of the total damage. Additionally, the category commercial accounts for some 13% of the flood damage.

The effects on losses from climate change are presented in Table 6.4. The percentage increase in expected damage from socioeconomic change is between 35 and 172% by 2040, while climate change would lead to an increase of between 46 and 201% (Table 6.4). Under climate and land-use change, the total expected flood damage would increase by approximately 96% in 2040 under the RC scenario, and by 719% under the GE scenario. The increases in the share of losses for different land-use categories remain largely unchanged, although under the GE scenario the share of damages in urban areas grows at the expense of damages in agricultural areas. The effect of assets increase on expected losses is quite significant, as estimates without the assets increase are roughly half the size of estimates that do include asset value increase (Table 6.4, lower rows).

Table 6.3. Expected potential losses for different land-use categories in the year 2000 and 2040 (at 2000 prices, future estimates corrected for increases in asset value).

ID	Land-use class	Baseline (2000)	RC (2040) [10^6 Euro/yr]	GE (2040) [10^6 Euro/yr]	RC (2040) change [%]	GE (2040) change [%]
0	Urban high density	7.6	10.4	60.9	37	706
1	Urban low density	7.3	14.5	63.4	98	764
2	Urban rural	0.7	4.2	7.3	480	903
3	Recreation	0.1	0.1	0.2	58	380
4	Commercial	2.9	5.1	24.2	78	747
5	Harbours	0.0	0.0	0.3	-	-
6	Nature	0.3	1.0	3.0	301	1072
7	Arable land	0.7	3.5	6.7	375	824
8	Grassland	1.7	1.8	6.2	5	254
9	Greenhouses	0.1	0.0	1.6	-100	1464
10	Livestock	0.1	0.3	1.6	293	1939
11	Infrastructure	0.9	3.7	11.1	299	1091
12	Building lot	0.4	0.0	0.0	-100	-100
	Total	22.8	44.6	186.6	96	719

For decisions on risk management, it is important to not only consider annual expected losses, as these do not provide insight on how risks are distributed, and what the extreme risks are. Loss-probability curves show all potential outcomes and their probabilities, including the extreme events. Such curves are regularly used for hazard risk assessments as they provide important information for decision-making, for instance the effect of risk reduction measures on the integral of the loss curve (Messner et al., 2007). By compiling the different loss estimates that follow from the inundation scenarios, together with their probabilities, loss probability curves can be constructed (Figure 6.3). The baseline curve shows the relation between probability and damage amount for the year 2000. Due to land-use change and increase in assets the curve shifts upward, indicating that the potential damage amounts increase, especially for the events that have a low return period (Figure 6.3a). Climate change causes the curve to shift to the right, indicating that the probability of damaging events will increase by 2040.

Plans to mitigate peak water level occurrence on the river Meuse are currently taking into account the WB21 mid scenario. The effect of such adaptation on the shape of the loss-probability curve is quite significant; reducing flood probabilities helps to reduce the probability of all damage events (Figure 6.3b). However, it is very important to note that although adaptation through flood prevention measures will be successful in reducing flood probabilities and therefore reducing the annual expected loss (Table 6.5), the impact of the most extreme damage events will remain unchanged (Figure 6.3b).

Table 6.4. Annual expected flood damage (10^6 Euro per year) and percent change (between brackets), under socioeconomic change, climate change, and combination.

	Baseline (2000)	RC/G (2040)	GE/W+ (2040)
Including asset value increase			
Base risk	23		
Socioeconomic		31 (35%)	62 (172%)
Climate change		33 (46%)	69 (201%)
All		45 (96%)	187 (719%)
Excluding asset value increase			
Base risk	23		
Socioeconomic		23 (3%)	33 (44%)
Climate change		33 (46%)	69 (201%)
All		34 (50%)	99 (334%)

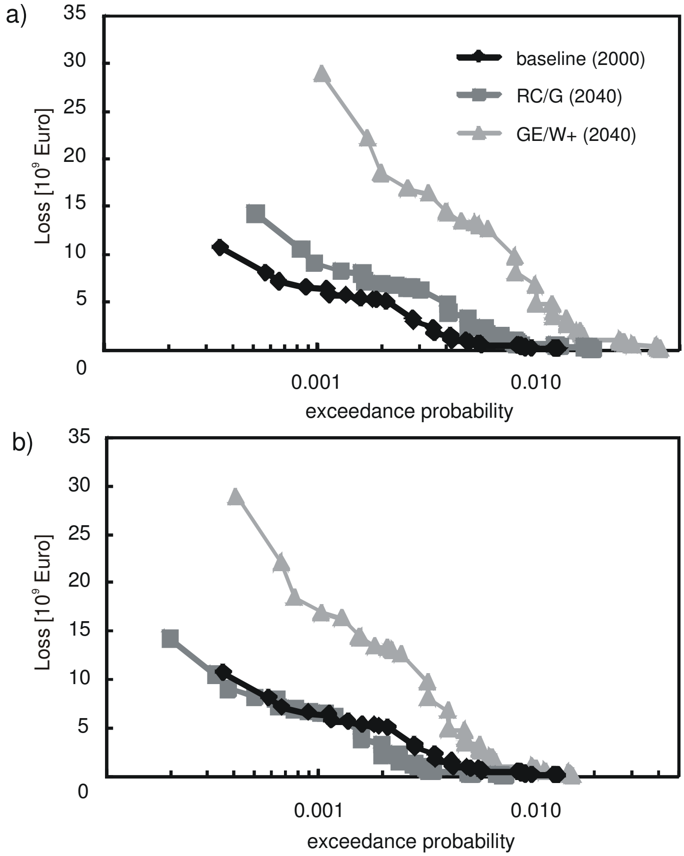

Figure 6.3. Loss probability curves for 2040 under the GE and RC socioeconomic change scenarios (a), compared to the baseline (2000), and assuming adaptation (b).

Table 6.5. Annual expected flood damage (10^6 Euro per year), including adaptation through flood protection measures.

	Baseline (2000)	RC/G (2040)	GE/W+ (2040)
Including asset value increase			
Base risk	23		
Socioeconomic		31 (35%)	62 (172%)
Climate change		13 (-44%)	26 (16%)
All		17 (-25%)	72 (215%)
Excluding asset value increase			
Base risk	23		
Socioeconomic		23 (3%)	33 (44%)
Climate change		13 (-44%)	26 (16%)
All		13 (-42%)	38 (67%)

The spread in estimated annual expected damages between the two scenarios is quite considerable. This spread is due to the wide range of possible socioeconomic change (land-use change and increases in wealth and consequent assets at risk) and the possible impacts of climate change on flood probabilities. In order to assess the relative contributions of socioeconomic change and climate change, we assess the increase of expected damage due to each of the categories. Figure 6.4 gives a break down, similar to the approach by Pielke (2007b). It shows the contribution to the change in expected losses from a) socioeconomic change only (land-use change and increases in assets at risk), b) climate change only, and c) the combination of both impacts. The base risk reflects the situation for the baseline (year 2000). Clearly, the contribution to increased losses from climate change is slightly larger than the contribution from socioeconomic change in both scenario combinations (RC/G and GE/W+). Moreover, the increase in exposure due to socioeconomic change is exacerbated by climate change, leading to an additional increase in expected losses. This is the top part of the future expected losses in Figure 6.4.

When we assume that by 2040 flood prevention measures are in place that protect from impacts according to the WB21 mid scenario, expected losses are substantially reduced (Figure 6.4b). Still, the maximum losses that can occur increase drastically, from an estimated 11.7 to 28.9 billion Euros, an increase of some 170% (see Figure 6.3b). Under the RC/G scenario, the impact of climate change on flood probability is more than compensated, and even the impact of socioeconomic change would be reduced by 25% (Table 6.5). In effect, flood risk would be lower, with respect to the base risk in the year 2000. Under the GE/W+ scenario climate change is almost compensated, but risks still increase by some 215%, mostly due to socioeconomic change (Table 6.5).

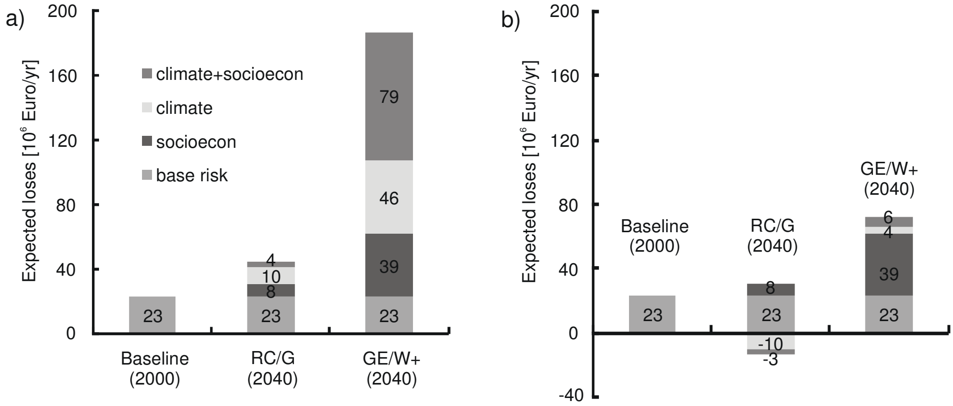

Figure 6.4. Projected annual expected losses for 2040, compared to the baseline (2000), and their components, supposing no adaptation (a) and adaptation through flood prevention (b).

6.4 Discussion

We project flood losses to increase at a rate of 1.7% to 5.4% per year for a combined scenario of high growth (GE) and high climate change (W+). In all, our projected increases in flood damages are relatively low compared to recent observed increase in losses from global natural disasters, which is estimated to be as large as 8.4% per year (Bouwer et al., 2007/Chapter 2). Arguably, the historic losses over the period 1977-2006 are reflecting a larger economic growth (3-3.8% per year) over that period. Additionally, the historic losses may be dominated by a number of very large disasters, as the median losses of natural disasters appears to have increased at a lower rate over recent decades (Bouwer et al., 2007/Chapter 2). Our estimates of future loss-increases in the case study area, excluding the effect of climate change, show an increase of between 0.8 and 2.5% per year. Still, this latter rate is higher than the rate of average projected asset value growth, which is between 0.7 and 1.7% per year.

Ongoing development in general will take place at low-lying grounds not yet occupied for housing and other activities, which has been shown to be similar for projections of loss of life (Maaskant et al., 2009). Our research underpins how important it is to explicitly take into account the exact location of land-use change in flood prone areas, since estimates on the basis of for instance asset value growth only, would underestimate changes in exposure. Still, increase in risk due to socioeconomic changes only (0.8-2.5% per year), is about as large as GDP growth (0.7-2.6% per year). Therefore, it seems that the relative risk of floods would remain constant, and only the additional risk from climate change is of concern then. However, this may be different for other areas. A high economic growth scenario (scenario GE) would obscure a low climate change signal (G). On the other hand, a low economic growth scenario (RC) in combination with a high climate change scenario (W+) would lead to a dominant climate signal in the risks and potential losses, also in the period up to 2040.

