Knowledge for Climate

# Adaptation to Meuse flood risk

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## Content

## Summary

The Meuse floods of 1993 caused over €100 million damages in the Netherlands alone. The risk of flooding is expected to increase in the future, so it is important to understand how and why this risk will change, and how we can adapt to it.

The research questions of this study are:

- What is the sensitivity of flood risk in the Meuse basin to changes in climate and land use?
- To what extent can various adaptation measures reduce Meuse flood risk?

For Dutch Limburg, we found the combined impacts of climate and land use change to be an approximately two- to three-fold increase in risk (by 2030 compared to 2010), with land-use change being the dominant driving factor. At the basin scale, we carried out a quick-scan assessment, and found the combined impact of climate and land use change to be an increase in risk of ca. 16-39% between 2000-2030. At this scale, the relative influences of climate and land use change are of the same order of magnitude. This is important, since local-regional stakeholders have more control over land use distribution than over climate change.

Currently ongoing spatial zoning projects in Limburg could reduce the risk increase between 2000-2030 by up to 45%, and household level flood mitigation measures have the potential to significantly reduce flood risk. However, there are few means to enforce or encourage the undertaking of mitigation measures by households. Further research is recommended into methods for motivating the implementation of such measures.

## Samenvatting

In 1993 leidde de overstroming van de Maas in Nederland tot een directe financiële schade van meer dan € 100 miljoen. Het risico van overstromingen zal naar verwachting toenemen in de toekomst. Het is dus van belang om te begrijpen hoe en waarom dit risico zal veranderen, en hoe we ons kunnen aanpassen aan dit risico.

De onderzoeksvragen van deze studie zijn:

- Wat is de invloed van het klimaat en van socio-economische ontwikkelingen op het toekomstige overstromingsrisico van de Maas?
- Wat zijn de effecten van diverse adaptatiemaatregelen op het overstromingsrisico?

Uit ons onderzoek blijkt dat in Nederlands Limburg de gecombineerde impact van het klimaat en van veranderingen in landgebruik leiden tot een toename in risico van ongeveer een factor twee tot drie (tussen 2000 en 2030). Op deze schaal heeft de gesimuleerde verandering in landgebruik een grotere invloed op de toename in risico dan de gesimuleerde verandering in het klimaat. Voor het gehele Maasstroomgebied voerden we vergelijkbare quick-scan analyses uit. Daaruit blijkt dat de gecombineerde impact van het klimaat en van veranderingen in landgebruik leiden tot een toename in risico van 39% tussen 2000-2030. Op deze schaal zijn de relatieve invloed van klimaat en veranderingen in landgebruik van dezelfde orde van grootte. Dit is belangrijk omdat lokale en regionale actoren meer controle hebben over landgebruik dan over klimaatverandering.

Projecten op het gebied van de ruimtelijke ordening die momenteel lopen in Limburg zouden de potentiële toename in risico tussen 2000 en 2030 kunnen verlagen met 45%. Daarnaast zouden overstromingsmitigatiemaatregelen op het niveau van huishoudens het risico flink kunnen verlagen. Er zijn op dit moment echter weinig middelen om laatstgenoemde maatregelen af te dwingen of aan te moedigen. Nader onderzoek wordt aanbevolen naar methoden en beleid om de uitvoering van dergelijke maatregelen aan te sporen.

# Extended summary



## Background and research questions

In 1993 and 1995 the Meuse River overflowed its banks; the direct financial losses of the 1993 flood were estimated at over €100 million for the Netherlands alone. Flooding in the Meuse basin has huge economic impacts in the Netherlands, but also in Belgium and France, and therefore adaptation to flooding is an enormous societal imperative in the Meuse region. Flood adaptation strategies in most parts of the world have traditionally concentrated on providing protection against floods through technical measures like barriers and dikes. However, international water management is shifting towards a more integrated system of flood risk management, whereby flood risk is defined as the probability of flooding multiplied by the potential consequences.

However, there is a lack of knowledge internationally on the sensitivity of flood risk to changes in various physical and socioeconomic parameters. Moreover, little is known on the effectiveness of measures designed to reduce flood consequences. As part of the *Climate changes Spatial Planning* ACER and AvV projects, methods have been developed to model effects of changes in climate and land use on flood risk in the Rhine Basin. The *Knowledge for Climate* project HSGR02 used these to develop a toolkit for flood risk assessment in the Rhine. However, less research has been carried out in the Meuse River, despite floods on this river in 1993 and 1995 leading to extensive flood damage.

Hence, this project was established to fill this knowledge gap. This report summarises the main findings of this project. The main research questions are:

- What is the sensitivity of flood risk in the Meuse basin to changes in climate and land use?
- To what extent can various adaptation measures reduce Meuse flood risk?

## Setup of main report

This report is setup as follows. In Section 2, we describe the Meuse basin, and provide an overview of past projects. In Section 3, we describe the overall research approach and the existing models used. In Section 4, we describe the setup and validation of a new inundation model (Floodscanner). In Section 5, we examine how flood risk estimates are affected by the return periods used to derive the risk curve. In Section 6, we estimate the impacts of climate and land use change on flood risk in Dutch Limburg, and discuss how several adaptation strategies could reduce that risk. In Section 7, we describe results of a quick-scan assessment of the impact of climate change, land use change, and adaptation, on flood risk for the entire Meuse section from the source to Cuijk in the Netherlands. Conclusions and recommendations are given in Section 8.



## Study area

In this project, we primarily assessed flood risk in Dutch Limburg. In Section 7, we also carried out a quick-scan of flood risk along the main section of the Meuse from the source in France to Cuijk in the Netherlands. The Meuse is a predominantly rain-fed river with a length of ca. 875 km, with a catchment extending over parts of Belgium, France, Germany, Luxembourg, and the Netherlands. The Meuse basin is one of the most densely populated areas of western Europe, and is inhabited by about 9 million people. Several past studies have assessed the impacts of climate and land use change on the hydrology of the Meuse. Although there are differences in the results, most studies suggest that the frequency of floods will increase in the future due to climate change. However, there are relatively few assessments of the impacts on flood risk.

## Rapid inundation modelling and the number of return periods required to assess flood risk

Since no inundation maps of the Meuse were available at the basin scale, we first developed a rapid inundation model for river-valley flooding, Floodscanner. Floodscanner performed reasonably well compared to historical floods of 1993 and 1995, as well as compared to results from a process-based 2-D hydrodynamic model (WAQUA). By developing this methodology, we were also able to investigate how flood risk calculations are affected by the amount and choice of return periods used to develop risk curves. The majority of flood risk studies use damage estimates for a small number of return periods to estimate risk. Often three return periods are used, which is the number of flood maps that member states are obliged to create for the European Flood Directive. However, we have shown that risk estimates are greatly affected by the number of data points used to construct the risk curve. For example, using just three return periods to develop the risk curve (low, medium and high probability, whereby medium probability is RP = 250 yr), we found risk estimates to be overestimated by between 33% and 100%.

## What is the sensitivity of flood risk in the Meuse basin to changes in climate and land use?

For Dutch Limburg, we found the combined impact of climate and land use change to be an approximately two- to three-fold increase in risk (by 2030 compared to 2000), with land-use change being the dominant driving factor. For the Meuse basin as a whole, we found the combined impact of climate and land use change to be an increase in flood risk of ca. 16-39% between 2000 and 2030. At this basin scale, the relative influences of projected climate and land use change are of the same order of magnitude.

These findings highlight the need to implement adaptation strategies to limit the increase in risk. The importance of land use change in driving the increase in risk is an important finding, since local and regional stakeholders have more control over land use distribution than over the evolution of the climate. Adequate land-use management could potentially decrease the overall risk compared with a situation without these measures.



### To what extent can various adaptation measures reduce Meuse flood risk?

We assessed the risk reduction capacity of several adaptation measures, namely: spatial zoning and mitigation measures at the household level. The effects of spatial zoning measures were analysed for a case study in Dutch Limburg, since information were provided by regional stakeholders on the ongoing 'Beleidslijn Grote Rivieren (BGR)' and the 'Beleidsregels', a Dutch law and the corresponding rules that are meant to limit and regulate developments in Dutch flood-prone areas. We found that the currently ongoing spatial zoning projects could reduce the risk increase between 2000 and 2030 by up to 45%.

We also show that household level flood mitigation measures have a large potential to significantly reduce flood risk. We specifically examined three strategies, namely dry-proofing, wet-proofing, and the combination of dry- and wet proofing. We found that all of these strategies can significantly reduce flood risk; this is one of few studies to quantitatively assess the flood-risk reduction capacity of such strategies at the regional scale. Particularly for the Wallonia region of Belgium, the potential risk reduction is high: up to 46% for dry-proofing. However, we also found that there are currently few means to enforce or encourage the undertaking of mitigation measures by households. Further research is therefore recommended into methods for motivating the implementation of such measures.

In the annexes, we provide flood risk maps showing how flood risk is projected to change between 2000 and 2030 if no adaptation measures are taken, and the potential of household level mitigation measures to reduce flood risk. Such maps are useful to decision makers for understanding where flood risk hotspots are, and for identifying strategies most likely to limit risk in those areas.

# 1 Introduction

Flood damage constitutes a third of economic losses inflicted by natural hazards worldwide and floods are, together with windstorms, the most frequent natural disasters [Munich Re, 2010]. In 1993 and 1995 the Meuse River overflowed its banks; the direct financial losses of the 1993 flood were estimated to be in excess of €100 million for the Netherlands alone [Wind et al., 1999]. Thus, flooding has huge economic impacts in both the Netherlands and elsewhere, and adaptation to flooding is an enormous societal imperative.



Flood adaptation strategies in most parts of the world have traditionally been concentrated on providing protection against floods through technical measures aimed at reducing the probability of a flood, like barriers and dikes [Vis et al., 2003; Merz et al., 2010]. However, international water management is increasingly shifting towards a more integrated approach to flood risk, whereby flood risk is defined as the probability of flooding multiplied by the potential consequences. The level of flood risk therefore depends on the [UNISDR, 2011]:

- **hazard** characteristics, such as flood depths, extent, duration, or velocity;
- **exposure** characteristics in flood-prone areas, such as number of people, land use, and value of assets;
- **vulnerability** of the exposed assets and population to the hazard.

In Europe, the flood risk management approach has been given added impetus by the European Flood Directive (EFD) (Directive 2007/60/EC), which requires Member States to assess whether water courses and coastlines are at risk from flooding, to map the flood extent, and to take adequate and coordinated measures to reduce flood risk. As a result, projects are being carried out at the national and international level to map areas most at risk of flooding, and to provide detailed localised estimates of potential damage. However, there is a lack of knowledge internationally on the sensitivity of flood risk to changes in various physical and socioeconomic parameters. Moreover, little is known on the effectiveness of measures designed to reduce flood consequences.

As part of the ACER and AvV projects, methods have been developed to model the effects of changes in climate and land use on flood risk in the Rhine Basin. The KvK project HSGR02 used these methods to develop a toolkit for flood risk assessment in the Rhine. However, less research has been carried out on flood risk in the Meuse River, despite the fact that floods on this river in 1993 and 1995 also led to extensive flood damage.

Hence, this project was established to fill this knowledge gap. This report summarise the main findings of this project.

The main research questions are:

- What is the sensitivity of flood risk in the Meuse basin to changes in climate and land use?
- To what extent can various adaptation measures reduce Meuse flood risk?

Next to these key questions, another issue that we addressed was whether the flood damage model developed for the Rhine basin, and applied in the project HSGR02, could be easily transferred to the Meuse basin.



The primary focus of our research, and this report, is on the Meuse in Dutch Limburg. This focus was chosen after several discussions with Rijkswaterstaat Waterdienst and *Knowledge for Climate*, because at the same time as our project, a large European INTERREG IVB project, entitled AMICE, was being carried out to examine flood risk at the basin scale. Our consortium contributed to AMICE by performing the flood risk analyses used in that project for the Dutch part of the Meuse. The results of these analyses can be found in Sinaba et al. [2013], and all project outputs of AMICE can be found at http://www.amice-eu.org/. However, for the current project, we did also perform a quick-scan analysis of flood risks at the basin scale, using the methods developed for our *Knowledge for Climate* project; these results can be found in Section 7 of this report.

This report is setup as follows. In Section 2, we describe the Meuse basin, and provide an overview of past projects. In Section 3, we describe the overall research approach and the existing models used. In Section 4, we describe the setup and validation of a new inundation model (Floodscanner). In Section 5, we examine how flood risk estimates are affected by the return periods used to derive the risk curve. In Section 6, we estimate the impacts of climate and land use change on flood risk in Dutch Limburg, and discuss how several adaptation strategies could reduce that risk. In Section 7, we describe the results of our quick-scan analysis of flood risk at the basin scale from the source to Cuijk in the Netherlands. Conclusions and recommendations are given in Section 8.

