Future flood risk estimates along the river Rhine


Abstract

In Europe, water management is moving from flood defense to a risk management approach, which takes both the probability and the potential consequences of flooding into account. It is expected that climate change and socio-economic development will lead to an increase in flood risk in the Rhine basin. To optimize spatial planning and flood management measures, studies are needed that quantify future flood risks and estimate their uncertainties. In this Chapter, we estimated the current and future fluvial flood risk in 2030 for the entire Rhine basin in a scenario study. The change in value at risk is based on two land-use projections derived from a land-use model representing two different socio-economic scenarios. Potential damage was calculated by a damage model, and changes in flood probabilities were derived from two climate scenarios and hydrological modeling. We aggregated the results into seven sections along the Rhine. It was found that the annual expected damage in the Rhine basin may increase by between 54% and 230%, of which the major part (∼three-quarters) can be accounted for by climate change. The highest current potential damage can
be found in the Netherlands (€110 billion), compared with the second (€71 billion) and third (€58 billion) highest values in two areas in Germany. Results further show that the area with the highest fluvial flood risk is located in the Lower Rhine in NordRhein-Westfalen in Germany, and not in the Netherlands, as is often perceived. This is mainly due to the higher flood protection standards in the Netherlands as compared to Germany.

4.1 Introduction

Over the last couple of decades Europe has witnessed a growth in the scale and frequency of extreme natural disasters. Storms and floods are the most frequent and costly extreme weather events occurring in Europe, representing 69% of the overall natural catastrophic losses. For example, flooding in the Elbe basin in 2002 caused approximately €8 billion of economic damage in Germany, Austria and the Czech Republic collectively (CEA, 2007). Total damage of the summer floods in 2007 in the UK amount to €4 billion (Environment Agency, 2007). In 2010, Poland suffered from major floodings, of which the total damages are yet unknown. When focusing on the Rhine basin in North-West Europe, flood events in 1993 and 1995 caused severe damage of €1.4 billion and €2.6 billion, respectively (Engel, 1997; Glaser and Stangl, 2003; Brakenridge and Anderson, 2008).

The impact of flood events on societies and economies in the Rhine basin is likely to increase further as a result of two complementary trends. First of all, climate change is expected to increase the frequency and magnitude of flood peaks in the Rhine basin (Hooijer et al., 2004; Pinter et al., 2006). Annual maximum peak discharges are expected to increase by 3–19% in 2050 due to climate change (Kwadijk, 1993; Middelkoop et al., 2001; Vellinga et al., 2001). Te Linde et al. (2010) estimate an increase in the occurrence of an extreme 1/1250 per year flood event in the Lower Rhine delta by a factor of three to five in 2050. Secondly, the economic impact of natural catastrophes is increasing due to the growing number of people living in areas with a high flood exposure level, as well as the increased economic activity in these regions (e.g. Bouwer et al., 2007; Pielke Jr. et al., 2008). The International Commission for the Protection of the Rhine (ICPR) estimated an increase in potential damage in flood-prone areas in the Rhine basin of 23% between 1995 and 2005 (ICPR, 2005a).

These projected trends have led to an increased interest in a risk-based approach in water management, addressing both the probability and potential consequences of flooding (Merz et al., 2004; Büchele et al., 2006; De Bruijn and Klijn, 2009; Kreibich and Thieken, 2009; Wheater and Evans, 2009). Such an approach, for example, is currently stimulated by the EU Flood Directive 2007/60/EC (EU, 2007a), obliging
member states to create flood risk maps and basin-wide flood risk management plans (De Moel et al., 2009).

Quite a lot of literature exists on how the discharge regime in the Rhine may alter due to climate change (e.g. Kwadijk, 1993; Middelkoop et al., 2001; Menzel et al., 2006; Te Linde et al., 2010). However, in terms of land-use change and flood-damage potential only a few studies exist. The ICPR uses the Rhine Atlas approach to estimate aggregated flood damage for the whole Rhine basin (ICPR, 2001, 2005b). The Rhine Atlas damage evaluation has some flaws, though, for two reasons. Firstly, it has been recognized that the Rhine Atlas yields rather low damage potential values for different land-use classes compared to other studies and probably underestimates potential flood damage (Thieken et al., 2008; De Moel and Aerts, 2010). Secondly, the Rhine Atlas differentiates between only six different land-use classes; it uses a single urban class, whereas differentiation between urban classes for flood damage estimates is essential (Apel et al., 2009).

Research, however, on assessing current and future flood risk (addressing both flood probability and potential damage) is still in its early stages and a basin-wide assessment of flood risk is lacking. For the Rhine delta in the Netherlands two studies are available that calculate current and future flood risks (Aerts et al., 2008b; Bouwer et al., 2010). These authors use a method in which the results of flood depths and land-use information are combined within a flood damage model. In this method projected land-use simulations using a land-use model are combined with inundation information to derive potential flood damages using stage-damage curves (Merz et al., 2007). Flood risk (in terms of expected annual damage) is assessed by multiplying the potential damage with the probability associated with the inundation information. Climate change is taken into account by simulating future discharges and probabilities using climate change scenarios as input for hydrological models (e.g. Te Linde et al., 2010). In addition to a current and future perspective, De Moel et al. (2011) also assessed the historical trends in the 20th century for flood damage in the central part of the Netherlands.

In order to conduct an assessment for trends in flood risk (in terms of flood probabilities and flood damage) for the Rhine basin we need to address the following two research issues. (1) A land-use model for the Rhine basin does not exist, and hence it is difficult to estimate future land use and potential flood damage. (2) Furthermore, despite existing research focusing on the (future) hydrology of the Rhine (e.g. Kwadijk, 1993; Middelkoop et al., 2001; Bronstert et al., 2002; Shabalova et al., 2003), few estimates exist for changes in future trends of low probability events. For the latter issue, climate impact simulations are required that allow for extreme value analysis techniques (Raff et al., 2009; Te Linde et al., 2010).

The goal of this Chapter is, therefore, to estimate current and future flood risk for the entire Rhine basin in a scenario study. For this, we first assessed changes in
flood probability at various locations along the Rhine using climate scenarios and hydrological models. Second, we developed a land-use simulation model for the Rhine basin to generate future changes in land use. Third, these future land-use maps were used to estimate potential flood damage in flood-prone areas using a damage model. Finally, we multiplied flood probabilities with flood damage to derive current and future flood risk for the Rhine basin.

The remainder of this Chapter is organized as follows. Section 4.2 describes the case study area. Section 4.3 provides a description of the data and research method we used. Results are presented in Section 4.4 after which we discuss these results and provide conclusions in Section 4.5.

**4.2 Case study area: The Rhine basin**

The river Rhine originates in the Alps in Switzerland, forms part of the boundary between France and Germany and continues flowing through Germany before it enters the Netherlands at Lobith (Figure 4.1a). The Rhine is one of the most important industrial transport routes in the world and connects one of the largest sea harbors, the port of Rotterdam, to the inland European markets and its large industrial complexes (Jonkeren, 2009). About 58 million people inhabit the river basin, of which 10.5 million live in flood-prone areas (ICPR, 2001). The average discharge at Lobith in the Lower Rhine is 2200 m$^3$/s and the maximum observed discharge was 12 600 m$^3$/s in 1926 (Pinter et al., 2006).

Water management has heavily influenced the characteristics of the Rhine. Prior to the 19th century, the Rhine was a multi-channel braided river system upstream of Worms and meandering from that point downstream. However in order to reduce flooding, the Upper Rhine was canalized between 1817 and 1890 (Blackbourn, 2006). Furthermore, to aid shipping, engineers further rectified and canalized the main branch until 1955, causing additional acceleration of flood wave propagation in the Rhine (Lammersen et al., 2002).

The basin area is 185 000 km$^2$ and in particular the flood-prone areas in the basin are densely populated (Figure 4.1b). Hence, flood management has predominantly focused on major dike reinforcements along the Rhine over the last 20–30 years. Safety levels vary from 1/200 to 1/500 per year in Germany to 1/1250 and 1/2000 per year in the Netherlands. The design discharge that is associated with a safety level of 1/1250 per year (the discharge used when designing flood defenses) is estimated at 16 000 m$^3$/s (Ministry of Transport, Public Works and Water Management, 2006b) Figure 4.1a). Due to lower safety levels in Germany, floods may occur at upstream sections in Germany while the Dutch dike system will still prevent huge areas from inundation downstream (Gudden, 2004; Apel et al., 2006).
4.2. Case study area: The Rhine basin

Figure 4.1: Maps of the Rhine basin: a) (estimated) safety levels and b) land use in the reference situation. Figure 1b) also shows the potential inundated area due to fluvial flooding from the Rhine.
4.3 Data and method

We followed the steps displayed in Figure 4.2 to estimate expected flood damage per year (risk) for the reference situation and different future scenarios for the year 2030. Economic value of land-use classes determines the potential flood damage in case of a flooding event. Current land-use information was based on the CORINE land cover data (Bossard et al., 2000). Future changes in flood damage was estimated using a land-use model, simulating future land use for two different socio-economic scenarios (see Section 4.3.1). Through combining existing basin-wide flood inundation depth maps (see Section 4.3.2) with land-use information, potential damage were calculated using a damage model (see Section 4.3.3). Flood risk was calculated by multiplying potential flood damage with the accompanying flood probability for different sections along the Rhine. Current flood probabilities were estimated using research by ICPR (2005b) and Silva and Van Velzen (2008) (Figure 4.1a). Changes in flood probabilities were calculated using a hydrological model and two climate change scenarios (Te Linde et al., 2010) (see Section 4.3.4).

The flood damage calculations were performed at spatial grids of 100×100 m and aggregated into seven regions along the Rhine (see regions A through G in Figure 4.1a) and the entire basin to calculate expected damage per year. The steps used in this method, as well as the data and future scenarios, are described in detail below.

4.3.1 Current and future land use

Current land use is based on the CORINE land cover map for 2000 (Bossard et al., 2000) that has a resolution of 100×100 m. Future land-use projections from the EUruralis project exist for the whole of the European Union for the year 2030 (Verburg et al., 2008). However, these projections distinguish only a single urban land-use class and have a relatively low resolution of 1×1 km, while it is important to have an accurate representation of urban land use in flood damage simulations (Bouwer et al., 2010). This is illustrated by De Moel and Aerts (2010) who show that urban land use contributes the largest share of flood damage (~ 80%) and because maximum damages differ substantially between different urban classes in their damage model (from €0.3 million/hectare for recreational areas to €9.1 million/hectare for high density residential areas), differentiation within urban land use is desirable for flood damage assessments.

To address this issue, we have set up a new and more detailed land-use model (the Land Use Scanner) to downscale land-use projections from the EUruralis project, both spatially and thematically. The Land Use Scanner for the Rhine basin is based on the method described by Hilferink and Rietveld (1999).
4.3. Data and method

Figure 4.2: Flowchart of the method used for estimating future flood risk.


**Land Use Scanner**

The Land Use Scanner simulates future land use and is based on demand-supply interaction of land, whereby different sectors compete for allocation of land within land suitability and policy constraints (Loonen and Koomen, 2008). The model has previously been applied in a number of policy-related research projects in European countries (Wagtendonk et al., 2001; Hartje et al., 2005; Koomen et al., 2005; Dekkers and Koomen, 2007). It was recently applied in studies on the long-term development of flood risk in the Netherlands and the evaluation of the effectiveness of various adaptation strategies (MNP, 2007; Aerts et al., 2008b; Bouwer et al., 2010). The land-use model for the Rhine basin operates on a spatial resolution of $250 \times 250$ m grid cells and provides information on 13 different land-use classes, such as infrastructure, nature, agricultural land uses and water, including six different urban functions (Figure 4.1b).

**Scenarios and land-use claims**

To be able to simulate future land-use patterns with the Land Use Scanner, the expected increase or decrease of each land-use class (called claims) has to be defined. These claims were derived from the EUruralis project (Verburg et al., 2008; Verburg and Overmars, 2009). In this project land-use projections and their underlying claims have been developed for four socio-economic scenarios, in line with the four scenarios in the Special Report on Emissions Scenarios (SRES) by IPCC (2000). For the present study, two of these projections and their land-use claims were selected: the ‘Global Economy’ (GE) and the ‘Regional Community’ (RC) scenarios which can be regarded as the upper and lower boundaries of possible future urban land-use change.

The ‘Global Economy’ scenario reflects a future with high economic and population growth, international economic integration as well as little environmental concern on behalf of governments, resulting in a large increase in urban land-use functions with no restrictions on urban sprawl. The Regional Communities scenario, on the other hand, represents a future with low economic and population growth, a regional focus and strict environmental regulations enforced by governments, resulting in a substantially lower increase in urban areas and restrictions on urban sprawl.