Our approach allows a more detailed and comprehensive assessment of changes in future flood risk than previously possible. The estimated changes in risk however also depend on our flood model and loss model. This is why a comparison is warranted with studies that applied the same range of scenarios. Other studies of changes in flood risk for individual dike rings in The Netherlands, most notably Klijn et al. (2007), used the Transatlantic Market (TM) and GE scenarios (WLO, 2006) for changes in land-use and value of assets at risk. They have estimated annual expected losses for the current case study area to increase by between 0.3 and 0.7% per year (Klijn et al., 2007), considering socioeconomic change only, thus excluding the impact of climate change. The differences with our estimates (1.7-5.4% per year) are for a major part due to the different approach toward the estimation of flood probabilities, as their report indicates that potential losses (excluding flood probabilities) can increase by up to 1.7 and 2.1% per year. The latter numbers compare well with our estimates of the impacts of socioeconomic change (0.8-2.5% per year).

Van Schrojenstein Lantman (2007) applied four flood scenarios from the Floris project (Rijkswaterstaat, 2005b), in combination with a detailed damage model for the estimation of a range of different possible damaging events for dike ring 14 (Randstad area in West Netherlands). He also projects large increases in losses from urban areas. He finds that losses may increase by between 1.0 to 3.1% per year due to land-use change under the WLO TM scenario by 2040, depending on the flood scenario. His estimates assume no climate change or increases in wealth. Our expected loss estimates numbers for land-use change only, and excluding asset value increase are lower (0.1-0.9% per year), probably owing to the lower rate of population and economic growth for this case study area.

Flood prevention measures are planned for the Meuse river basin that take account of a considerable change in peak river discharge probabilities due to climate change. Climate change does lead to significant increases in flood probabilities, but with current measures underway, these additional probabilities are likely to be greatly offset. In the low growth/low climate change scenario, the prevention measures are in addition likely to offset almost all of the additional increase in flood risk due to socioeconomic change. Under the high economic growth/high climate change scenario however, risks are however likely to increase due to increases in exposure and assets at risk. Also, the potential losses from the most extreme events are not mitigated by flood prevention measures, and these may drastically increase. This indicates that current flood prevention measures may be insufficient for keeping risks in the Meuse basin constant in monetary terms. While planned measures may offset these projected high impacts too, these adaptation measures do come at a cost, and long-term funding for these measures is required and needs to be secured.

Our approach and results have a number of limitations and uncertainties. Important sources of uncertainty that occur in the loss projections relate to the probability of flooding, the exposure of assets, as well as estimated vulnerability. All three factors are likely to change over time, due to socioeconomic and physical processes. First, the estimates for climate change are highly uncertain. This is evident from the uncertainty in the estimate of the baseline discharge for the present situation in the Meuse at Borgharen, which has recently been re-estimated to be 4000 $m^3 s^{-1}$ (De Wit et al., 2007) on the basis of high discharge events in 2003 and 2006. This new estimates is equal to the projected discharge in 2100 under the G scenario, and underlines that future discharge with a return period of 1250 years can currently not be assessed with much certainty. However, by applying a range of scenarios, we at least assess a range of possible future changes in risk, and this range is reflected in the estimated risks in Figures 6.3 and 6.4.

Second, the effect of increase in the value of assets is estimated to be responsible for more than half the increase in annual expected losses by 2040. Land-use change by comparison plays a relatively minor role (see upper and lower part of Table 6.4). Since increase in the value of assets is one of the key causes for increases in losses, it is therefore also one of the key uncertainties in this study. We used a relatively simple approach for estimating the potential changes in the value of assets at risk (see Equation 6.1), that could be potentially refined. Data is available for instance on the historic increases of home inventories in Dutch private households (Van Driel, 1999), which show annual increases of 2% over the period 1977-1993. It is difficult to estimate future increases in assets. However, our estimates of the increase of asset value of 0.7-1.7% per year seem conservative by comparison.

Third, vulnerability may change over time, as both buildings and assets are replaced or upgraded. In turn these changes affect the potential amount of damages associated with different flood inundation levels. We assume no additional damage reduction measures would be taken, and therefore that certain inundation depths in 2040 lead to the same fraction of losses as in the year 2000. In addition, changes in flood patterns and land-subsidence may also affect the vulnerability of various locations, and could either reduce or increase the losses, but these factors were kept constant.

6.5 Conclusions

We presented projections and an analysis of future flood risk. This was done by combining a large set of inundation scenarios, projections of future exposure and asset value increases, scenarios for increasing flooding probabilities under climate change, and a damage model. Our approach allows a more detailed and comprehensive assessment of changes in future flood risk than previously possible. It is found that annual expected losses may increase by between 35 and 172% by the year 2040, due to socioeconomic change, including changes in asset value and land-use mostly consisting of expansion of urban areas. If no additional measures are taken to reduce flood probabilities or consequences, climate change may lead to an increase in expected losses of between 46 and 201%. A combination of climate and socioeconomic change may push expected losses up by between 96 and 719%. This indicates that changes in climate may lead to disproportionate and therefore non-linear impacts, which has also been established for losses from extreme rainfall (Hoes, 2007).

As land-use change and increasing exposure appears to affect flood risks at least as much as climate change, adaptation or risk reduction measures would be the most effective response to reduce flood risks. The expansion and location of urban areas into areas that are at risk from flooding result in a considerable increase in risk. This underlines the role for proper spatial planning, although urban areas are likely to expand mostly in the vicinity of already existing agglomerations.

As flood risk policy is likely to take account of ongoing climate change and increasing exposure, it is unlikely that risks will increase as dramatic as presented in our most pessimistic estimates. In addition, local risk reduction measures can have drastic effects on flood losses. For instance, it has recently been found for flood losses in Germany that damage mitigation measures could substantially reduce losses, by up to 50 percent (Thieken et al., 2006). In The Netherlands, the willingness of homeowners to take damage reducing measures may have a considerable mitigating effect on losses. From surveys it is found that measures at the household level, consisting of investment in barriers that reduce inundation, the installation of water resistant floor types, and the moving of central heating installations to higher floors, could possibly mitigate losses by up to some 2.8 billion Euros in this case study area (Botzen et al., 2009).

The findings from this chapter also apply to other major urbanised areas around the world, where increasing exposure and asset value will contribute to increases in natural hazard risk. The possibility to discriminate between different drivers of flood risk is especially relevant for identifying effective adaptation strategies. In developing countries e.g., the impact from socioeconomic change on flood risk may be even larger than projected for the case study area presented here, as population and economic growth is expected to be much larger. Studies that take the approach proposed here may thus help to understand the underlying drivers of changing risks and to design adaptation strategies in other locations.

6.6 Acknowledgments

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Chapter 7. Projection of future disaster losses under climate change

Abstract

Many attempts are made to assess future changes in extreme weather due to anthropogenic climate change, but few studies have estimated the potential economic losses from such changes. Projecting losses is more complex as it requires insight in both the changes in the weather hazard, and changes in exposure and vulnerability to such hazards. Here I discuss the issues involved and a framework for projecting future losses, and I provide an overview and synthesis of some state-of-the-art projections. An estimate of changes in losses until the year 2040 is given, and particular attention is paid to the different approaches and assumptions underlying these projections. All projections show increases in extreme weather losses due to climate change, and flood losses are generally projected to increase more rapidly than losses from tropical and extra-tropical windstorms. However, for the period up to 2040, the contribution from increasing exposure and value of capital at risk according to current studies is substantially (about 2-10 times) larger than the contribution from anthropogenic climate change. Given the fact that loss events are stochastic, and their occurrence varies over time due to natural climatic variations, the relatively small signal from anthropogenic climate change is likely to be lost among the other causes. Few studies examined potential future increases in disaster losses using a comprehensive approach that includes quantification of the impacts of both climatic and socioeconomic change. More efforts are required to better incorporate the effects of changing exposure and vulnerability as well as adaptation in impact studies.

7.1 Introduction

Impacts from natural disasters matter. They cause human suffering, disruption and damages, and set back development in many nations. While the largest single catastrophes are related to geophysical events, in particular earthquakes, the many weather-related disasters around the globe create the highest number and greatest share of casualties and damages (Munich Re, 2009). Arguably, the most important indicator of the intensity of natural disasters is the level of economic losses, usually expressed as direct economic damages. Loss of life is also an important indicator (e.g. Jonkman et al., 2008b), and is included as a criterion for severe disasters in the analysis made by insurance companies (Bouwer et al., 2007/Chapter 2). While significant achievements have been made to reduce the loss of life from natural

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A slightly modified version of this chapter was submitted as L.M. Bouwer. Projection of future disaster losses under climate change. *Risk Analysis.*

disasters through better early warning, evacuation and preparedness (UN-ISDR, 2009a: p. 68), economic losses have been increasing rapidly over past decades. Extensive data for this metric is being collected and analysed by various organizations, including insurance companies (e.g. Munich Re, 2009).

The anticipated increasing impact of extreme weather events in the future is considered an important component of dangerous interference of humans with the global climate system (Smith et al., 2009). A series of studies has analysed changes in losses from extreme weather, such as storms, wildfires, heavy rainfall, and flooding, but have not found a signal from past anthropogenic climate change (Bouwer, in press/Chapter 3). However, more substantial changes in the frequency and intensity of weather extremes are expected for the future, due to the anthropogenic warming of the atmosphere (IPCC, 2007a: Table SPM.2). There are only few studies that have translated such extreme weather changes to economic impacts, and very little quantification is usually given of *how large* the impact from climate change on extreme weather losses potentially is.

A number of studies has made estimates of potential impacts from changes in weather extremes on the number of people affected (Oxfam, 2009), humanitarian costs (Webster et al., 2009), and economic costs (Stern, 2007). A number of authors have proposed and tested frameworks for projecting future impacts, using different approaches for estimating changes in hazard, and change in exposure and vulnerability (e.g. Evans et al., 2004; Hallegatte, 2008; Dawson et al., 2009; Mechler et al., 2010). At present however, a common and generally accepted analytical framework for estimating disaster costs is lacking. There is also disagreement on the right approach for projecting impacts on losses from weather extremes (see e.g. Pielke, 2007a). As the projections of future weather risks have recently motivated large-scale protection plans for coastal and delta areas (e.g. Kabat et al., 2009) there is a need to have a robust framework, in order to assess the causes of changing risk, and arrive at more reliable estimates that can be used for decisions. A quantification of future extreme weather impacts under climate change, on the basis of impact studies of individual weather hazards, may aid both scientists and policymakers, to find out where improvements in knowledge can be made, to estimate what is at risk and which responses would be appropriate.