A spin-off was an assessment of governance aspects related to flood risk management in cities, including Rotterdam. This research can be found in Ward et al. [2013], published in *Environmental Politics*. Below is a list of key publications from this project; a full publication list can be found in Annex 1.

## 1.1 Key publications from HSGR06


- Poussin, J.K., P. Bubeck, J.C.J.H. Aerts & P.J. Ward, 2012. Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse. Natural Hazards and Earth System Sciences, 12, 3455-3471, doi:10.5194/nhess-12-3455-2012.
- Poussin, J.K., J.C.J.H. Aerts & W. Botzen, 2012. Incentives for Damage mitigation through the French Insurance system. In review for Natural Hazards.
- Ward, P.J., W.P. Pauw, A.W. van Buuren & M.A. Marfai, 2013. Governance of flood risk management in a time of climate change: the cases of Jakarta and Rotterdam. Environmental Politics, doi:10.1080/09644016.2012.683155.
- Ward, P.J., H. de Moel & J.C.J.H. Aerts, 2011 How are flood risk estimates affected by the choice of return-periods? Natural Hazards and Earth System Sciences, 11, 3181-3195, doi:10.5194/nhess-11-3181-2011.
- Poussin, J., P.J. Ward, P. Bubeck, L. Gaslikova, A. Schwerzmann & C.C. Raible, 2011. Flood risk modelling. In: Aerts, J., W. Botzen, M. Bowman, P.J. Ward & P. Dircke, P. (eds.), Climate adaptation and flood risk in coastal cities. Oxford, Earthscan.
- Veldkamp, T.I.E & P.J. Ward, 2010. Onderzoek naar adaptatiemogelijkheden voor verminderen risico’s op overstromingen. H2O, 17, 4-5.

# 2 Study area and past research

The Meuse is a predominantly rain-fed river with a length of ca. 875 km from its source in France to its outlet in the Netherlands (Figure 2.1). The catchment extends over parts of Belgium, France, Germany, Luxembourg, and the Netherlands, and has an area of ca. 33,000km$^2$. The Meuse basin is one of the most densely populated areas of western Europe, and is inhabited by about 9 million people. The river itself is navigable and provides drinking water for about 6 million inhabitants [De Wit et al., 2007].

The mean annual discharge of the Meuse and its associated canals at the border of Belgium and the Netherlands is ca. 276 m$^3$s$^{-1}$; summer and winter half-year mean discharges are 146 m$^3$s$^{-1}$ and 406 m$^3$s$^{-1}$ respectively [Ashagrie et al., 2006]. The Meuse has a relatively rapid response to rainfall, so it is relatively sensitive to floods [Van Pelt et al., 2009]; flood waves mainly occur during the winter half-year.

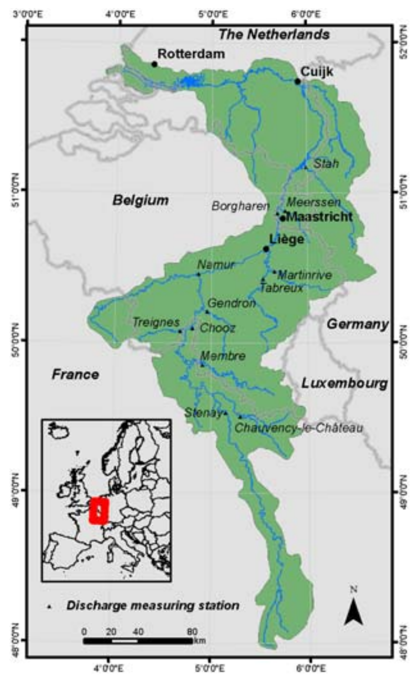



Figure 2.1: Map showing the location of the Meuse basin (Data source: RWS Limburg/IWACO, 2000). The inset shows the location of the Meuse basin in Europe

Detailed descriptions of both the physical and socioeconomic characteristics are available elsewhere; for detailed information the reader is guided to De Wit [2008], Woelders & De Keizer [2009], and Drogue et al. [2010].

## 2.1 Past studies

Since the floods of 1993 and 1995, considerable research has been carried out to examine the past and future climatology of the Meuse basin and the hydrological response of the Meuse river [Aerts et al., 2006; Booij 2005; Bultot et al. 1988, 1990; De Wit et al. 2001, 2007; Gellens, 1991; Gellens and Roulin 1998; Giorgi and Coppola 2007; Kwadijk and Rotmans 1995; Leander et al., 2008; Middelkoop et al. 2004; Pfister et al., 2000; Tu, 2006; Van den Hurk et al. 2007; Van Deursen and Middelkoop, 2002; Vanneuville and Holvoet, 2009; Van Pelt et al., 2009; Ward et al., 2007, 2008, 2011b; see also review in Woelders & De Keizer, 2009. Although there are differences in the results, most studies suggest that the frequency of floods will increase in the future due to climate change.

Notably, the analysis of the effects of climate change developed within the AMICE project (Drogue et al., 2010), gives a wider range including a possible decrease of floods in the future. This is mainly due to the inclusion of (dryer) climate models/scenarios used in France. The AMICE consortium also studied the effect of climate change on water levels in the international Meuse River applying the French, Walloon and Dutch hydrodynamic models (Detrembleur et al., 2011). In the Walloon case a 2-dimensional stationary model was used and in the French and Dutch cases a 1-dimensional non-stationary model. For selected hotspots, including Liege and Namur, inundation areas have been calculated.



In spite of the large number of studies described above, there are fewer studies assessing flood risk. Risk estimates for Dutch dike ring areas in the downstream region have been made in several major projects: Floris [Ministry of Transport, Public Works and Water Management, 2005]; Nederland Later [Klijn et al., 2007]; and Attention to Safety [Aerts et al., 2008]; and other scientific studies [Alkema and Middelkoop, 2007; Bouwer et al., 2009, 2010; De Moel et al., 2011]. However, none of these studies examined the Dutch Meuse upstream from river kilometre 166 (near Cuijk). Far fewer studies have examined the upstream area of the Meuse from river kilometre 166. Wind et al. [1999] report on observed damages in Dutch Limburg following the flood events of 1993 and 1995, based on damage assessments commissioned by the Dutch government. Several studies have modelled economic damage for relatively small sections of the river [Ernst et al., 2010; Van der Sande et al., 2003], but large scale model assessments remain elusive.

## 2.2 The AMICE project

THE AMICE project is part of the European INTERREG IVB program involving more than 17 universities, institutes, and local and national governments from France, Belgium, Germany and the Netherlands. The International Meuse Commission hosts the Partners' meetings and acts as an observer. The project started in 2009 and will finish in 2013. Its main objectives are: (a) to define a common adaptation strategy to the impacts of climate change on floods and drought; b) to realise a set of measures beneficial and transferable to the whole Meuse basin; (c) to strengthen and widen the partnership of stakeholders in the international Meuse basin; and (d) to involve the population and the public bodies through a better knowledge and the feeling of belonging to the Meuse basin, as well as the consciousness of flood and drought risks.

The first objective, elaborated in Work Package 1, includes studies on the effect of climate change on river discharges, in particular floods and low flows, flood and drought damage, and a roadmap towards climate adaptation. As methodologies and approaches were found to be rather different between the four countries, the main outcome may be the sharing and integration of nationally used methodologies related to climate change and hydrology.

# 3 Overall research approach and description of models

One of the original aims of this study was to examine whether the flood damage modelling approach developed for the Rhine basin, and applied in the Knowledge for Climate project HSGR02, could be easily transferred to the Meuse basin.

Detailed descriptions of this approach can be found in Bubeck et al. [2011] and Te Linde et al. [2011]. In brief, the method involves using the Damagescanner model to estimate the potential damage for several different inundation events and for several scenarios of climate and land use change. The inundation events were derived from maps available for the entire Rhine basin, showing inundation depths per grid-cell for several return-periods, namely 10 years, 100 years, and "extreme". Te Linde et al. [2011] used a rainfall-runoff model (HBV) to estimate how these flood probabilities would change under two future climate change scenarios. Land use maps for the years 2000 and 2030 were derived from the Landuse scanner model [Hilferink and Rietveld, 1999].

## 3.1 Application of HSGR02 approach to Meuse basin

In order to apply the aforementioned approach directly to the Meuse, the main data required are land use maps and inundation maps for the entire basin. However, as discussed in Section 2, there are currently no inundation maps available for the entire Meuse basin. Moreover, the approach used in HSGR02 actually only examined changes in flood damage for several different flood events, and did not assess risk in terms of expected annual flood damage (see Section 3.3.3). In the present study, we strived to develop methods to assess this risk, rather than the damage for several discrete events. For these two reasons (i.e. lack of existing inundation maps for the entire Meuse basin and our aim to develop estimates of flood risk in terms of expected annual damage, rather than for several discrete events), we could not carry out a straightforward application of the HSGR02 approach for the entire Meuse basin. Hence, we decided on the overall research approach outlined below.

## 3.2 Outline of research approach

Given the lack of existing inundation maps for the entire Meuse basin, we developed a simple rapid inundation model for river-valley flooding. The model, Floodscanner, was first setup and validated for current conditions in the Meuse in Dutch Limburg (Section 4), and used to assess which return periods should be used to derive a reasonable estimate of risk (Section 5). Following this setup and validation, we coupled Floodscanner to the Damagescanner, to estimate the impacts of climate and land use change on flood risk in Dutch Limburg (Section 6).We also used the models to assess how several adaptation strategies could reduce future flood risk. The modelling chain was then applied to the entire Meuse section from the source in France to Cuijk in the Netherlands (Section 7) to provide a quick-scan assessment of flood risk at the basin scale. We also contributed damage estimates for the Netherlands to the EU project AMICE (www.amice-project.eu), using both: (a) the Damagescanner approach; and (b) the AMICE common approach. For full results of AMICE, the reader is referred to aforementioned website.



## 3.3 Existing models used in this project

In the following paragraphs, we briefly describe the main existing models used in this project, namely the Damagescanner and the Landuse Scanner. Since both models are described extensively elsewhere, we only provide a general overview here, and provide references for the reader to find full details.

### 3.3.1 Damagescanner

We used Damagescanner [Aerts et al., 2008; Klijn et al., 2007] to calculate the potential direct economic damage for floods of different return periods in current conditions (2000), and in the year 2030 under two scenarios of climate and land use change. Damagescanner has been described in several studies [e.g. Aerts and Botzen, 2011; Bouwer et al., 2009, 2010; De Moel et al., 2011; Te Linde et al., 2011].

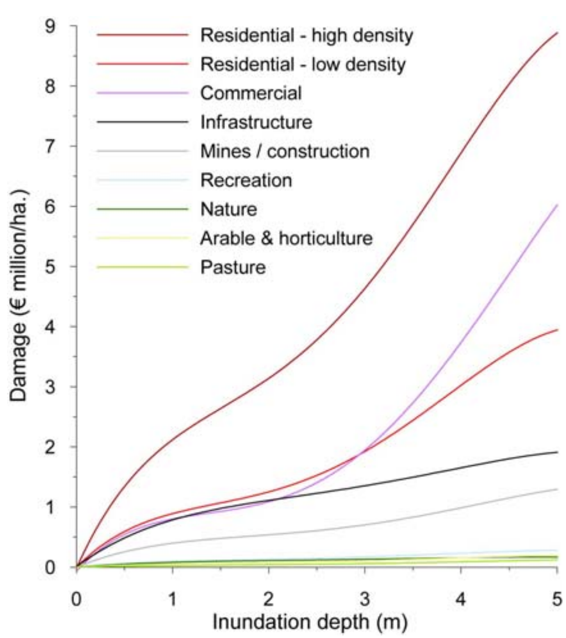



Figure 3.1: Stage-damage functions used in the Damagescanner

Damagescanner needs two inputs: a land use map and an inundation map. The land use maps used in this study were derived from the Landuse scanner model (see Section 3.3.2). The maps show land use at a spatial resolution of 250 m x 250 m, but were resampled onto a grid with 50 m x 50 m spatial resolution in order to use it in Damagescanner. The inundation maps show inundation depths (in centimetres) per grid-cell for different flood scenarios. The inundation maps are at the same resolution as the land use maps, i.e. 50 m x 50 m.