We have used the NUTS3 level to derive land-use claims and as a starting point for our downscaling. NUTS3 corresponds to level 3 administrative units under the Nomenclature of Territorial Units for Statistics in Europe for which socio-economic data is available. These are mainly rural districts and cities with more than 100 000 inhabitants. The land-use claims for the two future scenarios were derived by assessing the decrease or increase of each land-use class between the scenario projections and the baseline situation in 2000.
4.3. Data and method

Downscaling

We spatially scaled down the land-use change projections from the NUTS3 polygons to $250 \times 250$ m, which is the required level of detail needed for the Land Use Scanner. Furthermore, the single urban land-use class distinguished in the EUruralis projections was distributed into five urban land-use classes; residential land use, commercial, recreation, infrastructure and construction/mines. Using the CORINE 2000 land cover map the percentage of the five different urban land-use categories of total urban land use was calculated for each NUTS3 region within the study area. Subsequently, the total change in urban land use was assessed by comparing the EUruralis projections for 2030 to the start year, again at the NUTS3 regional level. The resulting change in total urban land use was then distributed over the five urban land-use classes according to the previously established divisions, taking into account the storylines for the two scenarios.

On top of differentiating the EUruralis urban land-use class, an extra residential class representing high-density residential areas was defined using the LandScan population data base (Landscan, 2009). This was done because the CORINE 2000 land cover data makes very little distinction between high and low urban density residential areas.

Suitability Maps

The land-use claims provide information on the scale of future land-use change but give no indication as to where these claims might be realized. This allocation process is carried out by the Land Use Scanner on the basis of suitability maps. These maps give a definition for every location (grid cell) of its attractiveness for the different land-use types available, depending on its current land use, physical properties, operational policies and expected relations to nearby land-use functions (Ritsema van Eck and Koomen, 2008). For example, a location (grid cell) with a steep slope (physical property) that is situated in a nature protection area (operational policy) and far away from existing urban infrastructure (relation to nearby land use) is thus considered as highly unsuitable for the realization of a residential land-use claim. The suitability maps can also be used to further reflect the effect of socio-economic scenarios and thus the land use change simulations by integrating flood-risk specific information. For example, the regional communities scenario assumes a world with a regional focus and strict environmental regulations enforced by governments. To reflect this, the 1/100 per year flood zone, which is mainly embanked river foreland, is given a low suitability value for further urbanization, a policy that has already been adopted in Germany. In contrast, the global economy scenario assumes a world where governments have little environmental concern, resulting in a large increase in urban land-use functions with no restrictions on urban sprawl. We, therefore, simulated land use according to
### Table 4.1: Suitability maps used for the ‘Land Use Scanner’.

<table>
<thead>
<tr>
<th>Category</th>
<th>Suitability Map</th>
<th>Extent</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical properties</td>
<td>Peat bog, marsh, moor</td>
<td>Basin</td>
<td>CORINE</td>
</tr>
<tr>
<td>Slope</td>
<td></td>
<td>Basin</td>
<td>SRTM</td>
</tr>
<tr>
<td>Population density</td>
<td></td>
<td>Basin</td>
<td>LandScan</td>
</tr>
<tr>
<td>Policy maps</td>
<td>Nature 2000 sites</td>
<td>Basin</td>
<td>DG Environment</td>
</tr>
<tr>
<td>Flood retention areas</td>
<td>Flood retention areas</td>
<td>Germany</td>
<td>ICPR / TU Dortmund</td>
</tr>
<tr>
<td>Flood zone (1/100 per year)</td>
<td>Flood zone (1/100 per year)</td>
<td>Basin</td>
<td>ICPR Rhine Atlas</td>
</tr>
<tr>
<td>Flood zone (extreme event)</td>
<td></td>
<td>Basin</td>
<td>ICPR Rhine Atlas</td>
</tr>
<tr>
<td>Relational maps</td>
<td>Distance to metropolitan areas</td>
<td>Basin</td>
<td>ESRI</td>
</tr>
<tr>
<td></td>
<td>Distance to long-distance train stations</td>
<td>Basin</td>
<td>TU Dortmund</td>
</tr>
<tr>
<td></td>
<td>Distance to passenger railway stations</td>
<td>Basin</td>
<td>TU Dortmund</td>
</tr>
<tr>
<td></td>
<td>Distance to motorway exits</td>
<td>Basin</td>
<td>TU Dortmund</td>
</tr>
<tr>
<td></td>
<td>Distance to international airports</td>
<td>Basin</td>
<td>ESRI</td>
</tr>
<tr>
<td></td>
<td>Distance to road network</td>
<td>Basin</td>
<td>ESRI</td>
</tr>
<tr>
<td></td>
<td>Distance to major rivers</td>
<td>Basin</td>
<td>ESRI</td>
</tr>
<tr>
<td></td>
<td>Neighborhood statistics</td>
<td>Basin</td>
<td>Own analysis</td>
</tr>
</tbody>
</table>

Moreover, the suitability of urban areas close to a river course is increased in the global economy scenario as it is assumed that more people would like to live near the water and are willing to pay for this location. This development has also been observed in the past during periods of economic growth (ICPR, 2005b). An overview of the suitability maps used for the Land Use Scanner for the Rhine basin is given in Table 4.1.

#### 4.3.2 Inundation map

One of the inputs for the flood damage model is a map displaying the water depth of a possible flooding event in the entire Rhine basin. Such a map was developed in 2001 by the International Commission for the Protection of the Rhine (ICPR), known as the Rhine Atlas (ICPR, 2001). This atlas contains a collection of maps that displays the potential flooded area in the Rhine basin at different flooding probabilities (1/10 per year, 1/100 per year, and ‘extreme’, without a probability estimate).

We used only the ‘extreme’ situation to indicate the inundated area in the case of flooding, since safety levels along the Rhine are all higher than 1/100 per year (Figure 4.1a). Based on the Rhine Atlas, we cannot predict how the flood extent will change in the future and therefore we have assumed that the inundated areas for the reference situation and in 2030 are the same. For the Netherlands, we have used...
flood risk maps made available by the Dutch government that are based on multiple inundation model runs (Van den Berg et al., 2010). We have only included inundated areas that are prone to flooding by the river Rhine and not areas that are influenced by storm surges from the sea.

4.3.3 Flood damage

Potential flood damage can be assessed in various ways, ranging from the use of very detailed, object-based data to the use of aggregated asset values per hectare (or square meter) for a certain land-use category (Messner et al., 2007). Given the spatial and temporal scale of the present study, which looks at the development of flood risk on a basin-wide level in the future, we used a simple damage model for land-use categories, the Damage Scanner (Aerts et al., 2008b; Bouwer et al., 2010; Klijn et al., 2007). This model is based on two input parameters: water depth and land use. Potential damage is calculated by the model using so-called damage functions that define for a land-use category the damage that can be expected when a respective inundation level occurs.

The model applies damage functions for the 13 land-use classes distinguished by the Land Use Scanner and reflects predominantly direct tangible damage caused by physical contact between economic assets and flood water. Note that direct intangible losses such as loss of life are not reflected by the model. However, the Damage Scanner also implicitly comprises approximately 5% of indirect damages as a surcharge on direct damages. Indirect damages refer to a loss of turnover due to business interruption during a flood event and can make up a substantial share of total flood damages (RebelGroup, 2007).

4.3.4 Climate change scenarios for changes in flood probabilities

Figure 4.1a shows current safety levels for seven regions along the main Rhine branch. In the Netherlands, there is a legal standard for flood defense safety levels. In Germany, dike heights are often legally defined and the related safety levels are estimated and described by ICPR (2005b) and Silva and Van Velzen (2008). The differences in safety levels were used to distinguish the regions for which aggregated flood damage and flood risk can be calculated. The seven regions have different surface areas. The larger the surface area, the larger the aggregated damage and risk will be, since we assume that at the given probabilities the entire region will flood. Nevertheless, we made no corrections in our results for the different surface areas of the seven regions. For an individual region, aggregated damage and risk define the dimensions of the hazard and can be compared to other regions, in contrast to damage or risk per km².
We assumed flooding occurs at probabilities corresponding to the safety levels in the reference situation. Hence, we did not simulate flood damage due to dike failures that may occur at lower probabilities and furthermore assumed that dike heights will not change in the future. The current policy in the Netherlands, however, foresees adaptation of the flood defenses (i.e. dike heightening or lowering of the flood plains) when flood probability increases in order to maintain current safety levels.

We used two climate change scenarios (a moderate and an extreme scenario) to estimate future changes in flood probabilities along the main Rhine branch, which were taken from Te Linde et al. (2010). The first climate scenario (referred to from now on as ‘Wp’) represents an extreme climate change scenario, based on Van den Hurk et al. (2006) and describes the most extreme scenario out of four in terms of winter precipitation and resulting floods along the Rhine in 2050 (Te Linde, 2007). This climate scenario corresponds with a 2°C Celsius increase in global temperature in 2050 with respect to 1990 and changes in atmospheric circulation resulting in drier summers and wetter winters.

The second climate scenario (further referred to as ‘RACMO’) displays more moderate climate change effects and follows the output of the RACMO2.1 regional climate model (Lenderink et al., 2003; Meijgaard et al., 2008; Bakker and Van den Hurk, 2009). This scenario corresponds with the IPCC SRES-A1B scenario and projects more spatial variation in meteorological changes than the Wp scenario does.

Both climate scenarios are available in time series of 35 years, and were resampled into time series of 1000 years of daily data. These resampled times series were subsequently used to drive the hydrological model HBV (Bergström, 1976) and to simulate river discharges and related flood peak probabilities (Te Linde et al., 2010). By comparing current flood probabilities with future flood probabilities, changes in flood-peak probability were derived for the seven regions along the Rhine (see Table 4.2). Te Linde et al. (2010) evaluated changes in flood probabilities between 1990 and 2050. Since the reference year in this study is 2000, and the scenario year 2030, we divided the projected changes in flood probabilities by Te Linde et al. (2010) by two in order to take the shorter timescale into account.

4.4 Simulation results

4.4.1 Discharges and probabilities

Figure 4.3 shows an extreme value plot for annual maximum discharges at Lobith, for the year 1990 and two climate change scenarios for 2050. The results represent 1000-year runs for the reference and each climate change scenario (Wp and RACMO). From the simulation results it can be derived that the discharge corresponding to a
Table 4.2: Climate change scenarios for increased flooding probabilities in 2030. Flooding probabilities (per year) for the reference situation are estimated based on literature. The probability ($p$) increase is displayed as a factor (Estimate, based on Silva and Van Velzen, 2008 and on the Evaluation of the Action Plan on Floods (ICPR, 2005a)).

<table>
<thead>
<tr>
<th>Region</th>
<th>Reference $^1$</th>
<th>RACMO</th>
<th>Wp</th>
<th>RACMO</th>
<th>Wp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p$</td>
<td>$p$</td>
<td>$p$</td>
<td>$p$ incr.</td>
<td>$p$ incr.</td>
</tr>
<tr>
<td>Alpine A</td>
<td>1/200 (0.0050)</td>
<td>1/139 (0.0072)</td>
<td>1/64 (0.0157)</td>
<td>1.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Upper Rhine B</td>
<td>1/1000 (0.0010)</td>
<td>1/691 (0.0014)</td>
<td>1/261 (0.0038)</td>
<td>1.5</td>
<td>3.9</td>
</tr>
<tr>
<td>Upper Rhine C</td>
<td>1/200 (0.0050)</td>
<td>1/160 (0.0062)</td>
<td>1/77 (0.0129)</td>
<td>1.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Middle Rhine D</td>
<td>1/200 (0.0050)</td>
<td>1/159 (0.0063)</td>
<td>1/80 (0.0125)</td>
<td>1.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Lower Rhine E</td>
<td>1/200 (0.0050)</td>
<td>1/134 (0.0075)</td>
<td>1/80 (0.0125)</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Lower Rhine F</td>
<td>1/500 (0.0020)</td>
<td>1/327 (0.0031)</td>
<td>1/162 (0.0062)</td>
<td>1.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Delta G</td>
<td>1/1250 (0.0008)</td>
<td>1/673 (0.0015)</td>
<td>1/437 (0.0023)</td>
<td>1.9</td>
<td>2.9</td>
</tr>
</tbody>
</table>

probability of 1/1250 per year at Lobith increases by 16% for the Wp scenario and by 13% for the RACMO scenario. The discharge currently corresponding to the 1/1250 event (about 16,000 m$^3$/s) will increase to 1/460 per year for the RACMO scenario and 1/265 per year for the Wp scenario, meaning the probability increases by a factor of 2.7 to 4.7 respectively (Te Linde et al., 2010). Similar projected changes in flood probabilities are available for several locations along the Rhine branch, representing the regions A through G in Figure 4.1a with different safety levels. The projected increases in flood probabilities for 2030 range from a factor of 1.3 to 3.8, depending on region and climate change scenario (Table 4.2).

### 4.4.2 Land-use change

Table 4.3 shows surface percentages of land-use classes in the flood prone area of the Rhine, according to the CORINE land cover map. Agriculture, cultivation and pasture have the largest combined share of 71% in the reference situation. High and low density residential and commercial areas comprise 17% of the total basin area. The RC scenario for 2030 displays by far the largest increase in nature (110%), whereas residential and commercial areas each increase on average by 19%. In the GE scenario, the residential and commercial areas each increase on average by 44%. Both scenarios project a decrease in agricultural area ($\sim -15\%$). Cultivated area and pasture remain fairly stable in both scenarios (less than 6% change).