In this chapter recent studies are presented and discussed that have projected potential future economic losses from weather extremes using detailed approaches. The comparison of approaches and results given here is intended to provide a basis for further discussing and developing frameworks for the projection of disaster losses under climate change. In the next section, some theoretical considerations are discussed, and a framework for estimating future disaster losses is presented. In the third section, a series of future loss projection studies is presented for windstorm and flood hazards. The fourth section addresses some key uncertainties and further needs for improving extreme weather loss projections. The final section concludes.

7.2 Theoretical framework

Some considerations are important when analysing losses from natural disasters:

- The impacts from natural hazards encompass a wide variety of aspects, mostly negative effects that are related to loss of life, human suffering, distress and discomfort, disruption, and economic damage. But potentially also some positive effects may occur, including increased investments and replacement, renewal and improvement of material assets, such as protective infrastructure and buildings. So how can the impact of natural disasters be accurately and comprehensively measured?
- Large variations occur in natural disasters, because of the highly variable characteristics of exposure and vulnerability over space and time. These disasters are therefore complex and difficult to assess or predict. So can we actually assess the risk of disasters?
- Estimates of future risk are difficult to make, given the uncertain pathways of climate, and economic and social development. In addition, planned adaptation may reduce risks. How can we quantitatively assess these pathways?

These three considerations will be briefly addressed below, before an analysis is presented of some current estimates of potential changes in future disaster risk.

What type of disaster losses?

The scope of this chapter is limited to the assessment of direct economic losses from weather disasters, since these impacts are relatively well documented, are monetized (priced) and therefore transferable between regions and over time. These losses are quantifiable with some precision using mathematical models. Moreover, direct economic and insured losses relative to a countries' wealth have generally been accepted as a relevant indicator for the relative severity of natural disasters (Munich Re, 2009). However, direct losses are only part of the total tangible and priced damages from natural hazards, which also include direct losses from business interruption, evacuation and rescue operations, etc. (Jonkman et al., 2008a). Additionally, there are priced indirect losses that may include damages outside the stricken area, and costs for temporary housing, etc. More difficult to estimate are intangible and unpriced losses that include injuries, fatalities, disruption, psychological trauma, and environmental losses (Jonkman et al., 2008a). These usually fall outside the scope of cost estimates of natural disasters. At the same time, it is important to note that considering only the priced direct losses is a serious limitation of the assessment of total impacts of disasters.

The paradigm of loss quantification

The reductionist view of natural disasters is that the size and origin of disaster losses can be assessed with some certainty. Even though many advances have been made in quantifying potential damages (Grossi and Kunreuther, 2005), the quantification of impacts is based on relatively simple model representations of a very complex reality. The limited model representation leads to uncertainty, called epistemic uncertainty (Merz and Thieken, 2005). This uncertainty may be partly resolved by improving observations or fundamental understanding of the processes at play.

However, the occurrence of natural hazards and their potential impact vary over space and time, and contain a certain element of chance. Due to their stochastic and rare nature, changes in the frequency of disasters are difficult to detect. The potential losses are highly uncertain too, as they are influenced by exposure and vulnerability of assets, which vary depending on location, time, and can be influenced by human actions and behaviour. This inherent uncertain nature of hazard and impact is called natural or aleatory uncertainty (Merz and Thieken, 2005), which cannot be resolved. Merz and Thieken (2009) show that it is useful to separate aleatory and epistemic origins, in order to assess which information can reduce the epistemic part of the uncertainties involved.

The limited framework that is available for analysis is that risk is the product of the probability of an event and its outcome, or impact. Analysing the components of risk can help to understand how they interact. Risk (R) is usually expressed as the average expected losses over a period of time (t), consisting of the impact (I) of an event, multiplied by the probability (p) of that event. Both probability and impact may vary over time. In formula:

$$R(t) = I(t) \cdot p(t) \qquad \text{(Equation 7.1)}$$

The potential impact I is a result of the number of people and capital exposed to the particular hazard, and their vulnerability, i.e. the extent to which they are affected by that hazard.

For an analysis of changes in historic or future disaster losses, both the change in the probability and the change in the potential impact need to be taken into account:

$$\frac{\partial R(t)}{\partial t} = \frac{\partial I(t)}{\partial t} \cdot p(t) + \frac{\partial p(t)}{\partial t} \cdot I(t) \qquad \text{(Equation 7.2)}$$

Any change in the potential impact of an event implies a change in risk, also if the probability remains the same. If the probability of an event also increases, an additional risk increase will result.

Finding the elasticity of the impact and probability component gives:

$$\frac{\frac{\partial R(t)}{\partial t}}{R(t)} = \frac{\frac{\partial I(t)}{\partial t} \cdot p(t)}{I(t) \cdot p(t)} + \frac{\frac{\partial p(t)}{\partial t} \cdot I(t)}{I(t) \cdot p(t)} \qquad \text{(Equation 7.3)}$$

$$\frac{\frac{\partial R(t)}{\partial t}}{R(t)} = \frac{\frac{\partial I(t)}{\partial t}}{I(t)} + \frac{\frac{\partial p(t)}{\partial t}}{p(t)} \qquad \text{(Equation 7.4)}$$

$$\tilde{R}_t = \tilde{I}_t + \tilde{p}_t \qquad \text{(Equation 7.5)}$$

Equation 7.5 shows that the relative change, or elasticity of *R* depends on the sum of the elasticities of *I* and *p*, which implies that any change in risk is equally dependant on changes in impact and probability. Historically, socioeconomic changes have been responsible for the majority of increases in disaster losses around the world (Pielke et al., 2008; Bouwer, in press/Chapter 3).

When considering changes in hazard probabilities and risk, it is therefore important to also consider changes in potential impacts, which are principally determined by population and economic growth, and changes in vulnerability. The models that are used for the assessment of contemporary risks of natural hazards usually involve the calculation of probabilities of hazards, and the level of potential losses based on an estimate of exposure and vulnerability. Usually, these models are based on the concept of risk. In Figure 7.1, natural and socioeconomic changes, and the interaction between to hazard probability and exposure are illustrated. Risk (*R*) depends on hazard probability (*p*), and exposure (*e*) and vulnerability (*v*)[8] which together determine the impact (*I*) of weather extremes mentioned above. Both vulnerability (*v*) and exposure (*e*) are influenced by socioeconomic changes, through a series of complex interactions with population and economic change. While both exposure and vulnerability are usually addressed in models of weather losses, changes in sensitivity/vulnerability are usually not taken into account, as indicated by dotted boxes in Figure 7.1. On the other hand, change in exposure is addressed by some studies. Hazard probability is principally governed by variations in extreme weather, but may be mitigated (or adversely affected, for instance in the

[8] Some authors integrate exposure into their definition of vulnerability. Here, the two are separated, in order to distinguish between physical exposure and sensitivity to extremes.

case of floods) by human actions. Below, methods for assessing these components of disaster dynamics are discussed.

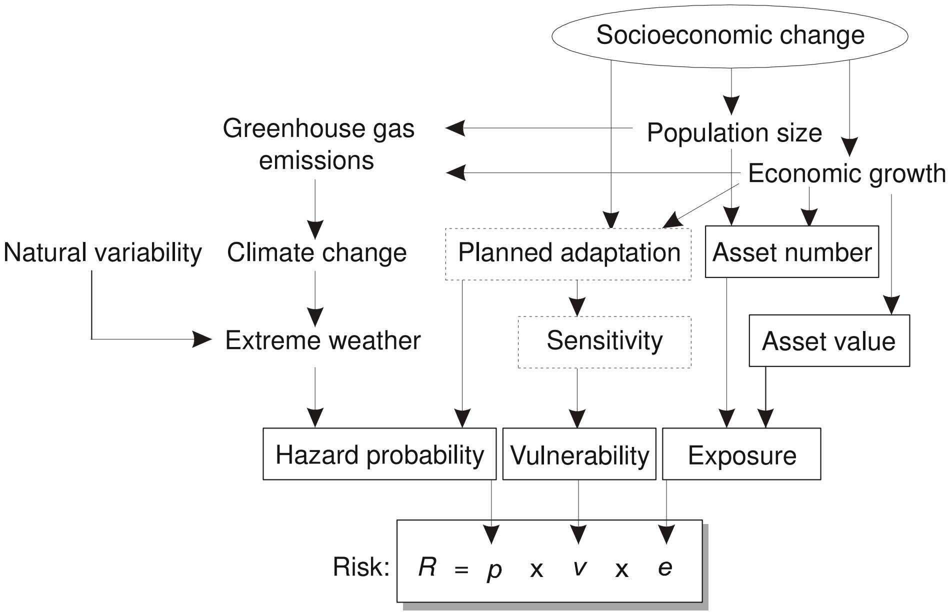

Figure 7.1. Framework for quantitative modelling of economic damages from extreme weather. Boxed items are usually present in catastrophe loss models, while integrated assessment models (IAMs) may contain all items displayed here.

Projecting future changes in hazard, exposure and vulnerability

Most approaches for the assessment of natural hazard risk yield single risk estimates, usually an annual averaged expected loss resulting from the multiplication of a series of event probabilities and their potential outcomes (see Equation 7.1). Stationarity of weather hazards however cannot be assumed, as the probability distribution of extremes will likely vary over time, due to natural variability and anthropogenic climate change (Milly et al., 2008) and other changes that affect natural hazard occurrence. Future developments are inherently uncertain, and such single estimates may have only limited value for decisions. It has been argued therefore that impacts and the robustness of management systems can be better assessed under a range of possible futures (Pahl-Wostl, 2007). Such an approach acknowledges the uncertainty about the future, and allows incorporation of a varying number of attributes that determine risk. For hazards, a range of scenarios can be taken to determine their potential future probabilities.

The SRES scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) attempt to account for the wide spread in possible pathways of socioeconomic development, consequent emissions of greenhouse gasses, and changes in the climate (IPCC, 2000). General Circulation Model (GCM) simulations based on these emission scenarios can show the range of potential changes in the frequency of occurrence of weather conditions in a specific region or locality. Similarly, changes in exposure and vulnerability can be derived from socioeconomic scenarios. Estimates of future exposure and vulnerability strongly depend on the assumptions made about the links between socioeconomic development and urbanization, wealth increases, and expenditures on protection from natural hazards. In general, economic and social development are expected to lead to increasing protection from the impacts of natural hazards, as shown by cross-country analysis (Toya and Skidmore, 2007), through risk reduction and adaptation (Figure 7.1). Indeed, in many countries considerable efforts have been made in the past to reduce natural hazard risks, and many countries are currently planning to adapt to anticipated climate change. However, the relationship between economic development and vulnerability to impacts from natural disasters is not straightforward. Empirical research has suggested that the relation may in fact be non-linear. Kellenberg and Mobarak (2008) show that impacts from floods, landslides and windstorms may initially increase up to an income level of around 4500-5500 USD Gross Domestic Product (GDP) per capita per annum, before they decrease with further GDP growth. This is possibly related to the rapid and uncontrolled urbanization and development in developing countries that initially leads to increasing exposure, before countries have sufficient resources for risk reduction. Wealth increases therefore may not always lead to risk reduction, and in uncontrolled and unprotected development are likely to significantly contribute to increasing risks in the future. Also developed countries that have similar levels of economic development may show large differences in protection levels against natural hazards. The large difference between the level of protection of highly urbanised areas in New Orleans (USA) and The Netherlands is an example.