Damagescanner combines information on land use and inundation depth using stage-damage functions (SDFs), which estimate the expected damage for a given inundation depth (x-axis) and a given land use (different curves) for each grid-cell; the SDFs used by Damagescanner are shown in Figure 3.1.

### 3.3.2 Landuse Scanner

Land use maps for the years 2000 and 2030 were derived from the Landuse scanner model [Hilferink and Rietveld, 1999; Loonen and Koomen, 2009]. The Land Use Scanner simulations used in this study were developed for the Rhine and Meuse basins, and are described in greater detail in Te Linde et al. [2011].



Each map represents the allocation of 13 land uses, from residential areas of high and low density, to commercial, infrastructure, mines, recreation, nature, agriculture, cultivation, pasture, and inland water. The future land-use maps are based on two future socio-economic scenarios, the “Global Economy” (GE) scenario and the “Regional Communities” (RC) scenario, which are comparable to the A1 and B2 scenarios developed by the IPCC [IPCC, 2000] respectively.

### 3.3.3 Flood risk estimation

In this study we express flood risk as the average expected annual flood damage. This is represented conceptually in Figure 3.2, whereby the total risk is represented by the integral of the area under the exceedance probability-damage curve (risk curve).

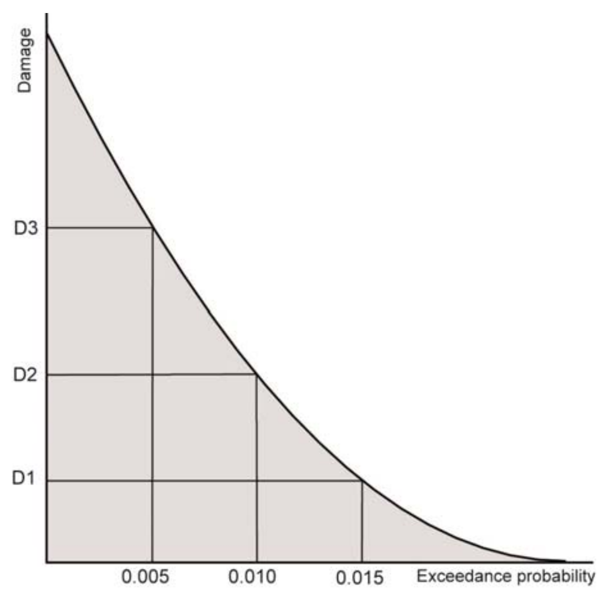



Figure 3.2: Theoretical risk curve; the area under the curve (in grey) represents the risk, expressed as the average expected annual damage

# 4 Floodscanner: setup and validation

## 4.1 Floodscanner: methodological framework

Floodscanner is a rapid inundation model using the zero-dimensional planar-based approach [Priestnall et al., 2000]. Its setup and development are described in detail in Ward et al. [2011a].



In brief, Floodscanner is raster-based, with a spatial resolution of 50 m x 50 m. It uses stage-discharge relationships to estimate the water level at each river grid-cell within a case-study region. These water levels are then assigned to the nearest non-river grid-cells, creating a planar surface representing the water level. This planar surface is intersected with a DEM, and the inundation depth is the difference between the cell values of water level and elevation. Several steps are required to carry out the simulation: (a) derive river network raster; (b) develop stage-discharge relationships; (c) simulate planar water level surface; and (d) estimate flood inundation depth.

a) *Derive river network raster*: We derived the river network from elevation data used in the WAQUA Meuse model (version 2005-02, J09_4), supplied by RWS Limburg. For areas outside the configuration, we used the AHN5 (Actueel Hoogtebestand Nederland) DEM. The DEM was regridded to a resolution of 50 m x 50 m.
b) *Develop stage-discharge relationships*: Stage-discharge (*Q*-*h*) relationships show the relationship between river stage (*h*) at a given point and discharge (*Q*) at that or another point [Braca, 2008]. For this study we used relationships derived from WAQUA, in the form:

   $$h = aQb \quad (1)$$

   where *h* is the water level (m.a.s.l. NAP), *Q* is the discharge, and a and b are coefficients empirically derived from the data described above.
c) *Simulate planar water level surface*: discharge at Borgharen (upstream) is given as input. The model estimates the corresponding water level at each downstream river grid-cell based on the *Q*-*h* relationships. All grid-cells in the study area are assigned to their nearest river grid-cell based on the Euclidean distance, resulting in a theoretical planar water-level surface.
d) *Estimate flood inundation depth*: The elevation of each grid-cell is subtracted from the planar water level surface, to give theoretical inundation depths per grid-cell. Inundated cells not connected to the river via a flow-path with direct connectivity (in at least one of 8 directions) are removed.

Note that the Floodscanner extrapolates river levels to the flood plain and does not account for the corresponding water volume.

## 4.2 Validation

### 4.2.1 Floodscanner results

We validated Floodscanner by comparing: (a) our inundation extent maps with observed inundation extents for the floods of 1993 and 1995; and (b) our inundation depth maps with those produced using WAQUA for RWS Limburg.

Maps showing the inundated area during the 1993 and 1995 floods were provided by RWS Limburg; these floods were associated with discharges at Borgharen of 3120 $m^3s^{-1}$ and 2861 $m^3s^{-1}$ [Wind et al., 1999]. Hence, we used these discharge values to force Floodscanner and derive modelled inundation maps (see Figure 4.1). In Table 4.1 we show the number of cells inundated in: the observed datasets only; the modelled datasets only; and both datasets. The agreement between the datasets is strong. Figure 4.1 shows only a few locations with large differences. For example, the modelled maps show an inundation area at the confluence of the Niers tributary and the Meuse (blue circles in Figure 4.1), showing that the simplified model has difficulty in dealing with hydraulically complicated backwater effects. A second source of anomalies is around several of the new 'Maasplassen'; these lakes were created by sand and gravel mining, and some were completed after 1995 (e.g. the Lange Vlieter; red circles in Figure 4.1). Hence, these lakes are 'inundated' in the model, but were not inundated in 1993 and 1995 because at that time the gravel and sands had not been extracted.



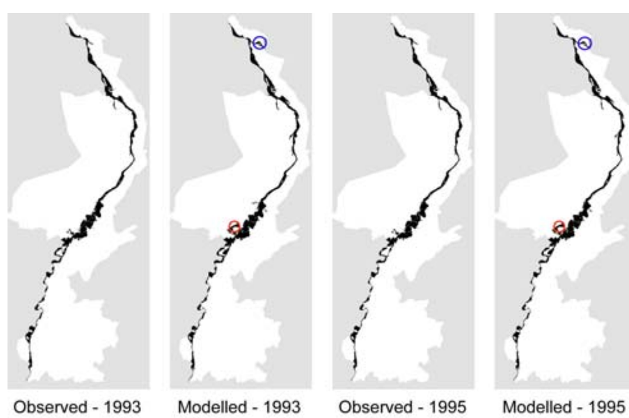



Figure 4.1: Inundation extent maps based on aerial photography and satellite imagery (observed) and Floodscanner (modelled) for the floods of 1993 and 1995. The circles show two locations at which the model did not perform well (blue: confluence of the Niers and the Meuse rivers & red: the lake known as the Lange Vlieter, completed post-1995).

Table 4.1. Number of inundated cells in the observed dataset, the modelled dataset, and number of cells that are inundated in both datasets. The grid cells have a resolution of 50m x 50m.

| | **Number of inundated cells** | | |
|---|---|---|---|
| **Year** | **Observed data only** | **Modelled data only** | **Both datasets** |
| 1993 | *48,867* | *53,291* | *47,497* |
| 1995 | *47,639* | *51,982* | *46,511* |

Next, we compared the simulated inundation depths with those simulated using WAQUA for RWS Limburg. The WAQUA results were provided by RWS Limburg for the following return periods: 2, 5, 20, 75, 250, and 1250 years. Depth anomalies per grid-cell (Floodscanner minus WAQUA) are shown in Figure 4.2, and are discussed in detail in Ward et al. [2011a]. Floodscanner overestimates mean inundation depths at very low return periods (2 years), has little bias at medium return periods (up to 20 years) and slightly underestimates mean inundation depths at high return periods (from 75 years upwards) with respect to the WAQUA estimates. Overall, for the return periods shown, the anomaly is ≤0.5 m for 71% (RP = 1250 years) to 93% (RP = 75 years) of the cells; and the anomaly is ≤1 m for 91% (RP = 1250 years) to 97% (RP = 20 years) of the cells. This is encouraging, since research carried out by De Moel and Aerts [2011] in the Netherlands shows that an overall change in inundation level by 0.5 m may lead to a change in damage by a factor of 1.35-1.44, whilst an overall change in inundation level by 1 m may lead to a change in damage by a factor of ca. 2.



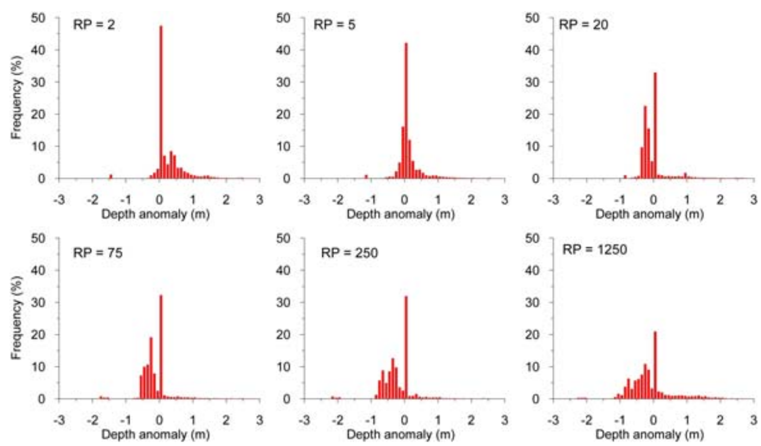



Figure 4.2: Frequency distributions (%) of the differences between the inundation depths (in metres) per grid-cell from the inundation maps produced using Floodscanner minus the WAQUA inundation maps for different return periods (RP).

### 4.2.2 Floodscanner-Damagescanner results

We also validated the results of the coupled Floodscanner-Damagescanner system by using the Damagescanner model to calculate damage for several return periods based on inundation maps from both: (a) Floodscanner; and (b) official flood inundation maps ('Risicokaart') for the Meuse (provided by RWS Limburg) (Table 4.2). In general, the data show reasonable agreement.

Table 4.2: Total damage simulated using Damagescanner with inundation maps of Floodscanner and Risicokaart: for both sets of inundation maps the results are shown for three return periods (RP).

| | **Total damage (€ million)** | | |
|---|---|---|---|
| | **RP = 100 years** | **RP = 945 years** | **RP = 1250 years** |
| Risicokaart | *408* | *2167* | *2505* |
| Floodscanner | *279* | *2144* | *2281* |

We also compared the results of the coupled Floodscanner-Damagescanner model with estimated damages in Dutch Limburg following the flood events of 1993 and 1995 from Wind et al. [1999], based on damage assessments commissioned by the Dutch government. They found losses of €149 million and €91 million respectively, compared to €283 and €238 for our model. Most of this difference can be attributed to difference in agricultural damages. Wind et al. [1999] report damages to “Agriculture and horticulture” almost ten times less than our simulated agricultural damages. To some extent, we would expect the modelled damage in the agricultural classes to be higher than the reported values, since Damagescanner also accounts for damage to buildings (e.g. residential houses) located on cells designated as agriculture on the land use map. However, the discrepancy is very large. In terms of damage to crops, the SDFs used in Damagescanner assume that the harvest is lost at maximum damage. In reality, the damage that would actually occur is highly dependent on the season in which a flood occurs [Förster et al., 2008]. Since most floods of the Meuse River occur during the winter season, this means that the standard SDFs will overestimate damage to agriculture. Damagescanner could be improved by integrating information on the seasonal distribution of agricultural losses. A more detailed discussion of the differences is provided in Ward et al. [2011a].

## 4.3 Uses and limitations

The flood inundation model developed above is simplified for use in rapid calculations. The simplifications also dictate the application of the method. Floodscanner is certainly not intended to replace the need for hydraulic modelling with more complex models. This approach is neither suitable for localised flood risk assessments (e.g. street to city scale), nor for presenting flood risk at the grid-cell level. Flood damage estimates at such fine resolutions need to employ more state-of-the-art methods that have been clearly designed for those applications [e.g. Ernst et al., 2010]. A more comprehensive discussion of limitations can be found in Ward et al. [2011a].

Rather, the approach should be complementary to such methods for use in reach-to-basin scale studies. In addition, the model is useful for Monte Carlo based uncertainty analyses, the evaluation of combinations of many different future projections, and probabilistic impact assessments. Indeed, the model has subsequently been applied to the Rhine basin to develop probabilistic scenarios of flood risk under climate change [Ward et al., 2011c, 2012].