These trends are also illustrated in Figure 4.4, showing output maps of the land-use simulations. The map shows a clear increase in urbanized areas close to the river in the GE scenario, whereas the increase in nature is the most apparent change in the
Figure 4.3: Extreme value distributions of annual maximum discharge at Lobith, and Generalized Extreme Value (GEV, Appendix C) fits (lines) for the reference situation, and the RACMO and Wp climate change scenarios for the year 2050 (adapted from Te Linde et al., 2010).

Table 4.3: Surface percentages of different land-use classes in the flood prone area of the Rhine basin, for the reference situation in 2000, and the RC and GE scenarios in 2030. Percentages and Euros in Tables 4.3 through 4.7 are rounded to two significant digits.
4.4. Simulation results

Figure 4.4: Land-use maps for the reference year 2000, and for 2030 under the RC and GE socio-economic scenarios. The image is zoomed on the Lower Rhine near the border between Germany and the Netherlands, and shows only land-use types in flood-prone areas.

RC scenario. These results obviously correspond to the scenario descriptions that were used in the simulations (see Section 4.3.1).

4.4.3 Flood damage

Table 4.4 and Figure 4.5a display the expected damage aggregated for the seven regions along the Rhine. For the reference year (2000), we estimated the total potential damage for the whole basin to be €300 billion. This is substantially more than the
Table 4.4: Expected damage for different regions in 2000 and 2030 (at 2000 prices) (\(^1\) The estimate of the ICPR (2005a)).

<table>
<thead>
<tr>
<th>Region</th>
<th>Reference 2005(^1)</th>
<th>ICPR 2005(^1)</th>
<th>Scen RC</th>
<th>Scen GE</th>
<th>Scen RC Change (%)</th>
<th>Scen GE Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpine A</td>
<td>0.46</td>
<td>0.0</td>
<td>0.39</td>
<td>0.50</td>
<td>-0.18</td>
<td>8.2</td>
</tr>
<tr>
<td>Upper Rhine B</td>
<td>21</td>
<td>1.6</td>
<td>21</td>
<td>26</td>
<td>1.8</td>
<td>18</td>
</tr>
<tr>
<td>Upper Rhine C</td>
<td>58</td>
<td>11</td>
<td>62</td>
<td>73</td>
<td>5.9</td>
<td>20</td>
</tr>
<tr>
<td>Middle Rhine D</td>
<td>15</td>
<td>1.5</td>
<td>12</td>
<td>18</td>
<td>-23</td>
<td>15</td>
</tr>
<tr>
<td>Lower Rhine E</td>
<td>71</td>
<td>22</td>
<td>80</td>
<td>90</td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>Lower Rhine F</td>
<td>25</td>
<td>170</td>
<td>30</td>
<td>37</td>
<td>18</td>
<td>34</td>
</tr>
<tr>
<td>Delta G</td>
<td>110</td>
<td>170</td>
<td>120</td>
<td>140</td>
<td>7.6</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>300</td>
<td>200</td>
<td>320</td>
<td>380</td>
<td>7.5</td>
<td>21</td>
</tr>
</tbody>
</table>

\(^1\) ICPR estimate of €200 billion. The ICPR damage estimates are, however, recognized to be rather low compared to other methods and studies. Several land-use types such as residential and commercial areas or agriculture have substantially lower maximum damage values compared to the damage model applied in our study (for more details see ICPR, 2001; Thieken et al., 2008; De Moel and Aerts, 2010). This can be explained, amongst others, by the observation that the results of the Damage Scanner also comprise a share of, on average, 5% indirect damages, which is not included in the Rhine Atlas estimates.

The expected damage gradually increases downstream. The delta in the Netherlands (region G) is the largest and most densely populated region, and has therefore the highest potential damage, both in the reference situation as well as in the future projections of both socio-economic scenarios. Between the two scenarios, the RC scenario yields the lowest increase in potential damage: 7.5% over the entire basin. In most regions potential damage changes little, with the exception of the Lower Rhine region (F) (+18%). In some areas, such as the Middle Rhine, the RC scenario even projects a decrease in potential damage. The GE scenario gives an overall larger increase in potential damage (21%). Moreover, expected damage seems to increase substantially in almost all regions, often by more than 15% and ranging up to 34%.

Results of expected damage per land-use class for the entire Rhine basin are presented in Table 4.5. The potential damage of residential and commercial areas in the Rhine basin is €200 billion, which comprises 63% of the total damage, and is projected to increase to €260 billion (RC) and €320 billion (GE) (Table 4.5). Agriculture, cultivation and pasture comprise €93 billion damage (29% of the total damage), which is projected to decrease to €61 billion (RC) and €63 billion (GE).
4.4. Simulation results

Figure 4.5: Potential damage (a) and flood risk (b), aggregated to seven regions along the Rhine.

Table 4.5: Expected damage for different land-use categories in 2000 and 2030 (at 2000 prices).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential H</td>
<td>73</td>
<td>86</td>
<td>110</td>
<td>23</td>
<td>25</td>
<td>27</td>
<td>18</td>
<td>46</td>
<td>28</td>
<td>46</td>
</tr>
<tr>
<td>Residential L</td>
<td>85</td>
<td>120</td>
<td>150</td>
<td>27</td>
<td>34</td>
<td>36</td>
<td>39</td>
<td>72</td>
<td>33</td>
<td>72</td>
</tr>
<tr>
<td>Commercial</td>
<td>42</td>
<td>53</td>
<td>66</td>
<td>13</td>
<td>16</td>
<td>17</td>
<td>28</td>
<td>59</td>
<td>31</td>
<td>59</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>7.0</td>
<td>6.3</td>
<td>6.2</td>
<td>2.2</td>
<td>1.8</td>
<td>1.5</td>
<td>-11</td>
<td>-12</td>
<td>-22</td>
<td>-22</td>
</tr>
<tr>
<td>Constr / mines</td>
<td>2.5</td>
<td>2.9</td>
<td>2.9</td>
<td>0.8</td>
<td>0.9</td>
<td>0.7</td>
<td>19</td>
<td>17</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>Recreation</td>
<td>4.7</td>
<td>2.0</td>
<td>2.3</td>
<td>1.5</td>
<td>0.6</td>
<td>0.6</td>
<td>-57</td>
<td>-51</td>
<td>-12</td>
<td>-51</td>
</tr>
<tr>
<td>Nature</td>
<td>9.1</td>
<td>14</td>
<td>7.9</td>
<td>2.9</td>
<td>4.1</td>
<td>2.0</td>
<td>56</td>
<td>-13</td>
<td>-13</td>
<td>-13</td>
</tr>
<tr>
<td>Agriculture</td>
<td>31</td>
<td>15</td>
<td>16</td>
<td>10</td>
<td>4.5</td>
<td>4.0</td>
<td>-49</td>
<td>-47</td>
<td>-2</td>
<td>-47</td>
</tr>
<tr>
<td>Cultivation</td>
<td>32</td>
<td>30</td>
<td>30</td>
<td>10</td>
<td>8.8</td>
<td>7.5</td>
<td>-5.4</td>
<td>-6.1</td>
<td>-0.6</td>
<td>-0.6</td>
</tr>
<tr>
<td>Pasture</td>
<td>30</td>
<td>16</td>
<td>17</td>
<td>10</td>
<td>4.6</td>
<td>4.3</td>
<td>-48</td>
<td>-43</td>
<td>-5</td>
<td>-5</td>
</tr>
</tbody>
</table>
Table 4.6: Basin-wide annual expected damage (risk) in € million per year. The factor of change is displayed in brackets. The reference year is 2000 and the scenarios represent 2030.

<table>
<thead>
<tr>
<th>Socio-economic scenario</th>
<th>Reference</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate Reference</td>
<td>880</td>
<td>950 (7.5%)</td>
</tr>
<tr>
<td>RACMO</td>
<td>1300 (43%)</td>
<td>1400 (54%)</td>
</tr>
<tr>
<td>Wp</td>
<td>2300 (160%)</td>
<td>2500 (180%)</td>
</tr>
</tbody>
</table>

4.4.4 Flood risk

Figure 4.5b shows estimates of expected annual flood damage in the reference year (2000) for the seven regions along the Rhine. In contrast with potential damage (Figure 4.5a), the highest flood risk estimates are not found in the Dutch Delta (G), but rather in the Lower Rhine (E) in the German state NordRhein-Westfalen and in the Upper Rhine (C). This is the result of the substantially higher flood protection levels in the Delta region G, which obviously determines and lowers the flood-risk estimates to a large extent. This also implies that uncertainties of flood probabilities heavily affect the reliability of (future) flood-risk estimates in this region.

For the future risk projections, the RACMO climate scenario is combined with the RC socio-economic scenario and Wp with the GE scenario. The combination RACMO-RC can be considered as the lower estimate and Wp-GE as the upper estimate in the risk simulations. Basin-wide results are displayed in Table 4.6. The flood risk estimates of the scenarios show a large variation. In the reference situation, we estimate the basin-wide expected annual flood damage to be €880 million on average per year. The RACMO-RC scenario projects the risk to increase to €1400 million per year, an increase of 54%. The Wp-GE scenario projects a much larger increase in flood risk, tripling it to €2900 million per year (an increase of 230%).

The contribution made by climate change is considerably larger than socio-economic change in both scenario combinations. Due to climate change, basin-wide flood risk increases by 43–160%, whereas land-use change results in an increase of 6.5–27% (Table 4.6). In order to illustrate the relative increase of annual expected damage due to each of the driving forces, we displayed the basin-wide flood risk scenarios in a bar chart (Figure 4.6). The bar chart displays the contributions to change in annual expected damage, from a) climate change only, b) socio-economic change only, and c) the combination of both impacts. Climate change accounts for ~ three-quarters (6/8) of the increase, whereas socio-economic change only results in ~ 1/8 of the total increase in annual expected damage. The combination of impacts adds the remaining ~ 1/8 to both scenarios respectively.
4.4. Simulation results

![Graph showing expected losses (€ million/year) for different scenarios: Socio-economic + climate, Climate, Socio-economic, and Reference risk.]

Figure 4.6: Basin-wide annual expected flood damage (risk) for 2030, compared to the reference situation.

<table>
<thead>
<tr>
<th>Region</th>
<th>Reference situation</th>
<th>RACMO and RC</th>
<th>Wp and GE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p</td>
<td>€ bln</td>
<td>€ mln/yr</td>
</tr>
<tr>
<td>Alpine A</td>
<td>0.0050</td>
<td>0.46</td>
<td>2.3</td>
</tr>
<tr>
<td>Upper Rhine B</td>
<td>0.0010</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Upper Rhine C</td>
<td>0.0050</td>
<td>58</td>
<td>290</td>
</tr>
<tr>
<td>Middle Rhine D</td>
<td>0.0050</td>
<td>15</td>
<td>77</td>
</tr>
<tr>
<td>Lower Rhine E</td>
<td>0.0050</td>
<td>71</td>
<td>350</td>
</tr>
<tr>
<td>Lower Rhine F</td>
<td>0.0020</td>
<td>25</td>
<td>49</td>
</tr>
<tr>
<td>Delta G</td>
<td>0.00080</td>
<td>110</td>
<td>87</td>
</tr>
<tr>
<td>Total</td>
<td>300</td>
<td>880</td>
<td>320</td>
</tr>
</tbody>
</table>

As this is the first assessment of basin-wide future flood risk, it is interesting to compare different sections along the Rhine and to evaluate if differences with regard to the drivers of future flood risk can be observed. To assess differences between regions along the Rhine, Table 4.7 shows annual expected damage for seven regions. Bar charts similar to Figure 4.6 are shown in Figure 4.7, but now disaggregated to seven regions along the Rhine. The bar charts show large variations in base risk and flood risk projections between regions, and, like the basin-wide projections, the dominant contribution of climate change to increased flood risk.

The Alpine area (A) and the Upper Rhine (B) display hardly any annual expected damage at the vertical scale they are presented (less than €110 million per year). Just as we have seen in Figure 4.5b for the reference flood risk, projections for annual expected damage in 2030 are the highest in the Upper Rhine (C) (up to €940 million per year in the Wp-GE scenario, an increase of 220%) and the Lower Rhine (E) (up to €1100 million per year, an increase of 210%). The Middle Rhine (D), the Lower
Figure 4.7: Annual expected flood damage, for the reference situation and projections for 2030, aggregated into seven regions along the Rhine.
4.5 Discussion and conclusions

Rhine up to the Netherlands (F), and the Dutch Delta (G) show risk projections of between €220 and €310 million per year in the Wp-GE scenario.

For the different regions, the relative contribution of climate change to increased flood risk varies between 5/8 and 7/8, whereas socio-economic change results in zero to 2/8 of the total increase in annual expected damage.

4.5 Discussion and conclusions

The aim of this Chapter was to estimate future flood risk in 2030 for the entire Rhine basin. We took the year 2000 as a reference and used scenarios in a model simulation to assess changes in flood probability due to climate change, and to assess changes in potential damage due to land-use change. The combined simulations provided different projections for future flood risk.

It was found that, in absolute terms, potential flood damage is highest in the Dutch Delta region (G), namely €110 billion, compared to €71 billion of the second highest value in the Lower Rhine region (E). Flood risk (damage × probability) is, on the other hand, much higher in other regions, most notably in the Lower Rhine region E (€350 million per year) and the Upper Rhine C (€290 million per year), whereas the Dutch Delta region (G) only reaches €87 million per year.