Results from climate modelling experiments have traditionally guided conclusions about future risks from natural hazards. These analyses of increases in hazards are then taken as an indication of possible increases in economic losses. Efforts are also made to integrate GCMs and loss models, for instance in order to increase the reliability of estimates of potential hurricane losses with low return periods (e.g. Jagger et al., 2008; Watson and Johnson, 2008). But the analyses that couple damage models and climate models for assessing future risks are still sparse (e.g. Leckebusch et al., 2007; Pinto et al., 2007; Schwierz et al., 2010). Some attempts have been made to develop common climate impact indicators that include population, poverty and economic production (Diffenbaugh et al., 2007), but assessments that systematically combine socioeconomic changes, exposure and vulnerability with climate projections for the assessment of weather hazards also remain scarce. This is an important area, where epistemic uncertainty involved in modelling of future disasters losses could be reduced.

7.3 Projections of future disaster losses

This chapter started by arguing that there is a need to quantify the potential future change in losses from extreme weather events, and to identify its causes. The quantification of potential future losses is however hindered, most importantly due to the lack of a common analytical framework for estimates of natural hazard risk over time. Some considerations for such analyses were given in the previous section. Studying impacts from climate change on natural hazards poses some additional challenges. First, anthropogenic climate change is a small signal, compared to the great natural variations that occur over time in the climate and the frequency of weather extremes, and there are large differences in projected changes in climate across different geographical regions. Second, these regions may show very different vulnerabilities and pathways of future socioeconomic development. Climate impacts are therefore very much hazard, time and location specific. It is not possible to arrive at a single quantification of future potential natural disaster loss, but only estimates that are valid for a specific hazard, place and time.

Most studies over the past decades on climate change impacts have been limited to estimating the more gradual changes caused by climate change, such as changes in sea-level, agricultural production, heating and cooling demand, and incidence of diseases (e.g. Tol, 2005). There are only a few scientific studies that have attempted to study the potential changes in economic impacts from those extremes in detail. Detail here means that studies have combined the empirical relation between these extreme events with projections of changes in the frequency of occurrence of weather events, in order to estimate the monetary damages and/or more comprehensive estimates of economics losses. To arrive at some assessment of the potential impact from climate change relative to other processes, a comparison can be made of the handful of impact studies on projected economic weather losses that exists today. These have been developed for specific weather hazards and for specific regions and countries.

It is important to note that the individual studies use different approaches and assumptions, which result in different outcomes and ranges. Also, changes in hazards and exposure vary depending on weather type and geographical location. However, a comparison can identify the current *range* of expected disaster losses in the near future for different hazards, and gives some indication of uncertainties. Especially the differences in outcomes may show the epistemic uncertainty that is due to the different approaches used. In addition, the individual studies show the ranges of different assumptions about parameter settings (also epistemic uncertainties), as well as the ranges due to uncertainties about future changes in climate, weather extremes, and developments of exposed population and assets (aleatory uncertainty).

In order to evaluate and compare the studies, they should have a number of features in common. Table 7.1 shows a basic classification of such features. Depending on the type of the features, the precision of the estimates of future risks can potentially be increased (Table 7.1, sixth column), but usually only with increasing model and data complexity (Table 7.1, fifth column). These features and criteria include:

- The estimated change in weather hazard probability needs some physical basis, which can consist of a large set of climate scenarios (Table 7.1, first column) generated by GCMs that are spatially explicit, a synthetic scenario, or simple estimate of changes in the probability of the hazard, possibly informed by climate model simulations. The estimate of potential future hazard probabilities can be improved by analysing the output for climate parameters (e.g. rainfall, or maximum wind speed) from a global climate model, or from a regional climate model (RCM) that better mimics local climatic variations. The use of regional models and downscaling of large-scale model output can provide more precise information that is needed for small scale impact assessments (IPCC, 2007a: p. 918). Using a regional climate model or applying advanced downscaling however requires more efforts. The application of a simple factor to account for changes in hazard probability does not mean that the outcome is less precise. Such factors can be derived from very extensive and comprehensive analyses of GCM and RCM output (e.g. Lenderink et al., 2008). Ideally, a series of different climate scenarios is used to explore the potential impacts under a range of greenhouse gas emission scenarios, in order to capture the uncertainty in potential changes of extreme weather in the future.
- Ideally, the studies would also take into account socioeconomic changes, as the impact of the weather event depends on changes in the exposed capital stock, and changes in vulnerability, i.e. changes that affect the relationship between the weather hazard and the loss (Table 7.1, second column). However, very few studies have actually assessed the particular contribution from socioeconomic change to risk from changes in exposure and capital at risk.
- The studies need to estimate losses on the basis of some empirical relationship between the weather hazard and the economic loss, the vulnerability. This can involve a simple single relationship that is applied to the entire area under study, or a more advanced loss model that specifies different damage categories and vulnerabilities, depending on land-use or exposed object (Table 7.1, third column). This detailed approach helps to improve accuracy, but also requires more information and increases the complexity of the analysis.
- Projections are usually made for the coming decades, up to the year 2100. In this chapter changes are given until the year 2040. Around this period the projected change in climate depends less on the assumed emission scenario, compared to projected climate at the end of the century. Parameter, process and initial condition uncertainties are relatively low, compared to the period up to 2040 (Cox and Stephenson, 2007). Climate projections around this period are

therefore characterised by the lowest total uncertainty. Also, estimates for this period allow combination with relatively realistic scenarios for population and economic development, and estimates until 2040 are of direct relevance to policymakers.

- The studies need to compare a projection of future losses against a certain baseline of current potential losses, in order to estimate relative changes.
- Finally, the studies need to have some credibility, i.e. they have preferably been published in the peer-reviewed scientific literature, or have been published by a major organization with reasonable standing.

Table 7.1. Some basic features of studies of future projected weather losses.

<table>
<tr><th>Hazard</th><th>Exposure</th><th>Vulnerability</th><th>Level of analysis</th><th rowspan="2">Complexity (relative)</th><th rowspan="2">Precision (relative)</th></tr>
<tr><th>Probability change</th><th>Socio-economic scenario</th><th>Damage estimation</th><th>Spatial scale</th></tr>
<tr><td rowspan="3">- Simple factor
- Low resolution climate model
- Coupled, high resolution or regional climate model
- Number of models, scenarios, or ensembles</td><td>None</td><td>Simple relation</td><td>Aggregate, global</td><td>Low</td><td>Low</td></tr>
<tr><td>(Single) factor</td><td>Simple or low resolution damage model</td><td>Regions</td><td>Medium</td><td>Medium</td></tr>
<tr><td>Multiple, many attributes; population, capital, location, vulnerability</td><td>Full damage model, including exposure and vulnerability components</td><td>Grid, typically 100-500 metres</td><td>High</td><td>High</td></tr>
</table>

Table 7.2 lists a number of studies that have estimated future losses from extreme weather under climate change. Different approaches are used (column 2), including risk approaches that take into account spatial characteristics of hazard and exposure (‘risk’), which are most frequently used, integrated assessment models (‘IAM’) that ingrate physical and economic modelling approaches, hybrid approaches (‘hybrid’) that share some features with risk approaches, but are generally less elaborated. Finally, some approaches (‘other’) do not have extensive model systems, but have simple (one dimensional) calculations of hazard and exposure, and are usually not spatially differentiated. As can be seen from the overview in Table 7.2, the main hazards addressed are windstorms, and some have studied floods (column 3). Floods and windstorms cause the most extensive damage, and have been studied by more authors than smaller scale extreme events. The large number of small damaging events may also significantly contribute to the total global cost of disaster. Studies that have assessed the impacts on losses from smaller scale events, such as hailstorms (McMaster, 1999; Niall and Walsh, 2005; Botzen et al., 2010b) and extreme rainfall (Rosenzweig et al., 2002), have used such varying approaches that they are difficult to compare, and are not addressed here. The studies ex-

Table 7.2. Studies of future projected weather losses (TS=tropical storm; ETS=extra-tropical storm; RF=river flood, LF=local flood).

	App-roach	Hazard type	Region	Hazard change	Climate scenarios /GCMs	Exposure scenarios	Vulnera-bility estimation	Reference
1	Other	TS	Atlantic	Factor	2	2	Simple relation	Pielke 2007b
2	Other	TS	USA	Factor	1	-	Simple relation	Nordhaus 2010
3	IAM	TS	Global	Factor	4	-	Regional relations	Narita et al. 2009
4	Hybrid	TS	USA	Factor	1	-	Simple relation	Hallegatte 2007
5	Risk	TS	USA, Caribbean	Factor	3	-	Loss model	ABI 2005a,b
6	Risk	TS	Japan	Factor	3	-	Loss model	ABI 2005a,b
7	Risk	TS	China	Factor	3	-	Loss model	ABI 2009
8	Hybrid	TS	USA	Factor	1	1	Simple relation	Schmidt et al. 2009b
9	Hybrid	TS	USA	GCM	4	-	Historic losses	Bender et al. 2010
10	IAM	ETS	High latitude	Factor	2	-	Regional relations	Narita et al. 2010
11	Risk	ETS	Europe	GCM	3	-	Loss model	Schwierz et al. 2010
12	Risk	ETS	UK, Germany	GCM	4	-	Simple relation	Leckebusch et al. 2007
13	Risk	ETS	UK	Factor	1	-	Loss model	ABI 2005a,b
14	Risk	ETS	UK	RCM	3	-	Loss model	ABI 2009
15	Hybrid	ETS	NL	Factor	2	4	Simple relation	Dorland et al. 1999
16	Risk	RF	NL	Factor	2	2	Loss model	Bouwer et al. 2010/ Chapter 6
17	Risk	RF	Europe	RCM	1	-	Loss model	Feyen e.a. 2009
18	Risk	RF	UK	RCM	3	-	Loss model	ABI 2009
19	Risk	RF	Spain	RCM	1	1	Loss model	Feyen et al. 2009
20	Risk	LF	Australia	GCM	2	-	Loss model	Schreider et al. 2000
19	Risk	LF	NL	Factor	1	0/4	Loss model	Hoes 2007

clusively assess risk in the developed world (Table 7.2, column 4), with the exception of two studies that address global losses from windstorms (Narita et al., 2009; Narita et al., 2010). Very few studies have directly used output from general circulation models to estimate changes in hazard probability (column 5), while most others have relied on factors. A third of the studies rely on a single estimate of future hazard probability change (column 6). Socioeconomic scenarios, that can help to estimate changes in exposure, and therefore potential impacts, are used in only six out of the twenty-one studies (column 7). For vulnerability estimation, about half of the studies apply an advanced loss model that includes different loss categories, and about a quarter uses simple relations between extreme weather and losses (column 8).