# 5 How are flood risk estimates affected by the choice of return periods?

In an ideal situation, flood risk estimates would be based on damage estimates for hundreds to thousands of return periods. However, the production of flood hazard maps is time-consuming and expensive [Gouldby and Kingston, 2007; Apel et al., 2008], so in practice only a few return periods are used. For example, in the flood EFD, member states are obliged to create flood maps for three flood classes (low, medium, and high probability) [De Moel et al., 2009]. By developing a rapid inundation model, we were able to address a key question ignored in almost all flood risk studies, namely how is the flood risk estimate affected by the choice of return periods used to estimate the flood risk curve?



## 5.1 Methods

To estimate the effects of the choice of return periods on the overall flood risk estimate, we first calculated flood damage for all return periods between 2 and 10,000 years, with intervals of 1 year. We then estimated risk based on the damage estimates for all of these return periods, and compared this to estimates based on only a limited number of return periods.

The damage estimates for each return period were carried out using the coupled Floodscanner-Damagescanner models described previously. The discharge at Borgharen for each return period, required as boundary input to Floodscanner, was calculated using standard formulae provided in the HR2001 guidelines [Van de Langemheen and Berger, 2001]:

For $2 \leq RP \leq 250$, $Q = 352.9 * \ln(RP) + 1329.6$ (2)

For $250 \leq RP \leq 10{,}000$, $Q = 324.4 * \ln(RP) + 1486.8$ (3)

where $RP$ is the return period (yrs) and $Q$ is the discharge at Borgharen ($m^3s^{-1}$).

## 5.2 Results

We first calculated flood risk based on damage estimates for all return periods of 2 to 10,000 years, with intervals of 1 year. We assumed damage at bankfull discharge (RP = 1.5 years) to be zero, and included this in the risk curve. This resulted in an estimated risk of €34 million p.a.; see Figure 5.1. Note the step-change in damage at a return-period of 250 years (exceedance probability = 0.004); this is due to the fact that the dike-ring areas are nominally protected up to this return-period, and therefore we have assumed no inundation in those areas for discharges with a lower return-period.

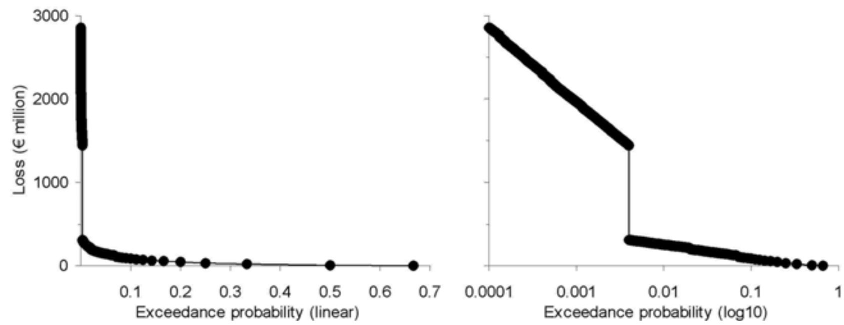



Figure 5.1: Risk curve for flood losses with return-periods from 2 to 10,000 years. The curve is shown with exceedance probability on a linear scale (left) and logarithmic scale (right). The area under the curves is the expected annual damage, or risk; in this case ca. €34 million p.a.



### 5.2.1 Effect of selection of three return periods on annual risk

We then tested how the above risk estimate compares to an estimate based on three flood hazard maps (low, medium, and high probability), i.e. as required by the European Flood Directive (2007/60/EC). For high probability, we used a return period of 10 years, for medium probability 250 years (assuming the small dike rings would not flood); and for low probability 1250 years (since this is the design standard for river flood protection downstream from Dutch Limburg). Again, we assumed zero damage at bankfull discharge, enabling us to make the risk calculation upwards from zero damage. This resulted in an estimate of risk of ca. €47 million p.a., i.e. 38% higher than that based on the damage estimate for 10,000 return periods.

We then carried out sensitivity analyses to examine the effects of using different return periods for the low and high probability events, but still using three return periods to estimate risk. We varied the return-period of the high probability flood between 2 and 25 years, and the low probability flood between 500 and 10,000 years (both with intervals of one year). The minimum risk estimate based on all combinations of these values is €44 million p.a., whilst the maximum is €67 million p.a. Hence, the selection of these three data points always led to a higher estimation of risk compared to the estimate made with all return periods from 2 to 10,000 years. This is mainly caused by the fact that the risk curve between return periods of 2 to 250 years is highly concave, and therefore a linear interpolation between these points (as in the former example) results in an overestimation of risk.

### 5.2.2 Effect of choice of highest return period on risk

To assess the effect of the choice of the maximum return period used to calculate annual risk, we calculated risk using different maximum return periods. Starting with a maximum return period of 2 years, risk was calculated using risk curves with successive maximum return periods increasing with 1 year intervals. All data points corresponding to return periods lower than the maximum return period were taken into consideration to estimate the annual risk (Figure 8). For example, for the point on the graph in Figure 5.2 at which maximum return period is equal to 2000 years, we calculated the risk using estimates of damage for all discharges with return periods from 2 to 2000 years inclusive (with a step of one year). This same procedure was carried out up to a maximum return period of 10,000 years. In Figure 5.2, we show how the annual flood risk estimate increases as the maximum return period used to estimate that risk increases. It is interesting to see that the curve flattens off rather abruptly at return periods between 1000 and 2000 years. In fact, when a maximum value of 1250 years is used, the risk is ca. €32 million p.a., i.e. just 5% lower than that using all return periods up to 10,000 years (€34 million p.a.).

Figure 5.2 also shows that the influence of floods with relatively low return periods on the risk is relatively high as risk shows a steep increase for low values of maximum return period used. In other words, low return period floods are responsible for a relatively large part of the total expected annual damage.



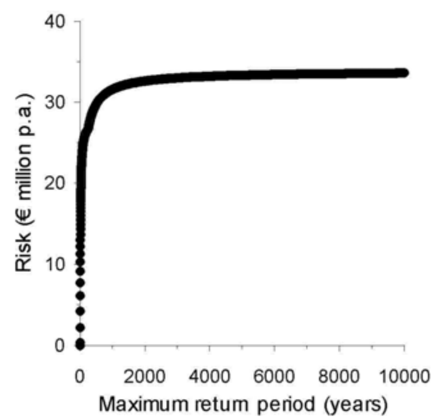



Figure 5.2: Figure showing risk when calculated using different maximum return periods. For example, for the point on the graph at which maximum return period is equal to 2000, we calculated the risk using estimates of damage for all discharges with return periods from 2 to 2000 years inclusive (with steps of one year).

## 5.3 Implications for flood risk assessment

The majority of flood risk studies use damage estimates for a small number of return periods to estimate risk. Often three return periods are used, which is the number of flood maps that member states are obliged to create for the European Flood Directive. However, we have shown that risk estimates are greatly affected by the number of data points used to construct the risk curve.

Hence, more attention is needed to identify the return periods required to give a good representation of risk. In this study, we did this by first estimating risk based on all return periods from 2 to 10,000 years (€34 million), and then estimating risk based on a smaller selection of inundation maps so that the overall risk estimate was similar to that of the former estimate. This resulted in the selection of nine inundation maps for return periods of 2, 5, 10, 20, 50, 100, 250, 251, and 1250 yrs. For this combination of return periods, the calculated risk is €32 million per year. Inundation maps for these return periods are used to calculate damage and risk in the subsequent chapters of this report.

# 6 Flood risk in Dutch Limburg: future scenarios and the impact of adaptation strategies

In this section, we use the approach described in the previous sections to assess the sensitivity of flood risk in the Meuse basin in Dutch Limburg to changes in climate and land use between 2000 and 2030. We then assess to what extent various adaptation measures can reduce Meuse flood risk. A more detailed description of methods and results can be found in Poussin et al. [2012].



## 6.1 Sensitivity of flood risk to changes in land use and climate

We calculated flood risk in 2000 and in 2030 under various scenarios of land use and climate change, using Damagescanner, and then examined how the risk will change over that period according to these projections

### 6.1.1 Scenarios

*Land use*

Land use in 2000 was represented using a reclassified CORINE Land Cover map for 2000. For 2030, we used land use maps from a Landuse Scanner (Section 3.3.2) simulation carried out for the Rhine and [Te Linde et al., 2011] for two socio-economic scenarios, namely Global Economy (GE) and Regional Communities (RC). Here, we refer to the GE scenario as ‘land use 2030 high’, and RC as ‘land use 2030 low’.

*Climate*

We used two scenarios of climate change for 2030, based on the Dutch G and W+ KNMI’06 scenarios (Van den Hurk et al., 2006). The G scenario assumes a lower level of climate change than the W+ scenario, so we here refer to them as ‘climate low’ and ‘climate high’, respectively. The KNMI’06 scenarios are available for 2050, but we adapted these to 2030 so as to correspond with the land use maps by assuming a linear rate of change between 2000 and 2030. The climate scenarios were used to simulate daily discharge time-series at Borgharen using the HBV model. From this, discharge magnitudes for different return periods were derived by fitting a Generalised Extreme Value (GEV) distribution to each discharge time-series (Drogue et al., 2010). These were then used to force Floodscanner, and to derive inundation maps for several return periods for each scenario. Since we have shown in Section 5 that the selection of return periods used to calculate risk has a large influence on the final risk estimate, we selected several return periods which led to a similar risk estimate as using all return periods. This resulted in the selection of inundation maps for return periods of 2, 5, 10, 20, 50, 100, 250, 251, and 1250 yrs. The simulated discharge at Borgharen corresponding to each of these return periods used in this study, and for the three climate scenarios are shown in Table A2.1 (Annex 2).

*Combined land use and climate change scenarios*

To assess the combined effects of land use and climate change, we linked the climate 2030 low (G) with the land use 2030 low scenario (RC), and the climate 2030 high (W+) with the land use 2030 high scenario (GE) [see also Bouwer et al., 2010], referring to these as 2030 low and 2030 high, respectively.

### 6.1.2 Results



Simulated risk in the 2000 scenario is €31 million per year. The relative percentage change in risk between the 2000 and 2030 scenarios is shown in Table 6.1, without implementing any additional measures. Compared to 2000, the 2030 low scenario shows a risk increase of 97%, and the 2030 high scenario shows and increase of 185%. The impacts of land-use change alone are increases in risk of 64% and 108% for the 2030 low and 2030 high scenarios, respectively, whilst the impacts of climate change alone are increases in risk of 20% and 37%. Hence, over this time-period, the projected relative influence of land-use change on overall risk increase is about three times greater than that of climate change.

Table 6.1: Increase in annual expected damage (risk) (in percentages), for the future scenarios (climate and/or land use) for 2030 compared with the 2000 scenario.

| | **Risk increase (%)** | | |
|---|---|---|---|
| **Scenario** | **Climate 2000** | **Climate 2030 low** | **Climate 2030 high** |
| **Land use 2000** | *N/A* | *20* | *37* |
| **Land use 2030 low** | *64* | ***97*** | *N/A* |
| **Land use 2030 high** | *108* | *N/A* | ***185*** |

## 6.2 Risk reduction through adaptation

Following discussions with RWS Waterdienst, it was agreed that this study should examine the potential effectiveness of several spatial zoning and mitigation measures in reducing risk, rather than focusing on measures to reduce flood hazard, which have been well studied in previous research. The measures, and their implementation in Damagescanner, are described below.

### 6.2.1 Adaptation strategies in Damagescanner

*Spatial planning*

Landuse Scanner simulations are based on projected socio-economic development, and while spatial regulations are included via the socioeconomic scenarios, specific local and regional spatial planning measures and restrictions are not included. Hence, in some areas the model may simulate urban development whilst in reality this may be an area in which such development is not allowed under local or regional spatial planning regulations. Examples of such locations were noted and discussed during our stakeholder workshop. Hence, we decided to examine the potential effects on risk of an ongoing spatial zoning project. In the Province of Limburg, a spatial zoning project is being carried out in accordance with the 'Beleidslijn Grote Rivieren (BGR)' and the 'Beleidsregels', a Dutch law and the corresponding rules that are meant to limit and regulate developments in Dutch flood-prone areas. RWS Limburg provided GIS maps showing areas where either: (0) there are no restrictions; (1) new buildings and developments are not allowed, except if they are river-bound (e.g. harbour); and (2) new buildings and developments are allowed under certain conditions, such as compensating for the loss of volume of water. To assess the effectiveness of these measures in reducing flood risk, we adapted the land use 2030 maps to reflect the information contained in the BGR zoning maps. For instance, areas shown in the BGR zoning maps to be planned to remain as they are now in the future (e.g. nature or agricultural fields), are sometimes projected to undergo new urban developments in Landuse Scanner. Hence, we modified such areas in the land use 2030 maps by reclassing new urban areas with the land use from the land use 2000 map.