Our research further projected that flood risk in the Rhine basin will not be stationary and might considerably increase over a period of several decades. Expected annual damage in the entire Rhine basin may increase by between 54% and 230%, due to socio-economic and climate change. The results display large variations in current risk and flood-risk projections between regions along the Rhine. The increase in flood risk can mainly be attributed to increasing probabilities of flood peaks due to climate change (43–160%, which is ∼ 6/8 of the total risk increase), whereas socio-economic change accounts for 7.5–27% increase, which is ∼ 1/8 of the total risk increase. This is in contrast with the findings of Bouwer et al. (2010), who found, for a Dutch polder, that the effects of socio-economic change and climate change are similar in magnitude (climate change: 46–201% increase; socio-economic change: 35–172% increase, which resulted in an estimated total increase of between 96 and 719%). However, they used 2040 as scenario year, while we addressed 2030. Also, Bouwer et al. (2010) included projections for increasing capital value in their socio-economic scenarios, in addition to projections for land-use change. This accounts for the major part of their estimate of the contribution from socio-economic change to total flood risk. When wealth increase is not included in Bouwer et al. (2010), the relative change in flood risk is much more similar (socio-economic change inflicts an increase of 3–44%). We omitted wealth increase projections for the Rhine basin due to lack of reliable future projections for the entire basin.
Our method provides a more comprehensive assessment of basin-wide flood risk in the Rhine than was previously possible as existing studies either assessed flood risk in the Netherlands or in upstream areas in Germany (Apel et al., 2004; Klijn et al., 2007; Aerts et al., 2008b; Bouwer et al., 2010). Furthermore, our method enables basin-wide scenario projections for future land use and potential damage, by integrating a land-use model with a damage model at a high spatial resolution.

We have shown that expected annual damage depends heavily on estimated flood-probabilities. Further work might focus on acquiring actual safety levels along the Rhine in more detail, by analyzing dike heights and water levels. In reality, there are no jumps in dike height or thus in safety levels along the Rhine between countries or Bundesländer, as we assumed here, but instead the shift is gradual. In addition, due to dike failure processes such as piping, the actual flood-probability might be much higher than the probabilities of flood events dikes are designed to cope with (Ministry of Transport, Public Works and Water Management, 2006a). On the other hand, due to over dimensioning of dikes, flood probabilities can also be much lower than currently perceived. Understanding this requires more research, which is ongoing in detail in the Netherlands (Ministry of Transport, Public Works and Water Management, 2006a), but, to our knowledge, not on a large scale in Germany and France.

Flood damage estimates contain uncertainties related to the choice of the damage model and the simulation of inundation depth. The uncertainty in absolute damage estimates and increases can be considerable when applying damage models (Apel et al., 2009; Merz and Thieken, 2009; De Moel and Aerts, 2010). However, the relative damage increase (increase as a percentage compared to the reference) is much more robust De Moel and Aerts (2010). For this reason, the absolute values of flood risk increase presented in this Chapter should also be interpreted with care.

In our approach, we assumed for the Netherlands that all areas (‘dike rings’) will inundate during a flooding event, while they might only partly flood in reality. Therefore, both basin-wide potential damage, as well as expected annual damage, do not provide information on the damage of a single event. For the part of the Rhine basin upstream of the Netherlands, we used inundation maps from the Rhine Atlas (ICPR, 2001) that are to date the best available. The Rhine Atlas assumes flood prone areas to inundate completely. However, several 2D hydrodynamic inundation simulations for the Lower Rhine by Lammersen (2004) showed that the flood-prone areas do not always entirely inundate, depending on breach locations and flood wave characteristics. We therefore recommend more inundation calculations upstream of the Netherlands which are currently only incidentally available, in order to aid further flood risk assessments.

Finally, the implementation of flood defense measures, such as retention basins and dike heightening, might prevent the increase in flood probability due to climate change, and thus the contribution of climate change to flood risk. This requires a thorough analysis of the effectiveness of flood management measures under different
climate change scenarios. Spatial planning policies and damage mitigation measures and risk transfer mechanisms, such as flood proofing of buildings and insurance, might further reduce flood risk. Such flood risk decisions may have implications for several decades. Therefore, flood risk management needs to deal with expected climate and socio-economic changes (Merz et al., 2010).

Acknowledgements

We would like to thank Christian Lindner and the Institut für Raumplanung Universität Dortmund for providing spatial data for the land-use model. The comments made by our colleague Peter Verburg are also gratefully acknowledged. Finally, we thank Walter Pfügner and an anonymous reviewer for their valuable comments. This research project was carried out in the framework of the Dutch National Research Programme Knowledge for Climate (www.knowledgeforclimate.org), which is co-financed by the Ministry of Housing, Spatial Planning and the Environment (VROM). Furthermore, the project was financed by Deltares and the Dutch Ministry of Transport, Public Works and Water Management (V&W).
Chapter 5

Effectiveness of flood management measures on peak discharges in the Rhine basin under climate change


Abstract

Climate change increases flood probabilities in the Rhine river basin, which complicates long-term flood management planning. This Chapter explores a method to evaluate the effectiveness of flood management measures for the river Rhine assuming a relatively extreme climate change scenario for the year 2050. Considered are planned measures described in the Rhine Action Plan on Floods and several additional measures, which include the restoration of abandoned meanders, a bypass around Cologne, the implementation of additional retention polders and land-use change to forest. The method includes resampling of meteorological data and a hydrological model to simulate long discharge series (10,000 years), and can be considered as a process-based approach to estimate peak discharges of low-probability flood events. It is found that upstream flooding in Germany has a profound decreasing effect on the simulated peak water levels and discharges along the main Rhine branch and downstream in the Netherlands. Currently implemented and proposed measures in the Action Plan
on Floods, as well as most additional measures, seem inadequate to cope with the increased flood probabilities that are expected in the future climate change scenario.

5.1 Introduction

Over the last decades, the number of fatalities and economic damage caused by river floods worldwide has increased considerably (e.g. Kron, 2009; Munich Re AG, 2008) and it is expected that flood risks will continue to increase due to climate change and the growth of economic wealth (Milly et al., 2005; Kundzewicz et al., 2007). A similar trend can be observed for the river Rhine in North-West Europe, where it is expected that climate change will have major implications for its discharge regime (Kwadijk, 1993; Middelkoop et al., 2001). Studies show that mean winter discharges are expected to increase by 5–30% and mean summer discharge to decrease by 0–45% by 2050 (compared to the current climate), using a range of climate change scenarios and hydrological modeling methods (Buishand and Lenderink, 2004; Hundecha and Bárdossy, 2005; Fujihara et al., 2008). As a consequence, the 1/1250 per year flood event for which dikes are designed in the lower parts of Rhine is estimated to increase from \(16,000 \text{ m}^3/\text{s}\) at present to between \(16,500\) and \(19,500 \text{ m}^3/\text{s}\) in 2050 (Kwadijk and Middelkoop, 1994; Te Linde et al., 2010).

Various flood management measures in the Rhine basin have already been developed according to the Action Plan on Floods (APF) that was initiated in the 1990s (ICPR, 2005a). Implemented and planned measures include dike relocation, the allocation of retention basins and land-use change to store water in headwatersheds. The APF is scheduled to be completely implemented by 2020. However, an evaluation of the APF in 2005 revealed that the targets for water level and risk reduction set out in the plan will not be met given current climate conditions (ICPR, 2005a). Moreover, the plan does not address the impact of climate change on peak discharges and questions exist as to whether the plan is effective in the long term, especially when focusing on managing extreme flood events.

Two methodological challenges exist, however, to evaluate the effectiveness of flood management measures targeted at managing extreme flood events. The first difficulties relate to the high safety standards in the Rhine basin (varying from 1/200 in Germany to 1/1250 per year in the Netherlands). These flood peaks have not been observed to date and current research extrapolates historical data to derive low-probability flood peaks (Lammersen et al., 2002; ICPR, 2005a; Bronstert et al., 2007). However, only a relatively short period of measured discharge data exists for the Rhine (\(\sim 110\) years) and extrapolation of these data may introduce large uncertainties (Klemes, 2000a,b; Shaw, 2002). Also, statistical extrapolation assumes stationarity of the observed data record. However, in the last 110 years, both meteorological conditions and the river
basin have changed, and the principle of stationarity does not hold, which probably adds to the uncertainty associated with the statistical extrapolation (Milly et al., 2008).

Hence, recent research suggests the use of resampling methods to create long time series (> 1000 years) of meteorological data (both current data and future climate scenarios) and use these data as input for hydrological models to create long discharge time series (Leander, 2009; Te Linde et al., 2010). In this way, meteorological and hydrological processes are simulated for extreme flood events and statistical extrapolation can be avoided.

A second challenge relates to the effect of upstream flooding in the Rhine basin. It appears that existing flood management evaluation studies for the Rhine did not incorporate the effect of upstream flooding, while it is known that upstream flooding does occur at extreme peak events and has a substantial reducing effect on peak discharges downstream in the Rhine delta (Te Linde et al., 2010).

This Chapter will explore a method to evaluate the effectiveness of flood management measures for different locations along the Rhine, assuming a climate change projection for 2050. To overcome the two methodological challenges mentioned above, our approach includes the resampling of meteorological data and a hydrological model to simulate long discharge series, including the effect of upstream flooding. Furthermore, using the long time series of possible discharges, an ensemble of different flood waves that belong to the same return period is selected, for different locations along the Rhine. A hydrodynamic model will then be used to evaluate measures that are proposed in the APF, as well as additional flood management measures, on their ability to reduce peak water levels and the probability of flooding.

The remainder of the Chapter is organized as follows. Section 5.2 describes the Rhine basin and briefly reviews its long history of flooding and flood management practice. In Section 5.3 the method and models are explained. Section 5.4 summarizes the results of the evaluation of flood management measures. Finally, Section 5.5 contains the discussion and conclusions and the outlook for further research.

5.2 Rhine basin

5.2.1 General description

The Rhine is a cross-boundary river located in North-West Europe and has a length of ca. 1320 km. It originates in the Swiss Alps and flows through parts of Germany, France, and Luxembourg, before it enters the Netherlands at Lobith (Figure 5.1). The Rhine basin comprises an area of ca. 185 000 km². Approximately 50% of the Rhine
basin is used for agriculture, 33% is forested, 11% is built-up, and the remaining 6% is surface water (Disse and Engel, 2001; Middelkoop et al., 2001). It connects one of the worlds largest sea harbors, the Port of Rotterdam, to the inland European markets and their large industrial complexes (Jonkeren, 2009). Approximately 58 million people inhabit the river basin and 10.5 million of these live in flood prone areas (ICPR, 2005c).
5.2.2 Flood management in the Rhine basin

Extreme flood events in the Rhine basin downstream of Maxau mainly occur during the winter and early spring (Beersma et al., 2008). Evaporation rates are low and soils are often saturated and sometimes frozen in winter, which can lead to increased runoff (Disse and Engel, 2001). Two more recent extreme flood events in the Lower Rhine and The Netherlands in 1993 and 1995 exemplified the vulnerability of the river basin to flood events.

Human activity has influenced the channel characteristics of the Rhine since the Roman era (Lammersen et al., 2002; Blackbourn, 2006). Prior to the 19th century, the Rhine was a multi-channel braided river system upstream of Maxau and meandering from that point downwards. In order to force an incision of the main Rhine branch with the aim of reducing flooding, the Upper Rhine was straightened between 1817 and 1890 (Blackbourn, 2006). Furthermore, to aid shipping, engineers further straightened and canalized the main branch up until 1955 and constructed weirs and dikes between 1955 and 1977.

These activities caused an acceleration in flood wave propagation in the Rhine (Lammersen et al., 2002) and hence increased flood risk downstream. This effect is illustrated in Figure 5.2, which displays the form of two flood waves originating from comparable rainfall volumes. One is before and the other is after the canalization of the main Rhine branch in the Upper Rhine. However, differences in the spatial distribution of the rainfall volumes might also add to the alteration of the discharge wave, since in the 1955 event the Neckar basin received a larger fraction of the precipitation than in 1882. Moreover, land-use change and urbanization directly along the main Rhine branch significantly contributes to increased flood risk, since urbanization in flood prone areas increase the potential economic losses due to floods (Hooijer et al., 2004).

These trends have led to major dike reinforcements along the Lower Rhine over the last 20 years. Safety levels vary from 1/200 to 1/500 per year in Germany, while in the Netherlands the 1/1250 per year flood peak is the basis for the design discharge of 16000 m$^3$/s (the maximum discharges for which flood protection measured are designed) (Silva, 2003). Due to lower safety levels in Germany, flooding may be occurring at upstream parts in Germany while the Dutch dike system is still protecting huge areas from inundation (Gudden, 2004; Apel et al., 2006).