Figures 7.2 and 7.3 show the ranges and averages of estimates of future disaster losses for a number of different weather hazards. The ranges indicate the effects of both the different scenarios and different parameters for hazard probability changes and vulnerability used in the studies (cf. Table 7.2). Losses are given as percentage change in the year 2040, relative to the baseline year 2000. The Appendix provides details on the derivation of the loss estimates from the various studies that are depicted in these figures. Numbers are taken from the studies for loss increases that reflect *only* the impact from climate change, and not from changes in exposure and/or vulnerability on the basis of socioeconomic scenarios used in those studies (Table 7.2). The latter effects are discussed separately below.

Windstorm

Windstorms are divided into tropical storms that occur at low geographical latitudes (hurricanes and typhoons) and extra-tropical storms at mid and high latitudes. The losses that are estimated in these studies consist primarily of damages to buildings, infrastructure and assets due to high wind speeds, but may also include losses from inundation of coastal lowlands that results from storm surges and extreme rainfall. Given that high wind speeds are the focus, they usually do not consider projections of sea-level rise that may influence inundation risks. The projection studies show that climate change is expected to have the following impacts on windstorms:

- Losses from tropical storms (studies 1-9) are projected to increase by between 9 and 417% on average by the year 2040, which creates a very wide range (Figure 7.2a). The median of the average estimates of these studies is 30% (Table 7.A1). The estimate by Pielke (2007b) stands out, which is due to the relatively high projected increase in hurricane intensity of 18% by 2050, and cubic, 6th, and 9th-power relationship between wind speed and damages[9]. This study purposefully assessed upper ranges, where others assume an increase in intensity of 10% (Hallegatte, 2007), and 4-9% (Narita et al., 2009) by the end of the century, or 5.5% (Nordhaus, 2010) per degree warming of tropical sea surface temperatures. Bender et al. (2010) studied changes in the frequency of intense (category 4-5) tropical storms, and find a possible decline in losses, due to a substantial decline in the frequency of category 1-3 tropical storms indicated by some GCMs.

[9] Pielke (2007b) also studied the effect of a 36% increase in intensity. These numbers are not included in Figure 7.2a, for reasons of clarity and comparability, and because this increase is not in line with recent projections. For instance, the review by Knutson et al. (2010) provides a range of 2-11% increase in intensity, by 2100. The projected average increase in losses from Pielke (2007) would amount to 417%, and the maximum increase would be 1356% by 2040. These high estimates however are included in Table 7.A1, and are used in this chapter to calculate the median increase for tropical storm losses.

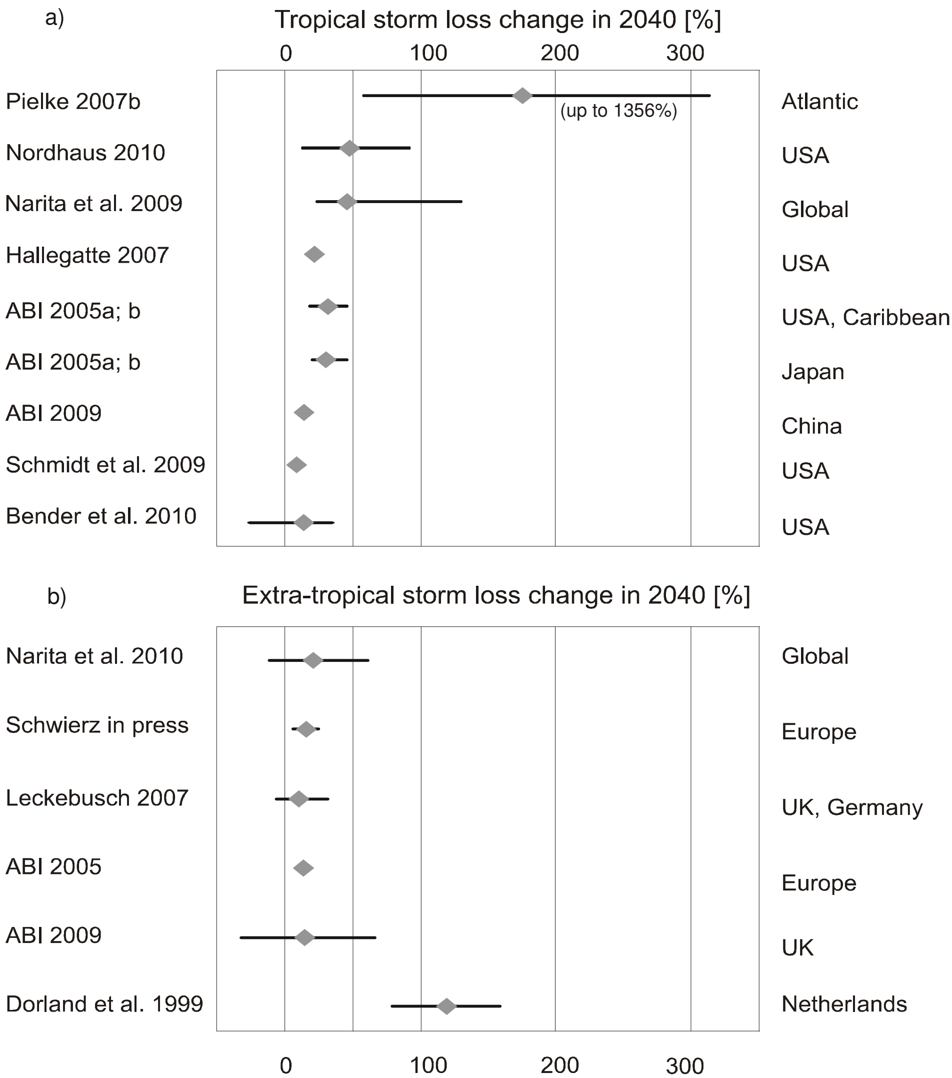

Figure 7.2. Projected changes in tropical (a) and extra-tropical (b) windstorm losses by 2040 due to climate change. Details of the studies are provided in Tables 7.2 and 7.A1. The ends of the bars indicate upper and lower estimates; the diamonds indicate the average of the different estimates made in the individual studies, or single estimates.

- Losses from extra-tropical windstorm (studies 10-15) are projected to increase by between 11 and 120% on average by the year 2040 (Figure 7.2b)[10]. The

[10] The study by Pinto et al. (2007) is not included separately here, as they studied a series of ensemble simulations with one model, that fall within the ranges of the multi-model study by Leckebusch et al. (2007).

median of the average estimated increase is 15%, which is half of the projected increase in losses from tropical storms. The early study (15) by Dorland et al. (1999) stands out, as it assumed rather high increases in maximum gust speeds of between 2 and 10% between 1990 and 2015. Three studies (Narita et al., 2010; Leckebusch et al., 2007; ABI, 2009) project the possibility of decreases in windstorm losses at some locations at temperate latitudes, which is due to projected shifts in storm tracks over the countries under study.

Flooding

Flooding due to excessive rainfall is usually divided into large-scale floods due to high discharges of rivers and streams, and local and urban floods that occur due to excessive rainfall that overwhelms local drainage capacities. Coastal flooding can occur due to storms surges, but is usually categorised as windstorm, as here high wind speed is the principal meteorological cause. Studies on projected economic losses from floods are relatively few: six studies (numbers 16-21 in Table 7.2), compared to fifteen studies on windstorm losses[11].

- Economic losses from river floods are projected to increase by between 7 and 124% on average by the year 2040 (Figure 7.3). Feyen et al. (2009) feature with two estimates, for Europe-wide and a case-study in Madrid (Spain).
- Smaller scale local flood events (studies 20 and 21) create potentially the largest changes in losses. Urban areas comprise the highest concentrations of capital, and consequently relatively small changes in rainfall intensity can lead to a rapid increase in losses. One study (Schreider et al., 2000) finds increases of more than 300% on average by 2040, and maximally more than 500% (Figure 7.3). One other study however reports a loss increase due to extreme rainfall of up to 47% on average by 2040 (Hoes, 2007; also reported in Hoes et al., 2005, and Hoes and Schuurmans, 2006). Studies on urban flooding contain the relative highest uncertainties, as the two different estimates reported here deviate quite considerably, and especially the spread of the estimates of study number 20 (Schreider et al., 2000) is large.
- The median increase of all projected flood losses is 65% by the year 2040. In comparison to the estimated median increase for tropical (30%) and extra-tropical storm losses (15%, Table 7.A1), flood losses are projected to increase more rapidly.

[11] The Foresight study on future flood risks in the UK, a major study that included various drivers of risk including climate change, was excluded from the analysis (Hall et al., 2003; Evans et al. 2004; Hall et al., 2005), as this study does provide separate estimates for losses from climate change and other causes. However, another study on future river flood risks in the UK using a catastrophe model from ABI (2009) is included here.

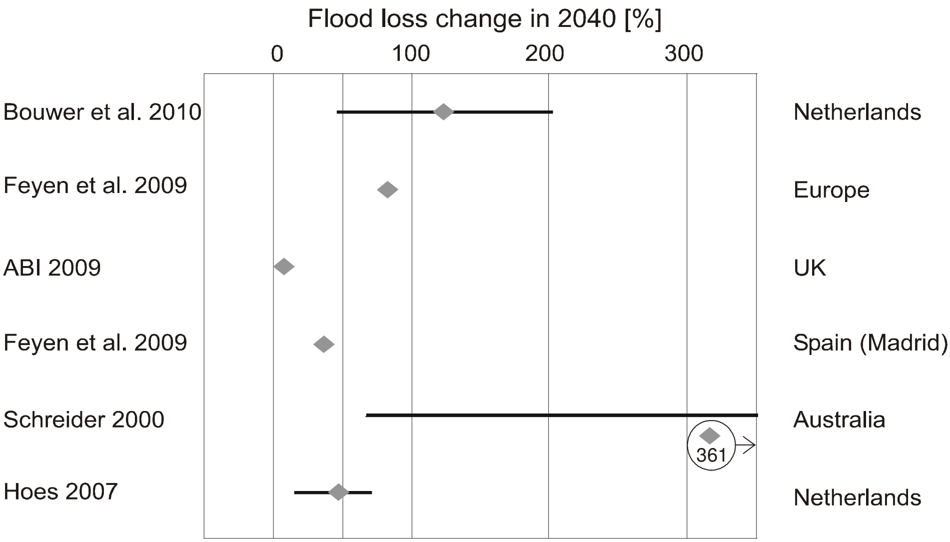

Figure 7.3. Projected changes in river and local flood losses by 2040 due to climate change.