*Flood damage mitigation measures*

To assess the effectiveness of flood-damage mitigation measures on risk in residential areas, we investigated three mitigation strategies in Damagescanner: (a) 'dry-proofing'; (b) 'wet-proofing'; and (c) 'combination of dry- and wet-proofing'. To implement these in Damagescanner, we developed damage reduction factors (0-1) to represent the proportion of damage that could be avoided at each inundation depth if they were applied. These damage reduction factors are used to adjust the original SDFs in Damagescanner. The factors are based on a literature review, and are described in Annex 3.

### 6.2.2 Results

*Risk-reduction capacity of spatial zoning measures*

Table 6.2 shows the change in risk between 2000 and 2030 when the land-use 2030 maps are adjusted to include the spatial zoning. The impact of land use change on risk is much lower when the spatial zoning is included. Compared with the 2000 scenario, land-use change alone now leads to an increase in risk of 23% for the 2030 low scenario, and 17% for the 2030 high scenario. Now, the results show that the increase in risk between the 2000 scenario and the 2030 low scenario is almost equally due to the changes in land use and climate. However, the same is not the case for the increase in risk between the 2000 scenario and the 2030 high scenario. In the latter case, the relative impact of climate change is higher than that of land-use change. The values in brackets

Table 6.2: Increase in risk (%) compared with the 2000 scenario for low and high climate and land-use scenarios, including spatial zoning. In brackets: risk-reduction capacity (%) of the BGR zoning, where the risk results with zoning are compared with the risk results without zoning, for the same scenarios



| | **Risk increase (%)** *(Risk reduction of spatial zoning - %)* | | |
|---|---|---|---|
| **Scenario** | **Climate 2000** | **Climate 2030 low** | **Climate 2030 high** |
| **Land use 2000** | N/A | **20** *(0)* | **37** *(0)* |
| **Land use 2030 low** | **23** *(25)* | **48** *(25)* | N/A |
| **Land use 2030 high** | **17** *(45)* | N/A | **60** *(44)* |

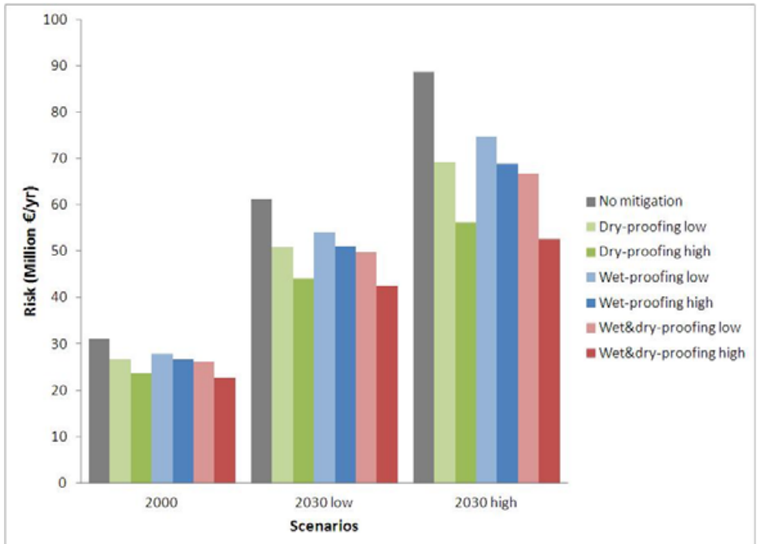
show the risk reduction of the spatial zoning when the results are compared with the risk without zoning for the same scenario (for instance, the risk for the 2030 low scenario with zoning is compared with the risk for the 2030 low scenario without zoning). We refer to these results as the risk-reduction capacity of the measures. In this case, spatial zoning alone would decrease risk by 25% for the low scenarios, and by up to 45% for the high scenarios.

*Risk reduction capacity of mitigation measures*
In Figure 6.1, we show the estimated flood risk for the different mitigation strategies, assuming them to be applied to all households. Although such a wide implementation is probably not feasible in practice, this calculation provides a maximum potential risk reduction. The absolute estimates are subject to high uncertainty, but the relative changes between the 2000 and 2030 scenarios give an indication of the order of magnitude of the potential risk change. The projected increase in risk due to land use and climate change (without adaptation) is not entirely compensated by the mitigation strategies; however, the strategies would decrease the risk from €61 and €89 million per year for the 2030 low and 2030 high scenarios, respectively, to about €43 and €53 million per year when the wet&dry-proofing strategy is implemented. In relative terms, the reduction in risk ranges from 10% for the wet-proofing strategy (when applied to the 2000 scenario) up to 40% for the wet&dry-proofing strategy (when applied to the 2030 high scenario).

Since an implementation of the strategies in all households would not be feasible in practice, in a second step we applied the mitigation factors only to projected new residential areas in 2030. Accordingly, the risk results are higher and range from €53 to €70 million per year, while the risk reduction percentages are lower, ranging from 7% to 21%, (compared with 10% to 40% for all residential areas that are flood-proofed). The damage reduction induced by the mitigation strategies for the 2030 high and 2030 low scenarios are as high as 25% and 14%, respectively, compared with the same scenario without mitigation.

Figure 6.1: Flood risk estimates for the 2000 scenario and the 2030 low and high scenarios (in million Euros per year), for different mitigation strategies applied to all residential buildings.

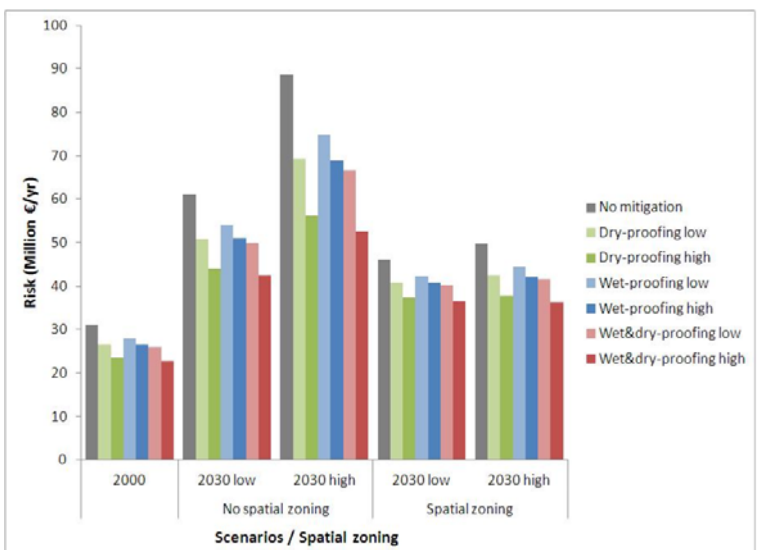





*Risk-reduction capacity of combined spatial zoning and mitigation measures*

The BGR spatial zoning measures were combined with the mitigation measures to assess the potential impact of the combined strategies (Figure 6.2). The combination of spatial zoning and mitigation measures could decrease risk in 2030 by about 40% for the 2030 low scenario (from €61 to €36 million per year), and 60% for the 2030 high scenario (from €89 to €36 million per year).

Figure 6.2: Risk results for low and high climate and land-use scenarios (in million Euros per year), for the different adaptation strategies (i.e. spatial zoning and mitigation measures) applied to all residential areas




*Geographical distribution of flood risk*

In Figure A4.1 (Annex 4), selected results are shown spatially per municipality, namely risk in million Euros per year without adaptation strategies, and the risk-reduction capacity of the following adaptation strategies: spatial zoning measures alone; dry-proofing strategy alone; and wet-proofing strategy alone.

## 6.3 Implications

According to the scenarios used in this study, between 2000 and 2030 the relative influence of projected land use change on risk increase is about three times greater than that of climate change. This is an important finding, since local and regional stakeholders have more control over land use distribution than over the evolution of the climate. Adequate land-use management could significantly decrease the overall risk compared with a situation without these measures. Indeed, when the ongoing spatial zoning is included in the simulations, risk is significantly decreased.



This study also shows that the maximum risk-reduction capacity of the mitigation strategies is up to 21% and 40%, when implemented only on new buildings in 2030 and in all residential units, respectively. Also, the dry-proofing strategy is more effective in reducing the risk than the wet-proofing strategy. This result differs from the findings of Kreibich et al. [2005] and Kreibich and Thieken [2009], which are based on past floods of the Elbe river in Dresden, Germany. However, the difference with our results could be related to the fact that the flood of 2002 was an extreme event and private water barriers were overtopped, and had no or little effect [Kreibich et al., 2005].

The already planned spatial zoning measures, combined with theoretical mitigation measures, could significantly decrease future flood risk, by up to 45%. After carrying out preliminary analyses, a workshop was held in Limburg with several regional decision makers to discuss the results, and refine the methods for the final analyses. During the workshop, an important remark was made that there are currently no legal means in Limburg, and in the Netherlands, to enforce the undertaking of mitigation measures by households. Further discussion would therefore be needed before the implementation of these measures could be considered. It would be useful to assess methods to stimulate households to implement measures. Incentives include measures such as limiting the financial intervention of governments to incite households to take measures prior to floods instead of relying on their government's help after the flood [Kunreuther, 2006]; regulating constructions with building codes [Camerer and Kunreuther, 1989; Kunreuther, 2006]; providing adequate information to households in flood-prone areas [Camerer and Kunreuther, 1989; Grothmann and Reusswig, 2006; Neuwirth et al., 2000; Sims and Baumann, 1987]. The existing literature on this subject could serve as a useful starting point for such an analysis.

# 7 Flood risk at the basin scale: future scenarios and the impact of adaptation strategies

As part of the AMICE project, flood risk maps have been developed for the entire Meuse basin, showing projected changes in risk between present and 2100 as a result of climate change [Sinaba et al., 2011a]. The risk calculations for AMICE were carried out by separate institutes in each of the riparian states, using a semi-uniform approach developed for the project. For the Dutch section of the Meuse, these calculations were carried out by our consortium, thus increasing interaction between the involved institutes. However, since the results of AMICE have yet to be published, we cannot discuss them here. When the AMICE reporting is completed, these results will be available at http://www.amice-eu.org/.

The risk calculations carried out for AMICE differ in method and concept to the calculations carried out for the present KvK project. Firstly, the AMICE scenarios are based on the national scenarios of the four Meuse countries, and here the Dutch KNMI ’06 scenarios are applied. Secondly, the AMICE scenarios only consider the impacts of climate change on risk, whilst land use change is not taken into account. Thirdly, the large scale (basin scale) impacts of adaptation measures have not been assessed. Fourthly, whilst a uniform damage modelling approach has been developed in AMICE, the hydrological calculations (i.e. inundation modelling) were carried out by institutes from each riparian state, using their own models. Hence, in the present project, we decided to carry out a quick-scan analysis of flood risks in the Meuse basin from the source in France to Cuijk in the Netherlands, using a uniform modelling approach, and including scenarios of both climate and land use change. Moreover, we carried out an assessment of the potential effectiveness of the flood risk mitigation strategies described in Section 6, at this scale. This approach and the results are discussed briefly in this section.

## 7.1 Methods

The methods applied are the same as those described in Section 6. However, the models were run for the entire basin between the source in France to Cuijk in the Netherlands. Hence, we needed to run the Floodscanner inundation model for this entire stretch. To achieve this, it was necessary to (a) derive Q-h relationships at locations over the entire section; and (b) estimate the discharge associated with different return periods at each of those locations, under each climate scenario (2000, 2030 low, and 2030 high). These steps are described below. As stated in Section 4.1, Floodscanner requires a DEM; in this case, we used the SRTM DEM (Jarvis et al., 2008). The DEM has a horizontal resolution of ca. 90 m x 90 m at the equator, and was first resampled to a horizontal resolution of 50m x 50m.