5.3 Methods

Let us assume that $T$ equals $1/p$, where $p$ represents probability and $T$ the return period. The most correct way to describe a low-probability peak event is to denote the probability of occurrence per year (i.e. $1/1250$ ($p = 0.0008$) per year), rather than
to claim an event will occur once every \( x \) years (i.e. a return period of 1250 years). However, in frequency analysis of flood-peak probabilities it is common to discuss return periods, in order to prevent the use of fractions and very small numbers. In this Chapter, we will therefore use return periods when discussing low-probability peak events.

The different steps of the research approach in this Chapter are displayed in Figure 5.3. Steps 1, 2 and 3 focus on simulating long discharge series using resampled meteorological data and the hydrological model HBV (Section 5.3.1).

Due to computation time limits, it was not feasible to test the effectiveness of measures on all the annual maximums of the long discharge series, or on a large number of peaks above certain thresholds. Therefore, within steps 4 and 5, flood waves were selected for use in the evaluation of measures. The selection takes into account the fact that no unique flood wave exists that belongs to a specific return period. Instead, many different flood waves (in terms of duration and shape) exist that belong to, for example, the 1/1250 per year event. Hence, a specific measure that is evaluated using a single 1/1250 per year flood wave may perform differently when another 1/1250 per year flood wave is used (Lammersen, 2004; Te Linde et al., 2008b). Also, a 1/1250 per year flood wave at location \( A \) is not a 1/1250 per year flood wave at location \( B \), due to differences in river geometry and inflow from side branches. Therefore, we used an ensemble of flood waves in order to create representative flood waves at different return periods and locations. We selected four flood waves with different
5.3. Methods

Measures

Resampled time series and climate scenarios

Run HBV

Control climate

10,000 yrs daily P and T

10,000 yrs daily P and T

Wp scenario 2050

Selection process flood waves

at 4 locations: Lobith, Andernach, Kaub and Maxau

10,000 yrs daily Q at

4 locations: Lobith, Andernach, Kaub and Maxau

Run SOBEK

1) APF2002

2) AFP2020

3) Land use change to forest

4) Extra retention polders

5) Bypass Cologne

6) Increased friction by reforestation of the flood plains

7) Restored abandoned meanders Upper Rhine

8) Increased dike height

16 flood waves

Model runs and analysis

Evaluation of results

Figure 5.3: Flowchart describing all steps of the method. APF2002 are existing measures implemented in the framework of the Action Plan on Floods (ICPR, 2005a). APF2020 are planned measures for 2020.
return periods, at four locations, resulting in sixteen flood waves that can be used for the evaluation of flood measures.

Finally, steps 6, 7 and 8 involved the evaluation of seven flood management measures in terms of their effect on peak water levels and discharges using the selected flood waves and the models SOBEK and HBV (Section 5.3.1). The simulations included the effects of potential floods in the Upper and Lower Rhine. Results were analyzed at the gauging stations at Lobith, Cologne, Andernach, Kaub, Worms and Maxau.

5.3.1 Hydrological modeling

The semi-distributed conceptual HBV model (Bergström, 1976; Lindström et al., 1997) was developed for the Rhine in 1999 and since then recalibrated several times for the period 1961–1995 (Eberle et al., 2005). The model performs well for the Rhine basin (e.g. Nash&Sutcliffe=0.85; $r^2=0.97$, for daily discharge in 1993, Te Linde et al. (2008a)), but this paper does not further consider hydrological modeling uncertainty. The Rhine basin is represented by 134 sub-basins in HBV, and the model simulates snow accumulation, snowmelt, actual evaporation, soil moisture storage, groundwater depth and runoff. The model requires daily values of precipitation, temperature and potential evaporation as input. It uses different routines in which snowmelt is computed by a day-degree relation, and groundwater recharge and actual evaporation are functions of the water storage in a soil box. In this study, HBV is used to simulate daily discharges and to simulate the effect of the measure land-use change on discharges.

SOBEK is an integrated numerical modeling package that is based on the 1D St. Venant equations (Chow, 1959) (Appendix B) and runs at an hourly time step (Delft Hydraulics, 2005). SOBEK - contrary to HBV - is capable of simulating flood wave propagation, backwater effects, and damping in low gradient river stretches where floodplain inundation plays an important role. In this study, SOBEK is used for simulating the effect of upstream flooding and for the implementation of structural measures, such as dike heightening, dike relocation, weirs and retention polders.

5.3.2 Simulating long discharge series (Steps 1, 2 and 3)

We used a weather generator to create 10 000 years of daily precipitation and temperature data (Figure 5.3, Step 1) for 134 sub-basins of the Rhine basin. This so-called nearest-neighbour resampling technique was developed by Buishand and Brandsma (2001) and uses a historical meteorological data set that contains precipitation and temperature for the period 1961–1995 (Sprokkereef, 2001), which is further referred to as the control climate period. The method produces resampled time series of
10,000 years that have the same statistical properties as the original input data and has been thoroughly described by Beersma et al. (2001), Leander and Buishand (2007) and Te Linde et al. (2010).

We also applied the resampling technique on 35 years of meteorological data representing the year 2050, in order to simulate 10,000 years of climate change data. We applied the W-plus scenario from Van den Hurk et al. (2006) on the Rhine region following Te Linde et al. (2010). W-plus is an extreme climate scenario, based on combined global climate model (GCM) and regional climate model (RCM) outputs, with an annual mean temperature increase of 2.5°C, an increase in mean monthly winter rainfall of 14%, and a decrease in mean monthly summer rainfall of −19% (Van den Hurk et al., 2006). The W-plus scenario of projected climate in 2050 was obtained by the delta change approach. In this approach, the outputs from RCMs describing both the reference situation and the projected climate in 2050 are compared, in order to derive average changes of climate parameters. These average changes of precipitation and temperature are used to perturb observed meteorological series. These data were used as input for the hydrological model HBV to simulate daily discharges series of 10,000 years, for both the control climate and changed climate in 2050 (Figure 5.3, Step 2). For more information on the application of the delta change approach on the resampled time series, see Te Linde et al. (2010) where the authors compared climate projections obtained by the delta change approach to direct RCM output. They concluded that bias-corrected direct RCM output is to be preferred over the delta change approach because it provides insight in geographical differences and can simulate change in the number of precipitation days. However, they also observed that the delta approach is more transparent and more robust than using bias-corrected RCM output. Therefore, the delta approach has been used in several studies in the Rhine basin (Beersma et al., 2008), and we chose to do so as well in this paper to make our results comparable.

### 5.3.3 Selection of 16 flood waves (Steps 4 and 5)

From the 10,000 year series, we selected flood waves at four locations (Maxau, Kaub, Andernach and Lobith) Figure 5.1 and at four return periods ($T=10$, 200, 500 and 1250), resulting in 16 flood waves. These return periods are relevant for flood management policies in the Rhine basin. A flood wave at location $X$ culminates from unique meteorological conditions and discharge contributions from the sub-basins, and we define those conditions as a unique flood event for location $X$. The selection was done both for the control climate and changed climate in 2050. To obtain results for the additional locations Worms and Cologne we used flood events that were set for relatively nearby locations. These locations showed comparable peak flow characteristics when we analyzed discharge data at multiple locations. The flood event
conditions at Maxau were also applied to Worms, and the flood events at Andernach were also applied to Cologne.

The selection process at each location consists of the following. First, we constructed probability plots of 10,000 yearly maxima that were extracted from the simulated daily discharges by HBV. Second, we fitted extreme value distributions through these points, and from these relations we derived the peak discharge at each return period of interest. Third, at each return period, we extracted an ensemble of five flood waves from the daily discharge series of 10,000 years that reach peak discharges closest to the derived peak discharge by extreme value analysis. These flood waves differ in shape and duration, but their peak discharges are considerably similar and thus belong to the same return period (the grey lines in the four $Q - t$ plots in Figure 5.3, Step 4). Finally, we created one representative flood wave per location and return period as being the mean of the ensemble (the thick black lines in the $Q - t$ plots in Figure 5.3, Step 4). More details on the selection process are available in Te Linde (2009).

5.3.4 Hydraulic modeling and description of measures (Steps 6 and 7)

We used the 16 selected flood waves as boundary conditions for the hydrodynamic model SOBEK (Figure 5.3, Step 7). The SOBEK schematization contains the main Rhine branch downstream from Maxau, including the branches in the Netherlands. The main tributaries (i.e. Mosel, Main, Neckar) are also schematized for several kilometers upstream of their mouth to the Rhine. The model contains geometry of the cross sections at every 500 m, includes retention polders as they currently exist in the Rhine, and is calibrated by tuning bed friction values (Van der Veen, 2007). Upstream flooding in Germany is schematized as large retention polders with regulated inlet and outlet structures (see for details: Van der Veen et al., 2004; Te Linde and Aerts, 2008). The total potential volume available for flooding is 3892 Mio m$^3$ (Eberle et al., 2004).

In addition to implementing measures from the APF (nos. 1 and 2 in step 6, Figure 5.3), we developed six flood management measures (nos. 3 to 8 in step 6, Figure 5.3). The measure land-use change to forest was simulated using HBV and the remaining measures were schematized in SOBEK. SOBEK was also used for simulating upstream flooding. Measure no. 8 simulates the effect of increased dike height to such an extent that upstream flooding cannot occur. See Te Linde (2009) for a more detailed description of the measures.
5.3. Methods

Existing APF measures (APF2002) and planned APF measures for 2020 (APF2020)

The APF measures are listed in Table 5.1; they can be divided into measures realized in 2002 (APF2002) and planned for 2020 (APF2020). The majority of the measures are controlled flood retention polders, while at some locations, dikes are relocated. The total retention volume in the reference situation in 2002 is $121 \times 10^6$ m$^3$ and in 2020 it is planned to have increased this to $294 \times 10^6$ m$^3$. APF2002 is the SOBEK model schematization that contains all flood protection measures of the APF that were implemented in 2002 (Table 5.1), and is used as the reference situation in this study. All measures under consideration are implemented upstream of Lobith (see also: Lammersen, 2004; ICPR, 2005a; Bronstert et al., 2007).

Additional retention polders

We implemented several additional retention polders to the APF measures to temporarily store parts of the peak discharge volume. Their location and size are displayed in Table 5.1, and are based on Raadgever et al. (2008). The total additional volume is 140 Mio m$^3$. The operational rules for these retention polders to start inundating at a defined water level or discharge were derived from surrounding retention polders as schematized in APF2020.

Land-use change to forest

Reforestation is often perceived as an efficient measure to reduce flooding. In theory, higher interception, evaporation and infiltration rates result in reduced runoff volumes (Hundecha and Bárádyossy, 2004). The effectiveness, however, of reforestation seems to depend on scale and reduces with increasing basin size (FAO, 2005; Bronstert et al., 2007) and the discussion continues on the links between deforestation, reforestation and floods (e.g. FAO, 2005; Bruijnzeel, 2008).

HBV distinguishes four land-use classes (forest, non-forest, lakes and glaciers) and these have different interception values, potential evaporation rates and soil structure. The more diversified land-use classes in the HBV schematization of the Rhine basin, such as arable land and built-up areas (Table 5.2), are represented by different factors for infiltration rates and potential evaporation (Eberle et al., 2000). In the reforestation measure, we replaced all non-forest classes in HBV with mixed forest, which results in a 96.2% cover of forest in the whole basin, 2.4% rock and glacier and 1.4% lake.
Table 5.1: Measures along the Rhine where RP is retention polder and DR is dike relocation. Displayed are the location and volume of implemented measures in 2002 in the Action Plan on Floods (APF2002) and planned measures for 2020 (APF2020), and the measure ‘additional retention polders’ (* is used to highlight the additional retention compared to APF2020).