Impact from changes in exposure

The changes in losses depicted in Figure 7.2 are the changes due to climate change alone. It has been shown that socioeconomic change, and consequent changes in exposure through the growing number of people and assets at risk, plays a very important role in the increases in historic losses (e.g. Bouwer et al., 2007/Chapter 2; Crompton and McAneney, 2008; Pielke et al., 2008; Bouwer, in press/Chapter 3). In projected future risks, increasing wealth and economic values of assets that are at risk also play a major role[12]. Therefore I contrast the changes in projected losses due to anthropogenic climate change with projected changes due to projected socioeconomic change, on the basis of studies that estimated the impacts from both these causes.

Figure 7.4 shows the impacts of socioeconomic changes from six studies that have assessed the impact of socioeconomic change on disaster losses (Table 7.2; column 7). The approaches in these studies generally include the increase in exposure (due to population increase in at-risk areas, and consequent land-use change and expansion of urban areas), as well as the increase in value of capital (due to wealth increase, related to ongoing economic development). The median increase in disaster losses due to socioeconomic change estimated by these studies is 172% by

[12] It is important to note however, that while socioeconomic developments may increase disaster losses, wealth increases also allow societies to sustain higher losses (irrespective of adaptation, which was discussed earlier). Some studies therefore refer to increases losses relative to wealth (GDP), and also in integrated assessments of the costs of climate change refer to impacts relative to GDP (e.g. Tol, 2005; Narita et al., 2009; Narita et al., 2010; Nordhaus, 2010).

the year 2040 (Table 7.A1). Although the spread of the estimated impact between the different studies is large, the median increase is larger than the median increases due to climate change found for windstorms and floods. It is striking that most of the impact studies do not take into account this very important socioeconomic driver of risk. Pielke (2007a) notes in this regard, that studies that only consider changes in climate are performing a sensitivity test only, and do in fact not produce a projection.

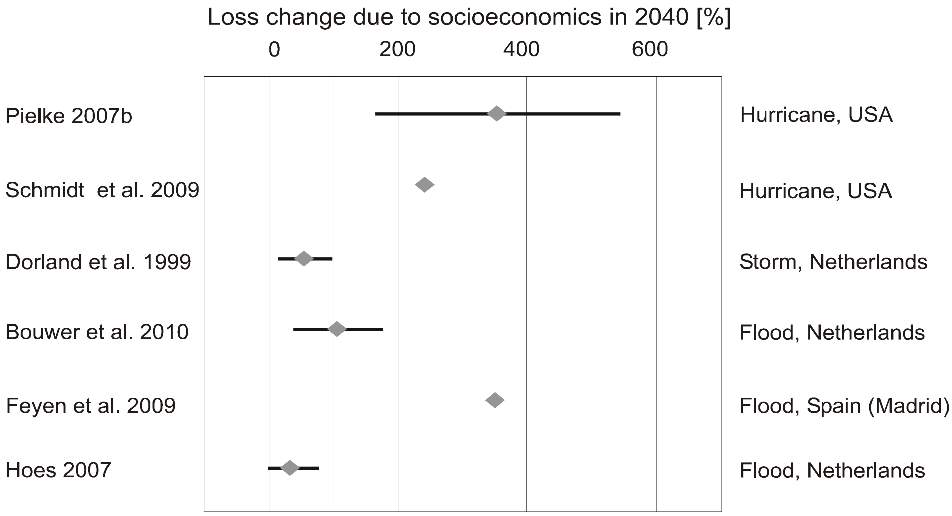

Figure 7.4. Projected changes in future losses by 2040 as a result of socioeconomic change, for windstorm and flood hazards. Note the different scale, compared to Figures 7.2 and 7.3.

Comparison of loss projections

In all, the comparison of loss projections shows that loss projections converge (i.e. are within the same range) for extra-tropical windstorms, and somewhat converge for tropical windstorms (Figure 7.2). This is mostly because these studies are based on similar assumptions about hazard-damage relations, and there is some consensus on the potential intensity increase of tropical windstorms, based on findings from meteorological and climate change studies (IPCC, 2007a; Knutson et al., 2010). For flood losses, more variation in projections exists (Figure 7.3), because of the high regional variability in projected changes in rainfall, the response of individual rainfall-runoff regimes in river basins and low-lying areas, and local differences in exposure to flooding. Notable outliers among the studies are as indicated before the studies by Pielke (2007b) and Dorland et al. (1999) for storms, and by Schreider et al. (2000) for floods. Also, the estimated increase in flood losses for the UK (7%) from ABI seems low compared to estimates for other countries (Feyen et al., 2009; Bouwer et al., 2010/Chapter 6), and compared to the Foresight study that assessed losses from fluvial and coastal flooding to differ by some 250% between low and high climate change by 2040 (Evans et al., 2004: Table 9.14).

The numbers in Figures 7.2 and 7.3 suggest that anthropogenic climate change might result in a substantial increase in risks from natural hazards. In the short-term, here taken as the period up to the year 2040, the impact of climate change is however expected to be relatively small compared to the increase in risk that is due to socioeconomic change. The contribution of socioeconomic change to exposure and wealth increase is very likely larger in the period up to 2040. Analysis of historic losses shows that the rapid economic development and accumulation of capital in high-density urban areas has contributed to a large increase in exposure, one that is greater than average economic growth (Bouwer et al., 2007/Chapter 3). Although past observations provide no prediction for the future, the developments of economic development and accumulation of people and capital in at-risk areas is very likely to continue at a comparable pace.

Studies of future losses that take account of socioeconomic change indicate that increasing exposure likely has a dominant impact, at least in the coming decades. From this analysis of impact studies it follows that the impact of anthropogenic climate change on losses from floods is substantially smaller than the impact of socioeconomic change (median increase of 65% for floods, compared to a median increase of 172% due to socioeconomic change). For tropical windstorms, the impact of anthropogenic climate change is about five times smaller than the impact of socioeconomic change (median 30%, compared to 172%). For extra-tropical windstorms, the impact from changes due to anthropogenic climate change on economic losses is one order of magnitude smaller than the impact from socioeconomic change (median 15% compared to 172%)[13]. However, continued ocean warming, sea-level rise, and the non-linear response of extreme weather, such as monsoon rainfall and convective weather, may all lead to greater hazards in the period beyond the year 2040. Therefore in the longer term impacts from climate change on disaster losses could become more substantial. Also, simple climate extremes, such as drought, heat waves, extreme rainfall and hail are likely to inflict increasing damage, but have been studied less.

[13] In this chapter, median values of the different averaged estimates from the literature are used (see Table 7.A1 in the Appendix). The median is chosen, in order not to give too much weight to extreme estimates. Using the mean would result in estimates of 70%, 33%, 110%, and 188% changes in losses by 2040 for tropical storms, extra-tropical storms, floods, and socioeconomic change, respectively. This approximately halves the ratios between climate and socioeconomic causes, but would not substantially alter the conclusions from this chapter.

7.4 Key uncertainties and research needs

The directions of climate change and the response of weather extremes for the decades up to 2040 are broadly known. At the regional and local level, there will however remain significant uncertainty about the precise changes in the frequency and intensity of extremes. As risk is the product of hazard, exposure and vulnerability, the contribution of changes in exposure to future risks is expected to be substantial, as shown above. This chapter has in particular underlined the need for the inclusion of socioeconomic scenarios in loss analysis and estimates, as changes in economic losses from extreme weather until the year 2040 will likely be dominated by increasing exposure. This is in line with the expectation that the majority of changes in extreme weather events associated with anthropogenic climate change will occur after 2050 (IPCC, 2007b: Table SPM.1). Key uncertainties that hinder the estimation of climate change impacts on disaster losses identified in this chapter, which are briefly discussed below, are:

- The lack of a common detailed and comprehensive analytical framework for the assessment of future disaster losses;
- The uncertainties in projections of future exposure and vulnerability, and;
- The role of risk reduction and adaptation to climate change.

The number of studies that have projected losses from weather hazards using a somewhat common approach, that combines estimates of future climatic parameters with estimates of future exposure and vulnerability, are scarce (Table 7.2). Given that risk depends on local characteristics, more studies need to identify the factors that contribute most to changes in risk over the next decades. Also, the effectiveness of risk reduction needs to be assessed, as there is ample indication, but very little quantification, of the mitigating effects of vulnerability reduction on loss potentials. In this way, approaches and strategies for risk reduction and adaptation can be tested.

Very few impact studies presented in this chapter have applied a comprehensive and integrated approach for addressing all three components of risk (hazard, exposure and vulnerability). This chapter has illustrated a framework (Figure 7.1), which could be applied to improve estimates of future disaster losses. The main problems seem to lie with the estimation of future exposure and vulnerability. Some researchers go as far as saying that for planning adaptation, there is a far greater need to understand the vulnerability to climate change, rather than to expand efforts to increase accuracy and precision of estimates of future climate change (Dessai et al., 2009). Still, calls for improved climate modelling dominate the debate on information needs for adaptation planning (e.g. Goddard et al., 2009).

Given the importance of exposure and vulnerability, it seems warranted to expand the efforts in analysing and projecting these for future disaster risks. At present, this area of study is underdeveloped, in particular when it comes to quantification of exposure and physical vulnerability, which would be comparable in detail to projections made in climate science, and at a level and precision that can be used in risk models. The studies included here usually take GDP, or projected population growth as proxies for future changes in exposed values (Pielke, 2007b; Schmidt et al., 2009b; Dorland et al., 1999), sometimes complemented by information on land-use change and changes in building stock (Hall et al., 2003; Hoes, 2007; Bouwer et al., 2010/Chapter 6). The spatial resolution of the information on actually exposed people and assets in the future is either lacking, or not sufficiently detailed at present in many studies.

Some studies have shown the large discrepancy between growth numbers for population based on socioeconomic scenarios at the national level, for instance, and the change in actual people at risk at the local level. The latter is often much larger, due to high concentration of people in urban areas at risk from natural hazards (see e.g. Maaskant et al., 2009). If this scaling issue is better addressed, some of the epistemic uncertainty involved in these studies can be reduced, and potentially more accurate estimates of exposure can be made. More studies could make use of the expanding branch of work on socioeconomic scenarios, as well as tools that may help to assess changes in exposure, such as land-use models, and quantitative approaches that can assess changes in vulnerability over time.