### 7.1.1 Estimating the discharge associated with different return periods

For each river kilometre we derived a stage-discharge curve. For Wallonia, these were taken directly from the schematisation of the SOBEK-Meuse model for the Walloon region (see Figure 7.1). The SOBEK model used was set up by WL|Delft Hydraulics in 1989-1991 (Van der Veen, 2007), and is also described in De Wit et al. (2002); it reflects the situation of the early 1990s. In brief, SOBEK was run with steady-state discharge boundary conditions at Chooz (upstream) with input discharges from 100 $m^3s^{-1}$ up to 4000 $m^3s^{-1}$, with steps of 100 $m^3s^{-1}$. For each discharge boundary condition, the simulation was carried out for 12 days, after which a steady state was obtained at all points. From this, discharge and corresponding water height were evaluated at approximately 1 km distances between Chooz and Borgharen, one hour before increasing the discharge at Chooz. Afterwards, these were linearly extrapolated for all river grid cells between the SOBEK nodes. Hence, the rating curves consist of Q-h value pairs for all river points.

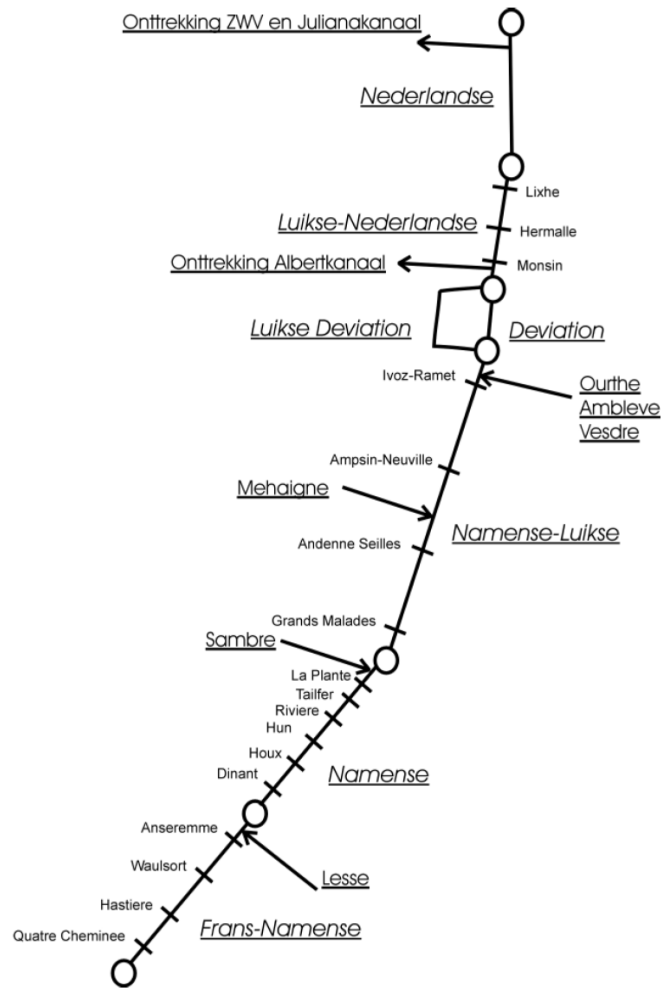



Figure 7.1: Schematisation of the SOBEK-Meuse model, between Chooz and Borgharen (De Wit et al. 2002)

As was the case in Section 6, this was achieved by fitting a Generalised Extreme Value (GEV) distribution to the maximum discharge time-series of Stenay, Chooz, Dinant, Namur upstream, Namur downstream, Monsin and Eysden resulting from a HBV-Meuse simulation for the period 1968 to 1998 (Van Deursen, 2004).

For France, the stage-discharge relationships were derived from observed discharge and water level data available from EPAMA *Banque Hydro* (http://www.hydro.eaufrance.fr/). Data were available for the following gauging stations: Goncourt, Neufchâteau, Domrémy-la-Pucelle, Vaucouleurs, Commercy, Saint-Mihiel, Stenay, Verdun, Sedan, Montcy-Notre-Dame, Monthermé, and Chooz. Between these gauging stations, the data were linearly extrapolated for all river grid cells.

We then estimated the discharge, for each grid-cell, associated with each of the return periods used in this study under the 2000 scenario. Then, we calculated change factors at Borgharen between 2000 and the 2030 scenarios for each of these return periods. Subsequently, these change factors were applied to the discharges under the 2000 scenario at each river grid-cell to derive the input for the 2030 scenarios.

## 7.2 Results



The results in this section should be considered as a quick-scan analysis of the *relative* impacts of climate and land use change on flood risk at the basin scale. The absolute results are subject to large uncertainties, especially since the Floodscanner model used here has not been specifically validated for this region (due to a lack of data for such validation), and does not account for the presence of dikes in the upstream areas. Hence, in this section, we only show the relative change in risk between scenarios.

In Table 7.1, we show the percentage change in risk between 2000 and 2030 under the low and high climate and land use change scenarios. These are shown for the basin as a whole (from the source to Cuijk in the Netherlands), as well as for the Dutch, Belgian, and French parts individually. Note that the results for the Netherlands are somewhat different to those shown in Section 6. This is because the present analysis includes flood damages along the Meuse in the province of North Brabant (between the Belgian-Dutch border and Cuijk), whilst the former only included damages in the Dutch province of Limburg.

At the basin scale, the results suggest that without adaptation measures, risk will increase by 16% in 2030 under the low scenario, and 39% under the high scenario. The relative impacts of projected climate and land use change on this risk increase are of the same order of magnitude. As a result of climate change only, risk is projected to increase by 9% and 18% under the climate 2030 low and high scenarios respectively. In comparison, risk increases by 6% under the land use 2030 low scenario, and by 17% under the land use 2030 high scenario. There are large differences between the countries of the Meuse. Overall, the projected increase in risk is the largest in the Netherlands (66-153%). The total increase for Belgium (13-32%) is similar to that of France (13-36%). Geographical differences per NUTS 3 region are shown in Figures A5.1 and A5.2 (Annex 5). Here, we see that risk is projected to increase under both the low and high scenario in all NUTS regions, except for FR214 (Haute Marne), in which it decreases due to a projected reduction in the residential area located within the flood-prone regions.

Table 7.1: Change in annual expected damage (risk) (in percentages), for the future scenarios (climate and/or land use) for 2030 compared with the 2000 scenario.



| **Risk change (%)** | | | |
|---|---|---|---|
| **Meuse basin (source to Cuijk in the Netherlands)** | | | |
| **Scenario** | **Climate 2000** | **Climate 2030 low** | **Climate 2030 high** |
| **Land use 2000** | *N/A* | *9* | *18* |
| **Land use 2030 low** | *6* | ***16*** | *N/A* |
| **Land use 2030 high** | *17* | *N/A* | ***39*** |
| **Netherlands (from border with Belgium to Cuijk in the Netherlands)** | | | |
| **Land use 2000** | *N/A* | *22* | *41* |
| **Land use 2030 low** | *35* | ***66*** | *N/A* |
| **Land use 2030 high** | *75* | *N/A* | ***153*** |
| **Belgium** | | | |
| **Land use 2000** | *N/A* | *10* | *17* |
| **Land use 2030 low** | *3* | ***13*** | *N/A* |
| **Land use 2030 high** | *12* | *N/A* | ***32*** |
| **France** | | | |
| **Land use 2000** | *N/A* | *1* | *12* |
| **Land use 2030 low** | *12* | ***13*** | *N/A* |
| **Land use 2030 high** | *20* | *N/A* | ***36*** |

It is possible to use the methods developed here to assess the effectiveness of the flood damage mitigation measures discussed in Section 6. In Figures A5.3 and A5.4 (Annex 5) we show the potential risk reduction between the 2030 high scenario with “wet-proofing” and “dry-proofing” respectively, compared to the 2030 high scenario with no adaptation measures. The results show that the potential for risk reduction through such measures is even greater in Belgium than in the parts of the Netherlands discussed previously in Section 6. The potential risk reduction is particularly high for the Wallonia region of Belgium: for dry-proofing 44-46% risk reduction compared to no measures; and for wet-proofing 29-31%. Moreover, the maps show geographical differences in the effectiveness of the dry- and wet proofing measures. The visualisation of such differences could provide valuable information for decision-makers in further workshop settings.



### 7.3 Concluding remarks

The results presented in this section have purposefully been kept brief, since AMICE also assessed flood risk at the basin scale, and will report on these findings shortly. However, our results provide important complementary information. In our project, we have examined the impacts of projected land use change on flood risk, and not only climate change. Moreover, we have assessed the potential risk reduction at the basin scale of the widespread implementation of household level mitigation measures. The reader is once again reminded that the basin scale analyses are expressly intended as a quick-scan of the possible *relative* impacts of climate and land use change on flood risk.

At the basin scale, the impacts of projected land use change on flood risk are of the same order of magnitude as the projected impacts of climate change. Hence, adaptation measures that attempt to reduce risk through spatial zoning deserve more thorough analysis in future studies. Moreover, we show that the potential to reduce flood risk through the widespread implementation of household mitigation measures is large, especially in Belgium. Although we have not addressed the feasibility of such adaptation options, the results serve to demonstrate that such measures do have the *potential* to complement more traditional measures of risk reduction, such as the building of dikes.

# 8 Conclusions

The main questions addressed in this research are:

- What is the sensitivity of flood risk in the Meuse basin to changes in climate and land use
- To what extent can various adaptation measures reduce Meuse flood risk?

In this section we first summarise our findings with regards to each of these questions, before presenting the other main findings of this research. The report concludes with a discussion of the main limitations and recommendations for future research.



## 8.1 The sensitivity of flood risk in the Meuse basin to changes in climate and land use

The first aim was to assess the sensitivity of riverine flood risk in the Meuse to projected changes in land use and climate until 2030.

For Dutch Limburg, we found the combined impact of these factors to be an approximately two- to three-fold increase in risk (by 2030 compared to 2000), with land-use change being the dominant driving factor. For the Meuse as a whole, we found the combined impact of climate and land use change to be an increase in risk between 2000 and 2030 of ca. 16-39% (for the low and high scenarios respectively). At this basin scale, the relative influences of projected climate and land use change are of the same order of magnitude.

These findings highlight the need to implement adaptation strategies to limit the increase in risk. The significance of land use change in driving the increase in risk is an important finding, since local and regional stakeholders have more control over land use distribution than over the evolution of the climate. Adequate land-use management could potentially decrease the overall risk compared with a situation without these measures. Hence, assessments of future flood risk need to consider changes in both of these parameters, instead of focusing on either climate or land use change.

## 8.2 Flood risk reduction capacity of adaptation measures

In this study, we have also assessed the risk reduction capacity of several adaptation measures, namely: spatial zoning and mitigation measures at the household level.

The effects of spatial zoning measures were only analysed for a case study in Dutch Limburg, since information were provided by regional stakeholders on the ongoing BGR zoning. We have shown that the currently ongoing spatial zoning projects can already reduce the increase in risk between 2000 and 2030 by up to 45%.



We have also shown that household level flood mitigation measures could potentially further reduce future flood risk, and limit the risk increase that would occur without their implementation. We specifically examined three strategies, namely dry-proofing, wet-proofing, and the combination of dry- and wet-proofing. We found that all of these strategies can significantly reduce flood risk; this is one of few studies to quantitatively assess the flood-risk reduction capacity of such strategies at the regional scale. Particularly for the Wallonia region of Belgium, the potential risk reduction is high: up to 46% for dry-proofing. However, there are currently few means to enforce or encourage the undertaking of mitigation measures by households. Further research is therefore recommended into methods for motivating the implementation of such measures.

Flood-risk maps, such as those produced in this study, are useful to decision makers for understanding where flood risk hotspots are, and for identifying the strategies most likely to limit the risk in those areas.

## 8.3 Other main findings

Since no inundation maps of the Meuse were available at the basin scale, a simple application of the framework for flood risk assessment developed for the Rhine basin in HSGR02 was not possible. To address this problem, we developed a rapid inundation model for river-valley flooding, Floodscanner, and used this to produce the required inundation maps. Floodscanner performed reasonably well compared to historical floods of 1993 and 1995, as well as compared to results from a process-based 2-D hydrodynamic model (WAQUA). However, 2-D hydrodynamic models will always be better suited for local scale flood risk analysis and Floodscanner does not aim to replace these more detailed process-based models. Rather, it is intended to supplement these existing numerical models for experiments in which a large number of model evaluations are necessary, or for basin scale assessments. Floodscanner could be useful to perform uncertainty and sensitivity analyses, probabilistic impact assessments, and for the evaluation of many different combinations of future scenarios.

By developing this methodology, we were also able to investigate how flood risk calculations from risk curves are affected by the amount and choice of return periods used to develop the curve. The majority of flood risk studies use damage estimates for a small number of return periods to estimate risk. Often three return periods are used, which is the number of flood maps that member states are obliged to create for the European Flood Directive. However, we have shown that risk estimates are greatly affected by the number of data points used to construct the risk curve. Using just three return periods to develop the risk curve (low, medium and high probability, whereby medium probability is RP = 250 yr), we found risk estimates to be overestimated by between 33% and 100%. We also found that the overall risk is greatly affected by the number of data points used to construct the part of the curve for high probability floods, even though much research tends to focus on extreme events with very low probability.