<table>
<thead>
<tr>
<th>Rhine km</th>
<th>Name</th>
<th>Type</th>
<th>Volume (10⁶ m³)</th>
<th>Measure APF2002</th>
<th>Measure APF2020</th>
<th>Additional retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>Basel</td>
<td>RP</td>
<td>6.5</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>235</td>
<td>Breisach/Burkheim</td>
<td>RP</td>
<td>7.7</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>253.5</td>
<td>Mouth of the Elz</td>
<td>RP</td>
<td>5.3</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>275</td>
<td>Erstein</td>
<td>RP</td>
<td>7.8</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>276</td>
<td>Ichenheim/Meisenheim</td>
<td>RP</td>
<td>5.8</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>Altenheim</td>
<td>RP</td>
<td>17.6</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>308</td>
<td>Freistett</td>
<td>RP</td>
<td>9.0</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>321</td>
<td>Söllingen/Grefferen</td>
<td>RP</td>
<td>12.0</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>330</td>
<td>Moder</td>
<td>RP</td>
<td>5.6</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>359</td>
<td>Daxlander Au</td>
<td>RP</td>
<td>5.1</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>Maxau</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>368</td>
<td>Neupotzh/Wörth</td>
<td>DR + RP</td>
<td>16.2</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>381.3–383.0</td>
<td>Elisabethenwörth</td>
<td>RP</td>
<td>11.9</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>384</td>
<td>near Germersheim</td>
<td>RP</td>
<td>40.0</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>388.4</td>
<td>Mechtersheim</td>
<td>RP</td>
<td>7.4</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>390.4</td>
<td>Rheinschanzinsel</td>
<td>RP</td>
<td>6.2</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>392.6</td>
<td>Flotsgrün</td>
<td>RP</td>
<td>5.0</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>409.9</td>
<td>Kollerinsel</td>
<td>RP</td>
<td>6.1</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>411.5</td>
<td>Waldsee/Altrip/Neuhofen</td>
<td>DR + RP</td>
<td>9.1</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>436</td>
<td>Petersbus/Bannen</td>
<td>DR</td>
<td>1.4</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>438</td>
<td>Worms</td>
<td>DR</td>
<td>3.4</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>440</td>
<td>Mittlerer Busch</td>
<td>DR</td>
<td>2.3</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>488</td>
<td>near Darmstadt</td>
<td>RP</td>
<td>40.0</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>490</td>
<td>Bodenheim/Laubenheim</td>
<td>RP</td>
<td>6.4</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>517</td>
<td>Ingelheim</td>
<td>RP</td>
<td>3.8</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>546</td>
<td>Kaub</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>614</td>
<td>Andernach</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>660</td>
<td>Upstream Cologne</td>
<td>RP</td>
<td>50.0</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>668.5–673.5</td>
<td>Cologne-Langel</td>
<td>RP</td>
<td>4.5</td>
<td>v</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>688</td>
<td>Cologne</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>705.5–708.5</td>
<td>Worringer Bruch</td>
<td>RP</td>
<td>29.5</td>
<td>v</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>707.5–713.5</td>
<td>Monheim</td>
<td>DR</td>
<td>8.0</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>723.5–727.5</td>
<td>Itter-Himmelgeist</td>
<td>DR</td>
<td>2.0</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>Downstream Cologne</td>
<td>DR</td>
<td>60.0</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>750.5–754.5</td>
<td>Ilvericher Bruch</td>
<td>RP</td>
<td>8.4</td>
<td>v</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>760.5–769.5</td>
<td>Mündelheim</td>
<td>DR</td>
<td>3.0</td>
<td>v</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>797.5–803.5</td>
<td>Orsoy Land</td>
<td>DR</td>
<td>10.0</td>
<td>v</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>818.5–823.5</td>
<td>Bislicher Insel</td>
<td>DR</td>
<td>17.4</td>
<td>v</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>832.5–833.5</td>
<td>Lohwardt</td>
<td>RP</td>
<td>25.0</td>
<td>v</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>837.5–847.5</td>
<td>Griether Busch</td>
<td>RP</td>
<td>25.0</td>
<td>v</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>882</td>
<td>Lobith</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5.2: Current land use and the measure land-use change to forest in the Rhine basin.

<table>
<thead>
<tr>
<th>Land-use class</th>
<th>Current Area (km²)</th>
<th>Current Area (%)</th>
<th>Land-use change Area (km²)</th>
<th>Land-use change Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>62 194</td>
<td>38.7</td>
<td>154 719</td>
<td>96.2</td>
</tr>
<tr>
<td>Arable land</td>
<td>36 304</td>
<td>22.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Grassland</td>
<td>45 294</td>
<td>28.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Built-up areas</td>
<td>7 930</td>
<td>5.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rock and glacier</td>
<td>3 797</td>
<td>2.4</td>
<td>3 797</td>
<td>2.4</td>
</tr>
<tr>
<td>Lakes</td>
<td>2 284</td>
<td>1.4</td>
<td>2 284</td>
<td>1.4</td>
</tr>
<tr>
<td>Other</td>
<td>2 996</td>
<td>1.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>160 800</strong></td>
<td><strong>100</strong></td>
<td><strong>160 800</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

**Cologne bypass**

Cologne suffered from flooding in the years 1993 and 1995. The economic damage in 1993 was estimated at €75 million. However, in spite of improved disaster management after the 1993 and 1995 floods, the city remains at high risk, since a flooding event at $T=200$ years (the current flood protection standard around Cologne) will result in water depths around 3 m in large parts of the city (Gocht and Vogt, 2008).

To lower the water levels around Cologne during extreme floods, a bypass is proposed. A potential location for this bypass is shown in Figure 5.1. Since a hilly region borders the region east of Cologne, we chose a western route with relatively little urbanization. The bypass has a length of 72 km, starting at Rhine kilometer ($rkm$) 664, and ending at $rkm$ 712, with Cologne being located at $rkm$ 688). The cross section of the bypass has a depth of 10 m and a width of 120 m, whereas the main channel through Cologne measures around 350 m in width. Identical cross sections were placed at every 500 m and the bottom level was linearly interpolated between $rkm$ 664 and 712. Friction values of the bypass are assumed to be the same as in the main Rhine branch.

**Increased friction by reforestation of the floodplains**

Increasing hydraulic friction in floodplains by reforestation or small dams is controversial as current policies in the Rhine are aimed at removing obstacles to increase flow velocity (Ministry of Transport, Public Works and Water Management, 2006c). Our hypothesis, though, is that reducing flow velocity in an upstream part of the river might be beneficial downstream.

We tested the effectiveness of the measure by assuming an emergent vegetation cover in all the flood plains in the Upper as well as in the Lower Rhine. We assumed the height of a soft wood production forest as more than 3 m. According to the literature
Table 5.3: Properties of the measure restored abandoned meanders. The location names are displayed in Fig. 1. Maxau is located at Rhine kilometer (rkm) 360 and Worms at rkm 438.

<table>
<thead>
<tr>
<th>Location</th>
<th>Length (km)</th>
<th>Width (m)</th>
<th>rkm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neupotz</td>
<td>7.5</td>
<td>400</td>
<td>367.5</td>
</tr>
<tr>
<td>Linkenheim</td>
<td>3.9</td>
<td>300</td>
<td>367.5</td>
</tr>
<tr>
<td>Hoerdt</td>
<td>13.2</td>
<td>200</td>
<td>373</td>
</tr>
<tr>
<td>Lingenfeld</td>
<td>14.8</td>
<td>200</td>
<td>385</td>
</tr>
<tr>
<td>Philipsburg</td>
<td>7.0</td>
<td>200</td>
<td>389</td>
</tr>
<tr>
<td>Roermerberg</td>
<td>7.6</td>
<td>200</td>
<td>391</td>
</tr>
<tr>
<td>Hockenheim</td>
<td>17.8</td>
<td>200</td>
<td>399</td>
</tr>
<tr>
<td>Otterstad</td>
<td>4.2</td>
<td>200</td>
<td>403</td>
</tr>
<tr>
<td>Ketsch</td>
<td>5.6</td>
<td>150</td>
<td>406</td>
</tr>
<tr>
<td>Waldsee</td>
<td>18.1</td>
<td>150</td>
<td>409</td>
</tr>
<tr>
<td>Bobenheim</td>
<td>11.3</td>
<td>150</td>
<td>436</td>
</tr>
<tr>
<td>Lampertheim</td>
<td>8.6</td>
<td>150</td>
<td>438</td>
</tr>
<tr>
<td>Gimbelsheim</td>
<td>11.3</td>
<td>400</td>
<td>466</td>
</tr>
<tr>
<td>Stockstadt am Rhein</td>
<td>16.9</td>
<td>300</td>
<td>467.5</td>
</tr>
<tr>
<td>Oppenheim</td>
<td>17.8</td>
<td>300</td>
<td>476</td>
</tr>
<tr>
<td><strong>Total length</strong></td>
<td><strong>200.7 km</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

the roughness coefficient (Manning) is 0.10 (Chow, 1959; Straatsma and Baptist, 2008). As only the floodplains will be forested, the value has been implemented only in the floodplain sections of the SOBEK schematization.

**Restored abandoned meanders of the Upper Rhine**

Increasing the river length substantially by restoring abandoned meanders is currently not implemented on a large scale in water management practices in the Rhine basin. However many abandoned meanders are still visible in the landscape as small depressions and sometimes as oxbow lakes. They are often not densely built upon, but are used for agriculture, grassland and nature. To simulate the restoration of these abandoned meanders, we schematized many additional branches in the Upper Rhine in the SOBEK model, based on Google Earth satellite images. We maintained the main channel, though, to allow for shipping. All additional branches are listed in Table 5.3 and displayed in Figure 5.1.

**Increased dike height**

We increased the dike height in our SOBEK model along all the branches to such an extent (several meters) that water levels would never reach the crest level. The
possibility of dike failure is ignored. In this way, we created a situation where upstream flooding cannot occur.

5.4 Results

Figures 5.4 and 5.5 summarize the modeling results for the change in peak discharge and water levels, respectively. In the left panels the APF2002 simulation with control climate boundary conditions is used as a reference. The crosses in the same panels display the effect of the APF2020 measures compared to the reference situation. The circles in the left panels indicate the effect of climate change in 2050 in combination with the APF2020 measures on maximum water levels, also compared to the reference situation.

In the right panels the APF2020 simulation with the climate change boundary conditions is used as a reference. All additional measures are evaluated against this reference situation and are indicated with different symbols (see the legend). Tables 5.4 through 5.7 contain all the numbers that are shown in Figures 5.4 and 5.5.

The effect of dike heightening is relatively large (about a factor 4 larger than the effects of other measures) and hence does not fit well on the vertical scale in the right panels of Figures 5.4 and 5.5 (see Section 5.4.1). Hence, the effect of (extreme) dike heightening to an extent that no flooding occurs is not displayed in Figures 5.4 and 5.5.

Furthermore, it should be noted that in the right panels of Figure 5.4, no effect of the measures at the location Maxau can be observed, except for land-use change to forest. This can be explained by the way the SOBEK model operates. SOBEK uses an imposed discharge series as upstream boundary conditions, which we derive from the HBV simulations. The model only calculates water levels belonging to the discharge series at this node. Thus, discharge remains the same, while water levels vary between different simulations due to adjustments in the river geometry or friction values downstream. In our model setup, Maxau is the upstream boundary node, and therefore, no effect on the discharge is observed at Maxau (Figure 5.4). The water level, on the other hand, does change between simulations at Maxau (Figure 5.5).

Land-use change to forest is the only exception, since it influences the discharge generation by HBV through changed soil characteristics. As a result, the boundary discharge imposed at Maxau changes, which can be observed in Figure 5.4. The water level due to land-use change also changes (Figure 5.5).
Figure 5.4: Effect of strategies and the Wplus climate change scenario on maximum discharge ($m^3/s$). In the left panels the APF2002 schematization with control climate boundary conditions is used as reference. In the right panels the APF2020 schematization with the climate change boundary conditions is used as reference (W plus scenario for 2050). All values are displayed in Table 5.4 and 5.6. L is Lobith, A is Andernach, K is Kaub, W is Worms and M is Maxau.
Figure 5.5: Effect of strategies and the W-plus climate change scenario on maximum water level. In the left panels the APF2002 schematization with control climate boundary conditions is used as reference. In the right panels the APF2020 schematization with the climate change boundary conditions is used as reference (W-plus scenario for 2050). All values are displayed in Table 5.5 and 5.7. L is Lobith, A is Andernach, K is Kaub, W is Worms and M is Maxau.
Table 5.4: Effect of planned measures for 2020 and W-plus climate change scenario on peak discharge (m³/s). The numbers are plotted in Figure 5.5, left panels.

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Table 5.5: Effect of planned measures for 2020 and W-plus climate change scenario on peak water level (m). The numbers are plotted in Figure 5.6, left panels.

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Table 5.6: Effect of additional measures on maximum discharge (m$^3$/s). The numbers are plotted in Figure 5.5, right panels.

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<td>109.13</td>
<td>-0.31</td>
<td>0.00</td>
<td>0.76</td>
<td>-0.19</td>
</tr>
</tbody>
</table>
5.4.1 Basin-wide effects

Climate change

The mean increase in peak discharge due to climate change in 2050, when APF2020 measures are implemented, is 770 m$^3$/s, but the increase shows a large variation among locations and return periods (Table 5.4, Figure 5.4, left panels). For example, at Andernach at $T=500$, the discharge increase is 755 m$^3$/s, while at Maxau at $T=500$, the increase is 1727 m$^3$/s. The mean increase in peak water level is 50 cm, but varies between several centimeters and 137 cm (Table 5.5, Figure 5.5, left panels).

Increased dike height

From Tables 5.6 and 5.7 we can read that at $T=10$ in the W-plus climate change scenario, raising dikes has hardly any effect on water levels and discharges. Apparently, under climate change, flooding does not occur at any of the five locations along the Rhine at current dike heights, and thus raising them has no effect. To be more precise we should explain that Kaub is located at the Middle Rhine, where the river flows through a narrow valley, and is currently not embanked by dikes. In the model setup with increased dike height, we also embanked the Rhine at Kaub.

At higher return periods, though, peak water levels rise when dike heights are increased. This implies that flooding will occur at these return periods under climate change, when dike heights are left at their current levels. The maximum water level increase at Lobith is 129 cm ($T=1250$), at Andernach 212 cm ($T=200$), at Kaub 325 cm ($T=500$) and at Worms 245 cm ($T=1250$) (Table 5.7). At Maxau, no flooding occurs in our model, and thus increasing dike height has no effect. This relates again to Maxau being the upper boundary node of the SOBEK model. From Figure 5.1 we can learn, though, that Maxau lies within the flood prone area of the Rhine, and the flood prone area extends even further upstream up to Basel.