Finally, adaptation is likely to mitigate a large part of the changes in risk due to increasing exposure and anthropogenic climate change. There is ample evidence that the creation of protective infrastructure, the improvement of building codes and early warning, can lead to the reduction of weather hazard losses (Hallegatte, 2008; Botzen et al., 2009). For instance, Hallegatte (2007) shows from an analysis of hurricane losses that on average vulnerability in individual counties in the USA is reduced after a hurricane makes landfall. The impact studies discussed here have not quantitatively assessed the potential result of adaptation and risk reduction on future disaster losses.

7.5 Conclusions

All projections of future weather risks show on average increases in disaster losses due to climate change. Flood losses are projected to increase more rapidly under climate change, compared to projected changes in losses from tropical and extra-tropical windstorms, until the year 2040. However, the contribution from increasing exposure and value of capital at risk to increasing losses is estimated to be substantially larger than changes in the incidence of floods, and in the case of storms between five and ten times larger, than the impact of projected anthropogenic climate change on tropical and extra-tropical storms. Since loss events are stochastic, and their occurrence varies over time due to natural climatic variations, the relatively small signal from anthropogenic climate change up until the year 2040 is therefore likely to be lost among other causes for increasing and varying losses.

Still, the comparison between the contribution to change in risk from anthropogenic climate change and socioeconomic change is quite uncertain, given the limited number of studies included here, different methods and assumptions underlying these studies, the large spread in estimates, and the rather crude assumptions about the relation between changes in socioeconomics and changes in exposure to hazards. Also, the estimates given here are based on average, or annual expected values. More frequent very large loss events may have severe economic consequences[14]. Finally, risks are moderated by the complicated interaction of the hazard with risk reduction and adaptation measures, that can influence hazard probability, and exposure and vulnerability of people and capital, human behaviour, and thereby the losses that can possibly occur. At the same time, adaptation aimed at reducing risk will come at a cost. And it remains uncertain if sufficient and timely adaptation will be achieved, given the long planning horizon of infrastructure projects, as well as behavioural changes, and the need to show the present benefits of investments in risk reduction.

Climate policy through the abatement of greenhouse gas emissions is important, given the likelihood that continued warming of the planet could lead to some irreversible impacts in the period after 2050. Mitigation policy therefore seems warranted for avoiding impacts beyond 2050. Also, changes in the frequency of other, smaller scale weather extremes, notably droughts, heat waves, wildfires, and extreme rainfall, although they have not been specifically assessed here, are likely to occur. But changes in risk from major weather hazards (storms and floods) in the short-term, up to the middle of the 21st century, are likely to be dominated by changes in exposure and vulnerability. This indicates the very important role for adaptation and risk reduction in strategies for reducing the impacts from weather disasters that are expected to occur in the short-term.

7.6 Acknowledgments

Helpful comments and suggestions on earlier versions of this chapter were provided by Pier Vellinga, Jeroen Aerts, Wouter Botzen, Thijs Dekker, and Hans de Moel. This research is part of the project 'Financial arrangements for disaster losses under climate change', supported by the Dutch National Research Programme 'Climate

[14] Many studies however do assess the impact from different event magnitudes, and these events are included in the estimated change in average annual expected losses, but the studies arrive at different conclusions whether high magnitude events become disproportionally more costly.

changes Spatial Planning' (http://www.climatechangesspatialplanning.nl. All responsibility for errors and opinions remains with the author.

7.7 Appendix

Estimated future losses depicted in Figures 7.2, 7.3 and 7.4, are given in Table 7.A1 as percentage change in the year 2040, relative to the baseline year 2000. Median changes in losses are calculated on the basis of the average change estimates from the different studies, for different hazard types (floods, and windstorms). The same was done for the impact of socioeconomic change on future losses. Estimates from studies that projected changes in losses for other periods or with reference to other baselines years (1990-2006) were scaled to reflect the percentage change in the 40-year period between 2000 and 2040. It was assumed that changes occur linearly, i.e. the same incremental change per year. This is a simplification, as changes in climate and consequent changes in weather extremes do not necessarily occur linearly. Some studies did not specifically identify a future time-slice or year for which the projection is valid (ABI, 2009; Hallegatte, 2007), here it was assumed that the full projected impact of climate change on the hazard that is reported will be realized by 2100. Some studies did not specify a baseline year or period (ABI, 2005a; b; ABI, 2009; Hallegatte, 2007; Feyen et al., 2009; Schreider et al., 2000); here it was assumed that the baseline year is 2000.

Although most of the projections separate between climate and non-climate drivers, some of the projections of climate change impacts in fact are not entirely free from inclusions of growth in exposure. For instance, Narita et al. (2010) do include the role of increasing GDP, but set this off against improved protection, leading to a net reduction of losses. Their estimate (Figure 7.2b) is therefore rather optimistic, compared to other estimates of future extra-tropical storm losses.

Additionally, it is important to note that the combination of changes in exposure and changes in hazard also have a combined effect (as risk is a multiplication of the two; see Figure 7.1). Some studies acknowledge this, and report this effect separately (e.g. Pielke, 2007b; Bouwer et al., 2010/Chapter 6). In the current study, the effect is ignored for sake of simplicity. However, the effect has a substantial contribution, and it means that the *total* estimated changes by 2040 are *higher* than a simple summation of the percentages reported in Figures 7.2, 7.3 and 7.4, and Table 7.A1.

Table 7.A1. Estimated change in disaster losses in 2040 due to climate change and exposure change, relative to the year 2000 from twenty-one impact studies (TS=tropical storm; ETS=extra-tropical storm; RF=river flood, LF=local flood).

A. Climate change

	Hazard type	Region	Estimated loss change [%] in 2040				Reference
			Min	Max	Mean	Median	
1	TS	Atlantic	58	1365	417		Pielke 2007b
2	TS	USA	12	92	47	30	Nordhaus 2010
3	TS	Global	23	130	46		Narita et al. 2009
4	TS	USA	-	-	22		Hallegatte 2007
5	TS	USA, Caribbean	19	46	32		ABI 2005a; 2005b
6	TS	Japan	20	45	30		ABI 2005a; 2005b
7	TS	China	9	19	14		ABI 2009
8	TS	USA	-	-	9		Schmidt et al. 2009b
9	TS	USA	-27	36	14		Bender et al. 2010
10	ETS	High latitude	-11	62	22	15	Narita et al. 2010
11	ETS	Europe	6	25	16		Schwierz et al. 2010
12	ETS	UK, Germany	-6	32	11		Leckebusch et al. 2007
13	ETS	Europe	-	-	14		ABI 2005a; 2005b
14	ETS	UK	-33	67	15		ABI 2009
15	ETS	Netherlands	80	160	120		Dorland et al. 1999
16	RF	Netherlands	46	201	124	65	Bouwer et al. 2010/Chapter 6
17	RF	Europe	-	-	83		Feyen et al. 2009
18	RF	UK	3	11	7		ABI 2009
19	RF	Spain (Madrid)	-	-	36		Feyen et al. 2009
20	LF	Australia	67	514	361		Schreider et al. 2000
21	LF	Netherlands	16	70	47		Hoes 2007

B. Exposure change

	Hazard type	Region	Estimated loss change [%] in 2040				Reference
			Min	Max	Mean	Median	
1	TS	Atlantic	164	545	355		Pielke 2007b
8	TS	USA	-	-	240	172	Schmidt et al. 2009b
14	ETS	Netherlands	12	93	50		Dorland et al. 1999
16	RF	Netherlands	35	172	104		Bouwer et al. 2010/Chapter 6
19	RF	Spain (Madrid)	-	-	349		Feyen et al. 2009
21	LF	Netherlands	-4	72	29		Hoes 2007

Chapter 8. Conclusions

This thesis has examined to what extent anthropogenic climate change will result in more damage from weather disasters during the next decades, in comparison to non-climatic drivers of risk. Previous chapters have provided a review of the scientific literature on historic disaster losses, as well as projections of future disaster losses. Also, an analysis was made of changing risks from flooding of rivers for a case study area in The Netherlands, and their climatic and socioeconomic causes. This final chapter draws some conclusions on the basis of the findings in previous chapters.

8.1 Past increases in weather disaster losses are due to non-climatic drivers

Economic losses from weather disasters have undoubtedly increased, but no scientific study of loss records has identified anthropogenic changes in extreme weather as the main driver for the observed trend at the global level. The overview of studies presented in Chapter 3 of this thesis shows that loss records that were corrected for changes (increases) in population and capital at risk show no long-term trends that could be attributed to anthropogenic climate change. Loss records for a wide range of natural hazards have been analysed in these studies, among which floods, windstorms (including hurricanes and typhoons), tornadoes, thunder-storms, earthquakes, wildfires and droughts. A number of studies, however, indicate that not all of the variations in historic losses can be explained by socioeconomic changes. Some studies find variations that resemble patterns of local or regional natural climate variability, which are reflected in the frequency of extremes. Such variations, occurring over timescales of decades, should not be mistaken for anthropogenic climate change.

These studies however usually fail to correct for changes in vulnerability that are harder to quantify than changes in exposure. Studies that are properly set-up would need to include the frequency of the hazard (geophysical data), exposure (population and wealth), as well as changes in vulnerability. Also, the studies need to be hazard and site-specific, as regional variations and changes in climate may be different, and exposure to different hazards has not evolved equally over time for all countries, locations and hazards.

That no trend has yet been found in economic losses from extreme weather events follows logically from the fact that geophysical changes (regardless of cause) have only been detected for a few weather extremes. Moreover, an impact from anthropogenic forcing of the global climate has been established for even fewer weather extremes. Only for temperature, there is a likely human contribution to the increasing frequency of hot days and nights, and decreasing cold days and nights (IPCC, 2007a: Table SPM.2). For windstorms and floods, it is more likely than not, that a human contribution is present in the observed trend (IPCC, 2007a: Table SPM.2). Geophysical data on the frequency of weather hazards is more likely to provide early signals of extreme weather impacts, given that the economic impact of weather disasters is complex, more difficult to measure, and that loss data is not systematically collected, reported and analysed.

There is a need for improved data collection on disasters losses, and especially for flood losses few data is available. Flood losses are generally not as much insured by the private sector as losses from windstorms. Consequently, flood losses are not as well recorded. Also, a high spatial or global aggregation is needed for loss monitoring studies, comparable to the study by Miller et al. (2008). This high spatial aggregation is required in order to find and attribute trends in the losses for these rare extreme weather events.