The research also highlights two problems in the use of stationary SDFs for estimating flood damage, namely: (a) using annual SDFs for agricultural land uses led to over-estimations of observed floods that occurred outside the growing season; and (b) the SDFs do not incorporate information on flood frequency, meaning that they do not account for the fact that people regularly exposed to flooding may already take individual adaptive measures that reduce the damage in the event of future floods. Flood risk research in the Netherlands (and elsewhere) could benefit from incorporating these aspects into their standard flood risk assessment methods.

## 8.4 Main limitations and further research

The modelling framework used in this study is relatively simple, but it does allow us to assess the sensitivity of flood risk to climate and land-use change, and to several adaptation options, at a large geographical scale. Hereunder, we outline some of the main limitations of the research, and point to future research needs to address these.

- The model chain used in this research has been setup and validated for the Meuse in Dutch Limburg, and then applied at the basin scale. Since no validation could be carried out at the basin scale (due to the lack of data for validation purposes), the results at that scale should be understood as quick-scan analyses, providing a general picture of the potential relative changes in risk between time-periods and scenarios.
- The flood inundation model developed in this project is simplified for use in rapid calculations. The simplifications dictate the application of the method. Floodscanner is not intended to replace the need for hydraulic modelling with more complex models. This approach is neither suitable for localised flood risk assessments, nor for presenting flood risk at the grid-cell level. However, it forms a useful tool for studies in which large numbers of simulations are required, or where basin-scale

analyses are carried out. The results suggest that more research is needed to develop relatively simple inundation models that can be used to produce large numbers of inundation maps, complementary to more complex 2-D hydrodynamic models.

- Similarly, the land-use maps are not very precise at the local level (e.g. street or neighbourhood level), which means that the results should not be used at that level. At that scale, much more attention is needed for local land use planning through intense involvement of all stakeholders involved in this process. Future efforts to model land use change at the regional scale would benefit greatly by first holding workshops with institutes involved in regional spatial planning, so that existing and expected spatial plans can be incorporated in the model.
- More attention is needed to identify the return periods required to give a good representation of the risk. Moreover, research into flood risk could benefit from paying more attention to the damage caused by relatively high probability floods (as long as they cause damage), since these have a large influence on the risk as derived from a risk curve. The use of simple inundation models could facilitate this.
- The risk reduction capacity of the adaptation measures described in this study assumes their perfect implementation. For example, we assumed that dry- or wet-proofing measures are taken in either all residential buildings, or all new residential buildings by 2030. This provides an indication of the maximum potential of these measures, but the feasibility of such a large-scale implementation has not been studied. Indeed, we found in our stakeholder workshop that that there are currently few means to enforce or encourage the undertaking of mitigation measures by households. Research and modelling with methods that allow for more precision on the degree of implementation of the mitigation measures at the town, region, or basin scale could further increase the precision of such a model. Methods to improve these results could include the gathering of data via workshops, interviews, or surveys. Modelling methods such as agent-based modelling could also prove useful in representing the behaviour of households.
- In this study we only assessed the potential benefits of the studied adaptation options, and not their costs. In future studies, research should also address both the costs of measures and the feasibility/difficulty of their implementation.

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# 10 Annexes

## Annex 1: Publications related to this project

Aerts, J., W. Botzen, M. Bowman, P.J. Ward & P. Dircke, 2011. Climate adaptation and flood risk in coastal cities. Earthscan, Oxford, UK, 330pp.

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Poussin, J.K., 2012. Kennis voor Klimaat. Adaptation strategies: (1) Domestic measures. Presentation at KvK Workshop Adaptation to Meuse Flood Risk, 07 March 2012, RWS Dienst Limburg, Maastricht, The Netherlands.

Poussin, J.K., 2012. Kennis voor Klimaat. Adaptation strategies: (2) Zoning. Presentation at KvK Workshop Adaptation to Meuse Flood Risk, 07 March 2012, RWS Dienst Limburg, Maastricht, The Netherlands.

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Ward, P.J., W.P. Pauw, A.W. van Buuren & M.A. Marfai, 2010. A tale of two cities: Governance lessons for flood risk management in a time of climate change - the cases of Jakarta and Rotterdam. Symposium on climate change adaptation in delta cities, 8-9 July 2010, City University of Hong Kong, Hong Kong.

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Ward, P.J., H. de Moel & J.C.J.H. Aerts, 2011. Rapid damage modelling for probabilistic risk assessment. Example from the Meuse in Dutch Limburg. IVM Report W-11/08, VU University Amsterdam, Amsterdam, The Netherlands, 43 pp.

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## Annex 2: Discharge under climate change scenarios

*Table A2.1: Simulated discharge at Borgharen corresponding to the different return periods used in this study for the 2000 climate scenario, and the 2030 low and high climate scenarios.*

| | Discharge ($m^3 s^{-1}$) | | |
|---|---|---|---|
| **Return period** | **2000** | **2030 low** | **2030 high** |
| 2 | *1589* | *1693* | *1716* |
| 5 | *1885* | *1957* | *2013* |
| 10 | *2112* | *2197* | *2278* |
| 20 | *2328* | *2453* | *2560* |
| 50 | *2720* | *2831* | *2950* |
| 100 | *2960* | *3072* | *3207* |
| 250 | *3258* | *3372* | *3523* |
| 251 | *3259* | *3373* | *3525* |
| 1250 | *3814* | *3933* | *4120* |

## Annex 3: Flood damage mitigation measures

***Dry-proofing***

The dry-proofing strategy includes measures such as the use of sandbags, coffer dams, or panels on doors and windows, to stop the flood waters entering. According to the ICPR report (2002), such measures can decrease damage, if a flood occurs, by between 60% and 100%. Research shows that these measures are most effective up to 1m of water height, because above 1m the chance of wall failure due to water pressure increases (ICPR, 2002; EA, 2003; Boulet-Desbareau et al., 2005). The reduction factors chosen for this research are therefore 60% reduction of damage per house up to 1m of water, for the low range, and 100% reduction of damage per house up to 1m of water, for the high range. Above 1m of water, it is considered that the reduction of damage is 0%.

***Wet-proofing***

The wet-proofing strategy includes all the measures, structural and non-structural, that can be taken to adapt the exterior, interior, and uses of a house, in order to decrease the damage if flood waters enter the house. It includes measures such as: the strengthening of walls against water pressure; adapting the flood-prone parts of the house with waterproof materials; not keeping non-waterproof objects and furniture in flood-prone parts of house; moving vulnerable appliances to upper floors; installing one-way valves on water evacuation pipes to stop the waters from entering the house via the pipes; and storing paints and chemicals in the upper parts of the home. The ICPR report (2002) shows that such measures can reduce damage to house contents by up to 40%, while according to Kreibich et al. (2005), flood damage mitigation measures can reduce damage to buildings by between 36% and 53%, and to house contents by between 48% and 53%. The reduction factors chosen for our research are 35% damage reduction up to 2m for the low range, and 50% damage reduction up to 2m for the high range. Above 2m of water height, it is considered that there is no reduction of damage, and hence the reduction factor is 0%.

***Combined dry and wet-proofing***

The third strategy examined in this study combines the dry-proofing strategy and the wet-proofing strategy; hereafter referred to as the 'wet&dry-proofing strategy'. For this strategy, we consider that a house can be protected by both wet and dry proofing, i.e. by preventing the waters from entering the house as much as possible, while also adapting the house to decrease the damage in case waters enter. The reduction factors for the low range are equal, for each corresponding height, to the lowest factors of the dry-proofing strategy up to 1m (60%), and the wet-proofing strategy up to 2m (35%). For the high range, the reduction factors are equal to the highest factor of the dry-proofing strategy up to 1m (100%) and wet-proofing strategy up to 2m (50%). Above 2m of water the reduction factor is 0%.

## Annex 4: Geographical representation of risk per municipality in Limburg

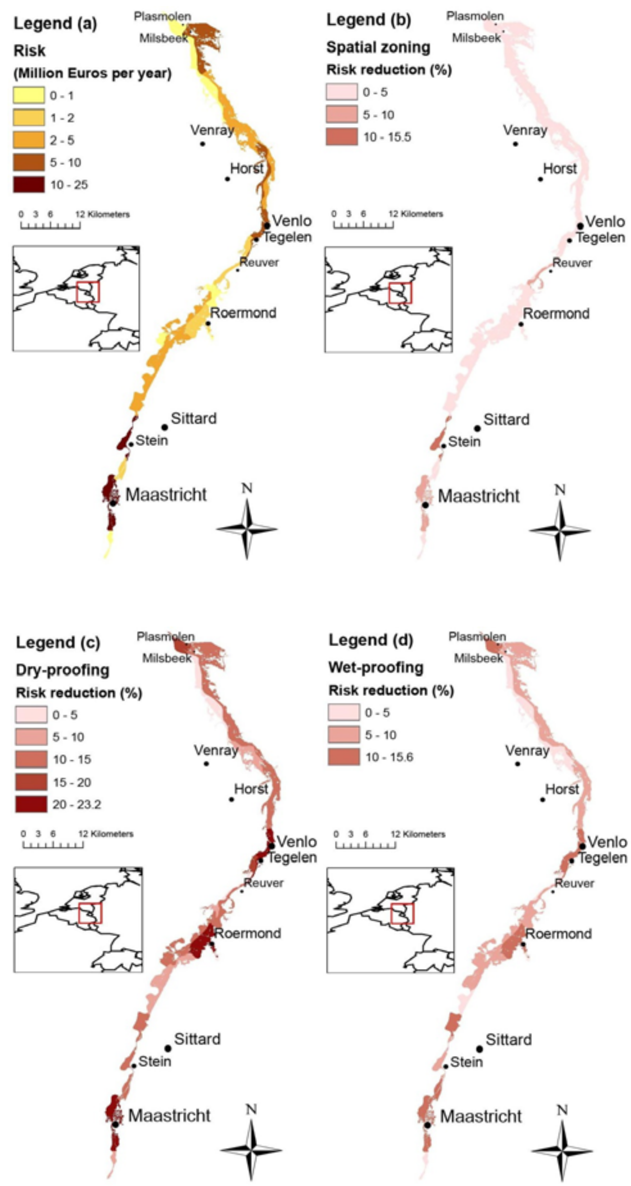


Figure A4.1: a) Risk results per municipalities, without adaptation strategies, in million Euros per year; (b) Average risk-reduction results of spatial zoning (%); (c) Average risk-reduction results of dry-proofing strategy (%); (d) Average risk-reduction results of wet-proofing strategy (%)

## Annex 5: Flood risk maps

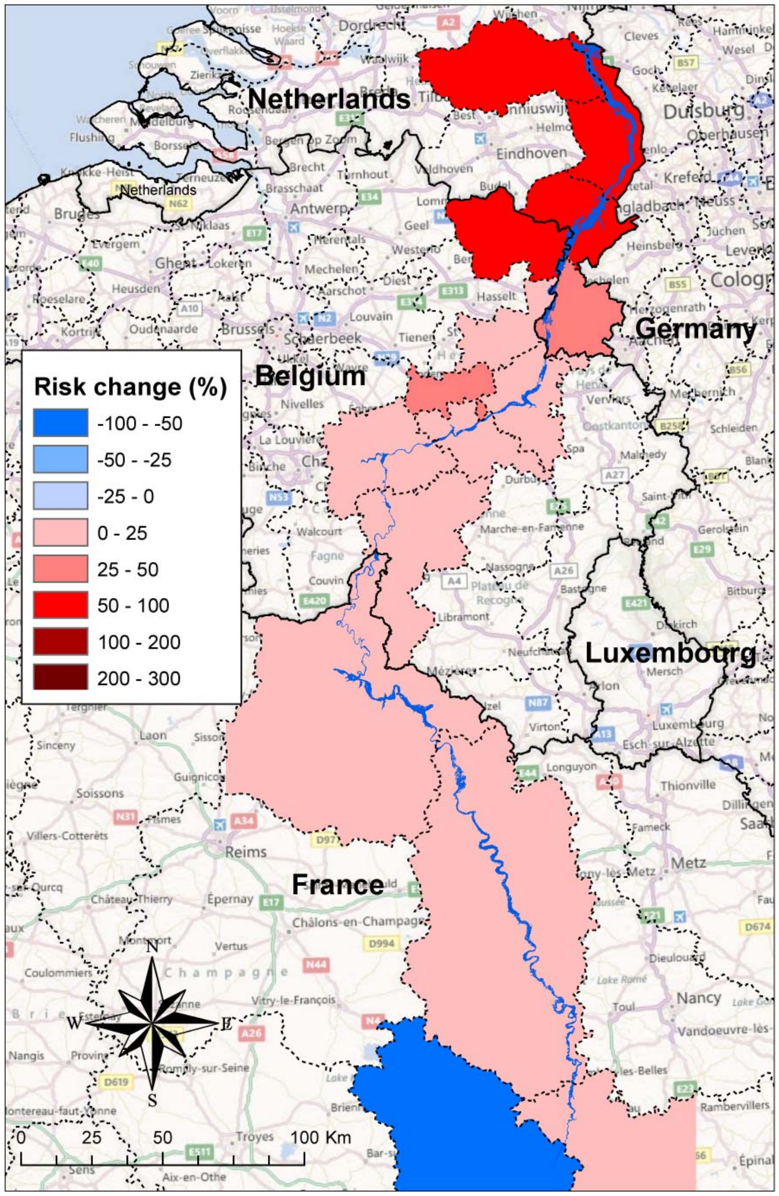


Fig A5.1: Change in flood risk (%) between reference conditions and the 2030 low scenario, aggregated to NUTS3 regions. The 2030 low scenario assumes climate change scenario G and land use change scenario RC.