Peak discharge at return periods above $T=10$ increase between 1238 m$^3$/s at Lobith ($T=500$) and 4378 m$^3$/s at Lobith ($T=1250$). Our results imply that a dike raise is needed along the Rhine that varies between 1.29 m and 3.25 m, depending on location, to prevent these areas from flooding.

Land-use change to forest

Land-use change to forest seems an efficient measure to reduce peak discharges and peak water levels at a basin-wide scale. All simulated annual discharge maximums decrease by 114 m$^3$/s up to 1012 m$^3$/s as a result of land-use change to 96% forest,
and water levels decrease between 4 cm and 53 cm (Tables 5.6 and 5.7, Figures 5.4 and 5.5, right panels). Reforestation in the Rhine basin results in lower peak discharges and water levels at all simulated return periods, i.e. even at the most extreme peak events. Reduced flood discharge from the tributaries is probably due to both higher evaporation and infiltration rates, causing a decrease in the baseflow.

5.4.2 Local effects of flood management measures

APF2020

The APF2020 measures result in peak discharge reductions of only $-80 \text{m}^3/\text{s}$ and water level reductions of $-5 \text{cm}$ both for current climate conditions and the increased discharges under climate change (Figures 5.4 and 5.5, left panels). The minor effectiveness of the APF2020 can be explained by two phenomena that relate to (1) the way the retention polders are operated and (2) on whether upstream flooding occurs, both illustrated in Figure 5.6.

(1) Retention polders are designed to reduce the maximum water level of a flood peak by inundating the retention area when the water level in the main river branch reaches a critical level. Retention basins in Germany become operational at $T=50$ to 100 (IKSR 2005). Their volumes are designed for peak events of corresponding size. At higher peak events, with return periods larger than 100 years, retention basins will be full when the maximum peak discharge arrives. In Figure 5.6a the APF2020 measures have some effect at $T=10$ at Lobith (indicated by the dashed line). Apparently, upstream of Lobith this particular flood wave reaches threshold levels (at $T=50$ or more) of several retention polders along the Rhine. Figure 5.6b shows that retention polders become operational at the same discharge as in Figure 5.6a ($\sim 10,500 \text{m}^3/\text{s}$), but that the flood peak reaches a level where retention polders fill up completely, and the efficiency of the retention polders declines. This explains partly the ineffectiveness of the retention measures in the APF2020 at extreme discharges of more than $12,000 \text{m}^3/\text{s}$ at Lobith at $T=200$ and more.

(2) Upstream flooding acts as a major retention basin, therefore blurring the effect of the actual planned retention polders. At $T=10$ and $T=100$ (Figure 5.6a and b), no upstream flooding occurs. At $T=200$, though, flooding does occur (Figure 5.6c). When the effectiveness of the retention polder is tested in a simulation run without flooding (black line), the retention polders become operational at $\sim 10,500 \text{m}^3/\text{s}$, as in Figure 5.6a and b, and manage to decrease the maximum peak discharge of $13,000 \text{m}^3/\text{s}$ by $\sim 100 \text{m}^3/\text{s}$ (the dark gray dotted line).

When flooding is simulated, the maximum peak discharge reaches only $12,000 \text{m}^3/\text{s}$ (the grey line in Figure 5.6c). Flooding apparently occurs at $11,000 \text{m}^3/\text{s}$ at Lobith
Figure 5.6: Effect of APF2020 retention measures on flood peaks with different return periods at Lobith, with and without the simulation of flooding. Flooding does not occur at $T=10$ and 100.
and retains a substantial volume, illustrated as the area between the black and gray lines. The relatively small volume of the APF2020 measures scarcely inflicts extra retention (the dotted line). This further explains why in Figures 5.4 and 5.5 the effects of APF2020 measures are scarcely visible.

Additional retention polders

The additional retention volume results in a mean decrease of flood peak water levels of 3 cm, and varies between 0 and 13 cm, depending on the location (Table 5.7). The operational rules of retention polders, i.e. at which water level or discharge they become operational, are the same as schematized for retention volumes planned for 2020 that are closest to the additional retention polders. This means that these additional retention volumes are also most effective at $T=50$ to 100. Furthermore, flooding obscures the dampening effect of these retention measures, in the same way as described above in Section 5.4.2 for the APF2020 measures.

Increased friction by reforestation of the floodplains

Increasing friction by reforestation of all floodplains is very effective in lowering the discharge at all locations and return periods by 280 $m^3/s$ down to 970 $m^3/s$ (Figure 5.4 and Table 5.6). However, lower flow velocities result in a storing effect and hence higher water levels, comparable to the effect of a bottleneck. This storing effect is visible both at the Upper Rhine (Kaub, Worms and Maxau) and the Lower Rhine (Lobith and Andernach) (Figure 5.5). At Maxau, the water level increases by a mean value of 64 cm, at Worms there is no effect and at Kaub, the water level decreases by 41 cm. At Andernach, the water level increases by a mean value of 21 cm before it decreases by 29 cm at Lobith (Table 5.7). In short, increased friction might be beneficial on a local scale, but can easily have an opposite effect in the upstream direction.

Restored abandoned meanders in the Upper Rhine

Based on historical descriptions of the Rhine and its discharge behavior (Blackbourn, 2006), it was expected that increasing the flow path of the Upper Rhine by restoring abandoned meanders in our model would reduce flow velocity and broaden and attenuate flood waves basin-wide. However the results contradict this theory. The restored meanders result in increased discharges at all locations and over all return periods (Figure 5.4). It appears that since the canalized channel remains in use in this schematization (to aid shipping), the restored meanders are merely additional branches, creating an increased flow capacity and therefore increasing discharge. The
Table 5.8: Effect of the bypass around Cologne on peak discharge (m$^3$/s) and peak water level (m).

<table>
<thead>
<tr>
<th>Climate</th>
<th>Wp2050</th>
<th>Wp2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use</td>
<td>Current</td>
<td>Current</td>
</tr>
<tr>
<td>Dike height</td>
<td>Current</td>
<td>Current</td>
</tr>
<tr>
<td>Measures</td>
<td>APF2020</td>
<td>APF2020 and Cologne bypass</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Return period</th>
<th>Q</th>
<th>h</th>
<th>dQ</th>
<th>dh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cologne</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10542</td>
<td>45.45</td>
<td>−1939</td>
<td>−0.96</td>
</tr>
<tr>
<td>200</td>
<td>12258</td>
<td>46.40</td>
<td>−2240</td>
<td>−0.99</td>
</tr>
<tr>
<td>500</td>
<td>12786</td>
<td>46.70</td>
<td>−2320</td>
<td>−0.97</td>
</tr>
<tr>
<td>1250</td>
<td>13560</td>
<td>47.03</td>
<td>−3542</td>
<td>−0.85</td>
</tr>
</tbody>
</table>

Water levels therefore decrease in the Upper Rhine (−19 cm to −72 cm, Table 5.7), which is a positive result. In the Lower Rhine, on the other hand, water levels increase (up to 34 cm, Table 5.7) as a result of increased discharge, where there is no change in the flow capacity.

**Cologne bypass**

The bypass results in a substantial lowering of the peak water level of almost 1 m at Cologne (Table 5.8) and thus is very effective, but the effect is only local. Twenty percent of the total discharge runs through the bypass in the case of a flood peak event, and the probability of flooding decreases significantly for the city of Cologne (a Q$_{10}$ event will become a Q$_{1250}$ event, Table 5.8).

### 5.4.3 Longitudinal profiles of peak water levels

Longitudinal profiles of peak water levels can help to determine in more detail the location and the extent of effectiveness of flood management measures along the Rhine branch. As an example, we plotted the effect on peak water levels of different measures but for only one particular flood wave (one of the 16 available flood waves) in longitudinal profiles in Figure 5.7. The displayed flood wave has a return period of 200 years at Andernach. The water levels are plotted at every cross section at 500 m intervals.

In Figure 5.7a, the effect of flooding is illustrated, under current climate conditions (light blue), and under the W-plus scenario in 2050 (dark blue). Because the discharge is expected to increase as a result of climate change, the lowering of peak water levels
Figure 5.7: Longitudinal profile of the change in peak water level ($dh$). The boundary conditions are $T=200$ at Andernach (see Section 5.3.3). Displayed are, a) the effect of flooding, under control climate conditions (light blue), and under the W-plus scenario in 2050 (dark blue); b) the effect of climate change, in a schematization with infinite dike heights (no upstream flooding) (magenta), and at current dike height (flooding occurs) (purple); c) the effect of Cologne bypass (grey) and 96% forest (black).
under the W-plus scenario is higher than under current conditions. The range of the decrease is 50 to 150 cm under current climate conditions and 100 to 250 cm under climate change in 2050.

In Figure 5.7b, the effect of climate change is displayed, in a schematization with infinite dike height (no flooding) (magenta), and in a schematization with current dike height (flooding can occur) (purple). The water level increases up to 200 cm as a result of climate change, when upstream flooding is not simulated. When upstream flooding is simulated, from \( rkm \) 600 and downward, there is no increase in water level. It seems that the increase in peak water levels from climate change is compensated completely by the effect of flooding. Nevertheless, on the Upper Rhine an increase of peak water levels due to climate change remains, even when flooding is simulated.

Figure 5.7c displays the local effect of the bypass around Cologne (light grey). The basin-wide decrease in maximum water level as a result of reforestation is also shown (black).

### 5.4.4 Flood-peak probability at Lobith

So far, we have evaluated the effect of climate change and flood management measures on reducing flood-peak discharges and water levels, at different return periods. These results, however, do not provide information on how extreme value distributions of yearly maximum flood-peaks, and thus flood-peak probabilities, might change.

Therefore, in this section, we will analyze the effectiveness of a few flood management measures, the effect of climate change and the effect of upstream flooding on flood-peak probabilities. We limit the analysis of flood management measures to APF2020 and land-use change to forest, and to the gauging station Lobith (at the border of the Netherlands and Germany). To do this, we made several extra runs of 1000 years using the same model setup with HBV and SOBEK. The reference situation contains all the flood protection measures of the APF that were implemented in 2002.

Simulation results of 1000 years of yearly maximum peak discharges for different scenarios are shown in extreme value plots in Figure 5.8 and Table 5.9. According to Figure 5.8a and 5.8b, flood probability will increase by a factor of 4 as a result of the Wp climate change. However, both in the control climate and when using a climate change scenario for 2050, the effects of flooding can be seen at discharges above 12 500 m\(^3\)/s. Without flooding, the extreme values describe more or less a straight line in the extreme value plots in Figure 5.8 (indicated by circles). As flooding tops off the highest peaks (crosses), a breakpoint can be observed in extreme value plots.

The increase in peak discharge as a result of climate change ranges from 16–19% when upstream flooding does not occur, and from 8–11% when upstream flooding is taken
5.4. Results

Figure 5.8: Extreme value plots for the yearly discharge maxima at Lobith for different climate conditions and measures. Contr cl is control climate, fl is flooding, clim ch (Wp) is the Wp climate change scenario for 2050.
Table 5.9: Estimated return periods obtained by ranking the 1000 years of simulated peak discharges at Lobith according to size, and linking return periods to the ranks.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Return period</th>
<th>Control climate Without upstream flooding</th>
<th>W plus (2050) Without upstream flooding</th>
<th>Control climate With upstream flooding</th>
<th>Wp (2050) With upstream flooding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>15694 (16.1) m³/s (%)</td>
<td>18215 (16.1) m³/s (%)</td>
<td>13918 (11.0) m³/s (%)</td>
<td>15445 (11.0) m³/s (%)</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>15047 (17.6) m³/s (%)</td>
<td>17696 (17.6) m³/s (%)</td>
<td>13719 (7.9) m³/s (%)</td>
<td>14809 (7.9) m³/s (%)</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>14321 (16.6) m³/s (%)</td>
<td>16704 (16.6) m³/s (%)</td>
<td>13052 (10.8) m³/s (%)</td>
<td>14457 (10.8) m³/s (%)</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>12880 (17.9) m³/s (%)</td>
<td>15186 (17.9) m³/s (%)</td>
<td>12554 (8.1) m³/s (%)</td>
<td>13576 (8.1) m³/s (%)</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
<td>11938 (18.5) m³/s (%)</td>
<td>14147 (18.5) m³/s (%)</td>
<td>11807 (10.3) m³/s (%)</td>
<td>13025 (10.3) m³/s (%)</td>
</tr>
</tbody>
</table>

into account (Figure 5.8a and 5.8b). The breakpoint due to flooding is at \( T=100 \) (≈12,500 m³/s) in the reference situation, while under climate change it corresponds to \( T=25 \) (i.e. a factor of 4 increase in probability of flooding). Flooding in areas upstream of Lobith significantly lowers discharge peaks at Lobith, with 2–13% in the control climate and 10–19% in the W-plus climate change scenario. The curve in Figure 5.8a and 5.8b indicates that there is a physical maximum of the peak discharge that can reach Lobith, due to upstream flooding.