8.2 Projections of future weather risks need a comprehensive approach

The analysis of the scientific literature on future losses from extreme weather presented in Chapter 7 shows that most studies have not sufficiently taken into account the consequences side of risk. Most scholars have only considered the possible change in the frequency and intensity of the weather hazard. The role of economic growth and population growth is in most instances ignored. The analysis of historic losses showed that until now, socioeconomic developments have lead to increasing exposure, and this is the main driver for increasing risks. As socio-economic development will continue to play an important role in future disaster risk, these development should form an important component of risk assessments for the coming decades, in order to be able to accurately project potential losses. Accurate potential loss estimates are in turn crucial for deciding on climate change mitigation policy, effective risk reduction and adaptation policy.

Studying future impacts poses some major challenges. First, there is a lack of a common analytical framework for dynamic estimates of natural hazard risk over time. While there are many approaches and models available to estimate contemporary weather risks, catastrophe models are rarely used for estimating losses in the near and more distant future. Second, there is inherent uncertainty in the projection of future losses. Third, there is very little quantification of the mitigating effects of vulnerability reduction or adaptation. The three most important sources of uncertainty that occur in the loss projections relate to the changing probability of natural hazards, the exposure of capital, as well as estimated vulnerability. There are large variations in projected changes in climate across different geographical regions. Also, these regions may show different pathways of future socioeconomic development, and very different vulnerabilities, which are difficult to project over periods spanning more than one or two decades. Scenarios of changing exposure and vulnerability, and changing weather hazards, may account for these uncertainties. This thesis proposes a comprehensive approach in Chapter 6, that combines such scenarios with a catastrophe model that was detailed in Chapter 5. The approach is aimed at quantifying the bandwidth of the possible development of future weather risks, in this case flood losses.

Climate impacts are very much hazard, time and location specific. Therefore, there is no such thing as *the* quantification of future disaster losses, but only estimates that are valid for a specific hazard, place and time. Very few impact studies that were analysed in this thesis have applied a comprehensive and integrated approach for addressing all three components of risk: hazard, exposure and vulnerability. Some studies have considered a combination of changes in hazard and exposure, and these studies currently provide the most reliable estimates of future risks, and the role of climate change compared to other causes of changing risk.

Few of the studies presented in Chapter 7 however included estimates of future changes in vulnerability, and the potential effect of vulnerability reduction and adaptation. Vulnerability to weather hazards may change over time, as buildings and assets are replaced or upgraded and improved to withstand extreme wind speeds or inundation by water. This in turn may affect the potential amount of damages, but these factors are not accounted for in loss projection studies. There is a need to quantitatively describe how physical vulnerability of assets, infrastructure, buildings, and content, changes over time. Above all, better analysis of exposure is key for accurate estimates of future weather risks. It seems warranted to expand the efforts in projecting and analyzing the role of exposure in future disaster risks. At present, this area of study is underdeveloped, in particular concerning the quantification of exposure that is comparable in detail to scenarios for meteorological and climatic parameters, and at a level of detail and precision so that the scenarios can be used in catastrophe models.

8.3 River flood losses could increase more rapidly than windstorm losses

The future increase in losses from river flooding due to anthropogenic climate change may be higher than the increase in windstorm losses. This expectation is based on the comparison in Chapter 7 of loss projection studies. The difference in the increase in risk is due to the difference in projected changes in the river flood and windstorm hazards, that show larger increases in flood frequency compared to windstorm frequency or intensity. Also, there is more certainty that intense precipitation will become more frequent. Anthropogenic signals have been detected in precipitation records, and according to the IPCC it is more likely than not that a human contribution is present in the increasing trend of heavy rainfall events (IPCC, 2007a: SPM.2). Intense tropical windstorm activity is more likely than not to have increased due to a human contribution (IPCC, 2007a: SPM.2). A possible historic increase in the number and intensity of hurricanes is still heavily debated. For the future, extreme precipitation events are very likely to increase in frequency, whereas intense tropical windstorm activity is likely to increase in the future (IPCC, 2007a: SPM.2). Projections of changes in floods are therefore somewhat more robust compared to projections of windstorms. Although there is no evidence for an increase in river flood hazards in all regions of the world, increases in extreme discharges have been observed in some river basins over the past, and further increases in extreme rainfall are projected for the future. Taken together, this indicates that it may be that pluvial and river flood losses will increase more rapidly in the future due to anthropogenic climate change, than losses from tropical and extra tropical windstorms. That this effect will be found in loss records in reality is uncertain, given that flood losses are often not well recorded. Also, differences in exposure to storms and floods, as well as risk reduction measures, may differentiate trends in both types of disaster losses.

The main driver for the occurrence of winter river floods in Europe is the variation in west atmospheric circulation, as shown in Chapter 4. High river discharges, associated with flood occurrence, are found to be more sensitive to variability in west circulation than the mean discharges. For some major climate indices, mean discharges vary on average between 8 and 44%, while peak discharges vary between 10 and 54% per unit index change. There are indications from other studies that the recent increase in sea level pressure gradients in the northern hemisphere since the 1970s is due to anthropogenic climate change. This implies an increased flood probability in northwest Europe, if climate change would lead to an increasing pressure gradient. At the same time, no systematic trends are found towards higher discharges. The analysis in Chapter 4 shows that some periods, in particular the 1990s, stand out in terms of high peak discharge occurrence in northwest Europe, but such periods have also occurred earlier in the record, in particular during the 1910s and 1920s.

8.4 The impact of climate change on weather losses will remain small in coming decades

In the case study presented in Chapter 6, future impacts on flood risk have been separated for projected climate change and exposure for flooding of the river Meuse in The Netherlands. It is found that anthropogenic climate change may lead to a substantial increase in potential flood losses for this case by the year 2040 (up to 201%), that is about as large as the increase in exposure due to land-use change and increasing value of capital combined (up to 172%). Important sources of uncertainty that occur in the loss projections relate to the probability of river flooding, the value of exposed capital, as well as estimated vulnerability. Since capital increase is one of the key causes for increases in losses, uncertainties in this parameter also cause great variation in future loss estimates.

A number of studies of future economic losses from weather extremes that were recently published have been assessed in this thesis. All projections of future weather risks show increases in losses due to anthropogenic climate change by the middle of this century. However, for the period up to 2040, the contribution from increasing exposure and value of capital at risk according to current studies is substantially (about 2-10 times) larger than the contribution from anthropogenic climate change. As shown in Chapter 7, losses from tropical windstorms are estimated to increase by some 30%, losses from extra-tropical windstorms by some 15%, and losses from river floods by some 65% by the year 2040. In contrast, increasing exposure of population and assets is estimated to lead to an increase in losses of some 170% by 2040. Given the fact that loss events are stochastic, and that their occurrence varies over time due to natural climatic variations, the relatively small signal from anthropogenic climate change until the year 2040 is likely to be lost among other causes for increasing and varying losses, at least for storms and floods. Simple weather extremes, such as drought, heat waves, extreme rainfall and hail are likely to inflict increasing damage, but these impacts have been studied less.

The comparison between the contribution from anthropogenic climate change and socioeconomic change is quite uncertain, given the limited number of studies, the large spread in estimates, and the rather crude assumptions about the relation between population and economic growth and exposure to hazards. In addition, adaptation will likely reduce potential losses, which will mitigate the impact of both climate change and ongoing development, largely to an unknown degree. Also, loss data is not systematically collected and often inaccurate, so these effects may not be empirically found. These factors will further complicate finding a signal of anthropogenic climate change in disasters losses.

Some might argue that the main cause for increasing losses, which is increasing wealth, could alleviate an important part of the expected increase in losses. However, this need not be true, for a number of reasons. Increasing exposure due to land-use change and increasing habitation of risky areas may result in disproportionate exposure, which may be detrimental to a subset of the global population, and which cannot be fully compensated by wealth increases. Ultimately, this may be an economic distribution problem. Additionally, it is unlikely that all growth of wealth can or will be spent on compensating losses or prevention of disasters. One empiric studies shows that economic growth, especially in middle income countries, is not spent on risk reduction, but rather leads to increasing exposure. For risk reduction, on the other hand, by comparison only relatively small investments are needed. For example, the Dutch Delta Committee has recently proposed to increase the budget for investment in prevention and maintenance from the present 0.2% to some 0.4% of national GDP, or about 3 billion Euros per year, on flood risk prevention in 2020.

8.5 Implications for climate policy

Attribution of increases in disaster losses to anthropogenic climate change will remain very difficult in the decades to come. This is an important signal for the negotiations under the UN Climate Convention (UNFCCC), where funds are proposed for adaptation to anthropogenic climate change, including adaptation to weather extremes. Adaptation and risk reduction will however have many benefits beyond the avoided impacts from anthropogenic climate change, i.e. it will also reduce current high disaster risk levels. There are other impacts from climate change, apart from changed impacts of extreme weather, that should be the primary motivation for the reduction of greenhouse gas emissions. For instance, irreversible impacts on ice-sheet mass balances, and feedback mechanisms of soils are projected. It will likely be necessary to avoid these and other impacts beyond the middle of this century, as well as high future adaptation costs by that time, through the abatement of emissions.

Adaptation to changing risks seems the most effective way of reducing the increasing impact from extreme weather in the short term, until the middle of this century. The analysis of the causes of historic and future losses from weather disasters has shown that the main cause is the growth of population and capital in areas at risk from natural hazards. This indicates the huge potential for reducing losses and costs in the coming decades, by addressing the historic 'adaptation deficit' as well as future risks, through reduction of exposure and vulnerability. Therefore efforts in climate policy and other policies could be focussed on better understanding the actual causes of risk, and on promoting adaptation also in the short term, in addition to efforts for emission reduction.

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Curriculum vitae

Laurens Menno Bouwer werd geboren op 24 december 1975 te Lochem. Hij behaalde in 1995 zijn VWO diploma aan het Staring college te Lochem, en ging Aardwetenschappen studeren aan de Vrije Universiteit in Amsterdam. In 1999 werd hij studentassistent bij prof. Pier Vellinga, die op dat moment directeur was van het Instituut voor Milieuvraagstukken (IVM) aan de VU. In 2001 kwam het derde assessment rapport van het Intergovernmental Panel on Climate Change (IPCC) uit, waar Laurens als auteur een bijdrage leverde aan het hoofdstuk over natuurrampen en verzekeringen. In 2001 studeerde hij af in de fysische geografie, met een specialisatie vrij doctoraal (sedimentologie en paleoklimatologie). Sindsdien werkt hij als onderzoeker bij het IVM, waar hij wetenschappelijk onderzoek doet en advies geeft aan overheid en bedrijfsleven in binnen en buitenland. Samen met collega's publiceerde hij 23 artikelen in wetenschappelijke tijdschriften op het gebied van klimaat, hydrologie, waterbeheer, economie, en verzekeringen. Sinds 2010 is hij manager van het Europese onderzoeksproject RESPONSES over de integratie van klimaatbeleid, en draagt hij bij aan het IPCC special report Managing the Risks of Extreme Events and Disasters en aan het vijfde assessment rapport van het IPCC.