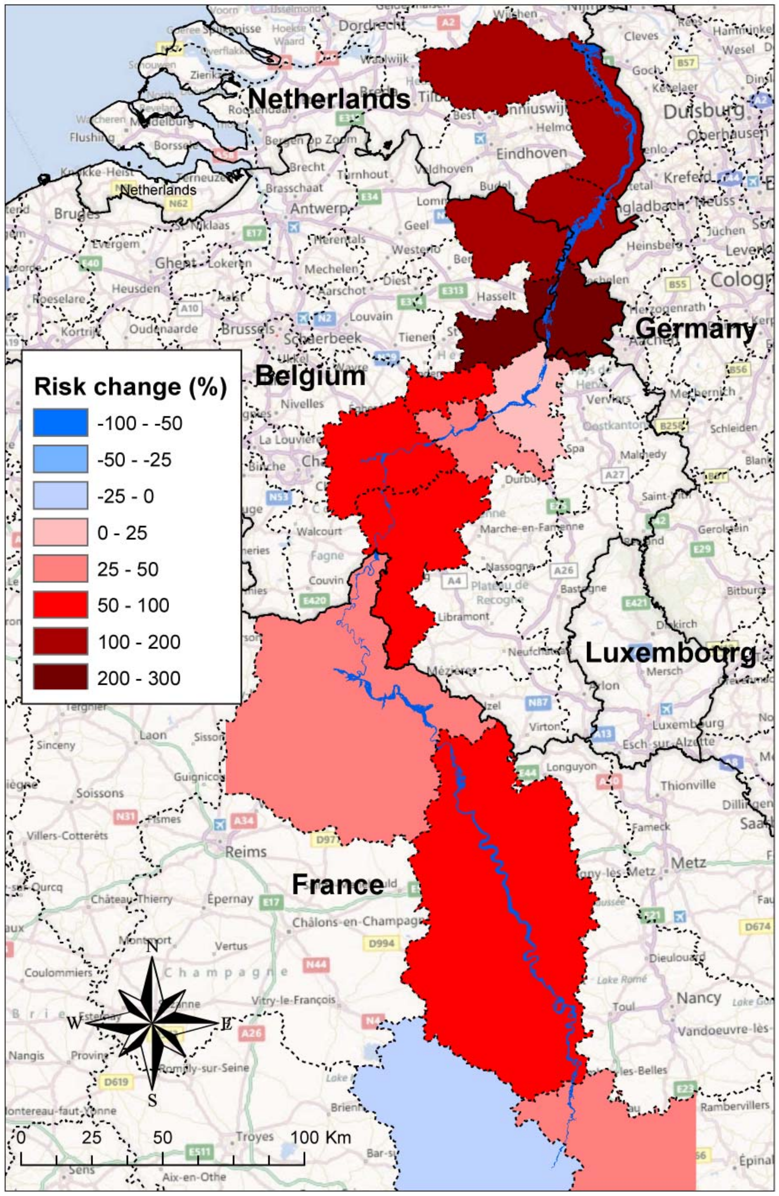


Fig A5.2: Change in flood risk (%) between reference conditions and the 2030 high scenario, aggregated to NUTS3 regions. The 2030 high scenario assumes climate change scenario W+ and land use change scenario GE.

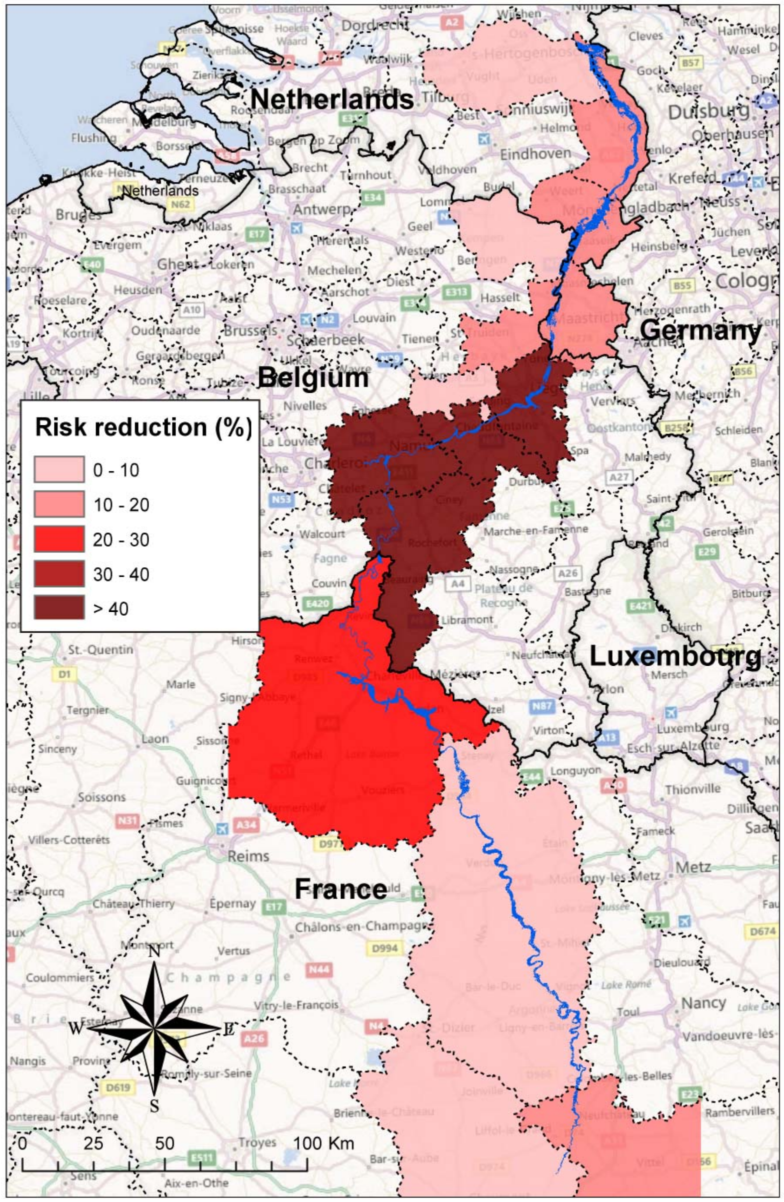


Fig A5.3: Potential reduction in risk (%) between the 2030 high scenario with "dry-proofing", compared to the 2030 high scenario without adaptation measures. Data are aggregated to NUTS3 regions.

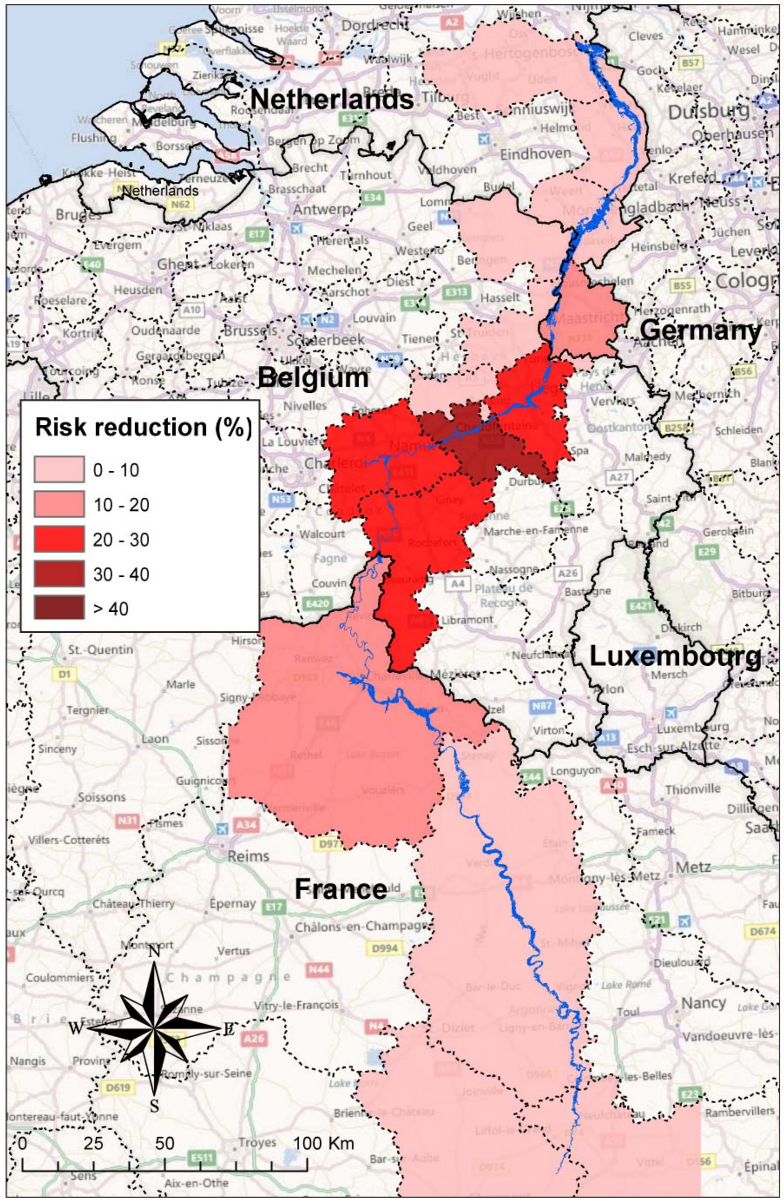


Fig A5.4: Potential reduction in risk (%) between the 2030 high scenario with “wet-proofing”, compared to the 2030 high scenario without adaptation measures. Data are aggregated to NUTS3 regions.

## Annex 6: Adaptation workshop details

| | |
|---|---|
| **Title**: | KvK Workshop Adaptation to Meuse Flood Risk |
| **Location**: | RWS Limburg, Avenue Ceramique 125, Maastricht |
| **Date**: | Wednesday 7th March 2012, 13:00-16:00 |

**Agenda**

| | |
|---|---|
| 13:00 - 13:15 | Opening (Otto de Keizer, Deltares) |
| 13:15 - 13:35 | KvK Meuse project (Philip Ward, IVM) |
| 13:35 - 14:00 | Brainstorm flood adaptation measures |
| 14:00 - 14:45 | Domestic adaptation measures<br>a) Introduction (Jennifer Poussin, IVM)<br>b) Discussion |
| 14:45 - 15:00 | Coffee break |
| 15:00 - 15:45 | Zoning for flood adaptation<br>a) Introduction (Jennifer Poussin, IVM)<br>b) Discussion |
| 15:45 - 16:00 | Conclusions (Otto de Keizer, Deltares) |

**Attendees**

| | |
|---|---|
| Rinus Potter | Waterschap Roer en Overmaas |
| Jan Molleman | Provincie Limburg |
| Siebolt Folkertsma | Rijkswaterstaat Dienst Limburg |
| Paul Konings | Rijkswaterstaat Dienst Limburg |
| Hendrik Buiteveld | Waterdienst (planning of meeting) |
| Philip Ward | IVM-VU |
| Jennifer Poussin | IVM-VU |
| Noortje Vromans | VU |
| Otto de Keizer | Deltares |

To develop the scientific and applied knowledge required for Climate-proofing the Netherlands and to create a sustainable Knowledge infrastructure for managing climate change

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