Figure 5.8c and 5.8d visualize the effect of the APF2020 measures in a control climate situation without and with flooding. It shows that the retention polders become operational between \( T=20 \) and 200, with a minimal decreasing effect on peak discharge. Considering Figures 5.8a through 5.8d, it is obvious that the APF2020 cannot restrain the impact of climate change. Finally, Figure 5.8e shows the effect of land-use change in the Wp climate change scenario. All flood peaks are lowered by ≈ 1000 m³/s as a result of reforestation to 96% forest in the Rhine basin.

### 5.5 Discussion and conclusions

#### 5.5.1 Methods

The aim of this Chapter was to explore a method to evaluate the effectiveness of flood management measures that are planned in the Action Plan on Floods (ICPR, 2005a) and additional measures along the river Rhine, assuming a climate change scenario for 2050.

Our approach addressed two methodological challenges needed to evaluate the effectiveness of flood management measures in the Rhine basin. First, we explained the issue of high safety standards in the Rhine basin (up to 1/1250 per year) that requires
extrapolation of historical time series to reach peak flows at such low probabilities of occurrence. In addition, extrapolation assumes stationarity of the data record, while both meteorological conditions in and physical conditions of the river basin have changed. Both issues introduce uncertainty. In the traditional way of estimating dimensions of low-probability flood peaks based on 100 years of observations, the statistical uncertainty is 13\% more or less discharge volume at the 1/1250 per year event (Silva et al., 2001; Te Linde et al., 2010). In order to tackle this uncertainty, we applied a weather generator to create long time series of meteorological data (10 000 years) at multiple locations that were used as input for hydrological models in order to simulate long discharge series. These long time series have proven to be useful in reducing the statistical uncertainty from 13\% to 3\% at Lobith when estimating dimensions of low-probability flood peaks, because extrapolation of extreme value distribution fits is no longer necessary (e.g. Te Linde et al., 2010).

Also, in our simulation approach, the impacts of climate change and the alterations in river geometry and land use due to human influence are parameterized in models, in an attempt to physically describe extreme situations and the consequences of changed conditions. In doing so, we reject the basic assumption of stationarity of water systems, following Pielke Sr. et al. (2009). Such a simulation approach is referred to as `process-based` by McMillan and Brasington (2008), and is advocated by Sivapalan and Samuel (2009) and Raff et al. (2009). The method allows us to simulate flood waves at very low probabilities to test the effectiveness of measures upon extreme events. However, the use of a resampling technique to generate extreme events inherits an unknown uncertainty, since it has been trained using a relatively short reference period (35 years) which does not necessarily include such extremes.

The second methodological issue was the necessity to include hydrodynamic modeling to allow for the simulation of upstream flooding. Existing flood management evaluation studies for the Rhine did not incorporate upstream flooding ICPR (2005a); Bronstert et al. (2007), while upstream flooding does occur at extreme peak events and has a substantial reducing effect on discharges downstream in the Rhine delta (Lammersen, 2004). We found that flooding in the Upper and Lower Rhine in Germany, upstream of Lobith, has a profound decreasing effect on discharge peaks at Lobith. The decrease varied between 2–13\% in control climate conditions and 10–19\% in the W-plus climate change scenario. The curve in Figure 5.8a and 5.8b indicate that there is a physical maximum of the peak discharge that can reach Lobith, due to upstream flooding.

Hence, upstream floods in Germany are favorable for reducing flood risk in the downstream areas of the Netherlands. However, it is possible that future flood policies in Germany will aim at raising their dikes, especially in a scenario with increased flood probabilities due to climate change. This may increase peak discharges and water levels downstream (in the Netherlands).
5.5.2 Effectiveness of measures

The mean increase in peak water level due to climate change in 2050 is 50 cm, but varies between several centimeters and 137 cm (Table 5.5, Figure 5.5, left panels). Currently implemented and proposed measures in the Action Plan on Floods, as well as most additional measures we evaluated, seem inadequate to cope with increased flood probabilities that are expected in a future climate change scenario. According to our results, the only measure that can prevent the Rhine from flooding is drastic dike heightening of between 1.29 and 3.25 m, depending on location, on the assumption that these dikes cannot fail.

The APF2020 measures, as well as additional retention polders, reduce peak water levels by 5 cm to 13 cm over medium return periods (between 50 and 100 years) for the control climate. At $T=200$ and more, they have no effect at all. The minor effectiveness of the APF2020 can be explained firstly by the way the retention polders are operated. We have shown that retention polders as outlined in the APF2020 become operational between $T=20$ and 200, and require well-defined control rules and excellent flood forecasting in order to operate optimally, which is also explained by (Lammersen, 2004). At higher flood peaks with longer return periods, such as in our simulations, they are not effective.

Second, upstream flooding acts as a major retention basin, therefore blurring the effect of the actual retention polders. Flooding retains a substantial volume, illustrated as the area between the black and gray lines in Figure 5.6, and the relatively small volume of the APF2020 measures and additional retention polders hardly imposes extra retention.

Increased friction by reforestation of the flood plains showed to be beneficial at a local scale by lowering the water level several decimeters. However, higher friction values resulted in a storing effect that caused increased water levels in the upstream direction. Swiatek and Kubrak (2007) explain in an experimental study how vegetation causes the reduction of an active area of a cross-section, increases flow resistance and finally generates rising water levels.

The bypass around the city of Cologne reduced water levels at a local scale. Restoration of abandoned measures in the Upper Rhine was also very effective in reducing water levels locally, but resulted in increased water levels in the Lower Rhine.

Land-use change to forest decreased maximum water levels between 4 cm and 53 cm. The range in percentage of decrease in discharge is between 2% and 9%. However, modeling land-use change with conceptual models, such as HBV and RhineFlow (Van Deursen and Middelkoop, 2001), has limitations, since these models cannot represent all the processes influenced by land-use change. For example, simulations of the HBV model are very sensitive to changes in the maximum field capacity (Seibert, 1999).
The basin-wide model might perform well, while field capacity parameters might be over- or underestimated for different land-use classes. Also, HBV assumes higher evaporation rates in forests, which results in smaller saturated areas in case of heavy rainfall. A change in land use can then inflict a large shift in the simulated discharges by HBV, but these can be model artefacts.

Physically-based rainfall-runoff models describing soil-surface processes in more detail than conceptual models should be able to perform better, but are very demanding in terms of data requirement, parameter estimation and computation time. Hurkmans et al. (2009) therefore used the land surface model VIC in an effort to simulate relative changes in peak discharge due to land-use change by describing several processes in more detail than HBV does, such as infiltration and evaporation rates. As a result, VIC requires more input data and calibration parameters. Te Linde et al. (2008a). The authors used a scenario of 80% forest, 11% grass and 4.6% urbanized area. However, in their results, even at a $Q_{1000}$ event, this scenario hardly inflicted any change in peak discharge (< 1%) at Lobith, nor in sub-basins such as the Mosel or the Neckar. Moreover, Pfister et al. (2004) points out that no clear evidence exists from 20th century historical time series that land-use changes influenced flood probability and magnitude in the main channel of the Rhine. Bronstert et al. (2007) reveal that land-use change to forest might be beneficial on a sub-basin scale in the Rhine basin, but the effect diminishes with increasing scale.

In short, our results on the effectiveness of land-use change must be questioned, when compared to earlier work. The only exception is a study by Hundecha and Bárdossy (2004) who used the HBV model in a similar simulation setup for the Rhine basin. They found reduced peak discharges of 10% to 19% for several historical events, resulting from reforestation of the entire basin. Therefore, the simulated land-use effect might be a limitation of HBV. Based on the fact that a 96% forested area (the remaining 4% being bare rock and surface water) is a very unlikely scenario in the Rhine basin, we do not consider land-use change to forest a profitable or efficient option to reduce flood probability on a basin-wide scale in the Rhine basin.

5.5.3 Further work

In this Chapter, we only evaluated measures to lower peak water levels and the probability of flooding. If a continuous dike raise is undesirable, new research could also focus on flood damage reduction measures. Based on our results (expected increase in flood probability due to climate change, and flood management which seem to be not very effective in water level reduction), we are inclined to support the conclusions made by Hooijer et al. (2004) and the Action Plan on Floods (ICPR, 2005a) that more could be gained from damage reduction and spatial planning than from flood defense measures to lower flood risk in the Rhine basin. This assumption, however, is not yet
confirmed by research. This would also require an upgrade from 1D to 2D inundation modeling to perform a process-based flood risk assessment, which needs 2D inundation information to meet the needs of advanced flood mitigation measures (McMillan and Brasington, 2008). Also, for simulating the effects of upstream flooding and restoration of abandoned meanders a 2D model application is advised.

We made an improvement in modeling techniques towards assessing low-probability flood events under climate change. Several uncertainties remain of which some might be tackled in further research. We chose an extreme climate change scenario to test the robustness of measures, but to address the uncertainty of climate change impact models, a stochastic approach with multiple scenarios might be considered. In order to improve the simulation of the effects of flood management measures and upstream flooding above Maxau, the hydrodynamic model we used can be extended in the upstream direction (up to Basel). Finally, we did not take into account changes in morphology, while the Rhine currently incises with an average rate of 2 cm a year at Lobith (Silva, 2003) and deposits its sediments in other areas. If the current erosion continues, this would significantly influence peak water levels in 20 or 50 years time.

Acknowledgements

The meteorological dataset was kindly provided by the International Commission for the Hydrology of the Rhine basin (CHR) and we thank the Dutch Ministry of Transport, Public Works and Water Management and the Bundesanstalt für Gewässerkunde (BfG) for providing discharge observations. We also thank the BfG for sharing land-use data and for the use of HBV. Delft3D and the Dutch Ministry of Transport, Public Works and Water Management are kindly acknowledged for sharing their SOBEK model. Special thanks to Rolf van der Veen and Rita Lammersen for their assistance in obtaining and improving the SOBEK schematizations. We are also grateful to Marcel Ververs and Albrecht Weerts for their work on the implementation of the simulation models in GRADE. This research project was carried out in the framework of the Dutch National Research Programme Climate changes Spatial Planning (www.klimaatvoorruijnt.nl).
6.1 Summary of results

The overall objective of this thesis was to assess the effect of climate and socio-economic changes on flood risk in the Rhine basin and where needed to improve simulation methods. The focus was on the estimation of the probability of flooding and the development of cross-boundary flood management measures to cope with expected changes. This section first describes the improvements made to the simulation method. Next, results are summarized for the projected changes in flood-peak probability and flood risk, and the effectiveness of flood management measures. The additional sections of this Chapter subsequently respond in more detail to the research questions addressed in the thesis and provide implications, recommendations and remaining challenges.

Previously available methods for simulating the effect of climate change on flood-peak probabilities in the Rhine basin contained various shortcomings. First, the prevalent method for estimating future low-probability peak discharge events provides results only with considerable uncertainties, because it extrapolates observed discharge records (∼100 year) to estimate the peak discharges, with probabilities of 1/200 to 1/1250 per year. The observation records are too short for that purpose. In addition, such an approach assumes stationarity of the system; the idea that a natu-
eral system fluctuates within a fixed range of variability (Milly et al., 2008). However, both human interventions and climate change effects imply that stationarity may not apply to the Rhine basin. Second, in many cases of transforming climate model output to discharge, either inadequate rainfall-runoff models or too simple climate scenario transformation methods have been used, or a combination of both.

Thus, improvements are necessary. For accomplishing this, we coupled the available simulation tools to interpret the climate change scenarios, rainfall-runoff modeling, and extreme flood-peak estimation. The methods used in this thesis address the need to define the most relevant uncertainties and processes in the cause-effect chain of climate change and integrate these into a process-based simulation approach. In addition, a flood risk model that can interpret the scenarios for both climate and socio-economic change was previously not available for the Rhine basin, and is newly developed in this thesis (Chapter 4).

The improvement of the simulation method for low probability flood events in the Rhine basin is not primarily found in a more detailed description of hydrological processes (Chapter 2), but in carefully coupling different methods and models needed to simulate low-probability flood events. On the basis of this research, it is recommended to improve the projections of the intensity and duration of future extreme meteorological events, and a better description of routing processes in flood peak generation. The use of a weather generator results in long series of resampled meteorological data (1000 years of daily values), which considerably decreases the statistical uncertainty within the extreme value analysis (Chapter 3). The weather generator was implemented both for the present situation, and for different climate scenarios in 2050. In order to explore the uncertainties of the climate change scenarios, we used different climate models and downscaling methods. A hydrodynamic model was introduced to simulate flood wave propagation, backwater effects, flood plain inundation and even upstream flooding, as these processes have been largely ignored in existing climate impact studies to date in the Rhine basin. The hydrodynamic model was also used to simulate the impact of flood management measures (Chapter 5).

The impacts of climate change and the alterations in river geometry and land use due to human influence were parameterized in models, in an attempt to improve the simulations of extreme flood events and its consequences. In doing so, we avoided the basic assumption of stationarity of water systems (e.g. Pielke Sr. et al., 2009). This simulation approach is referred to as ‘process-based modeling’ by McMillan and Brasington (2008), and is advocated by Sivapalan and Samuel (2009) and Raff et al. (2009). The method allows us to simulate flood waves at very low probabilities to test the effectiveness of measures upon extreme events and can be applied to other river basins. The improved process-based modeling method involved:

1. Selection of an adequate hydrological model.
2. Downscaling of the GCM output to meteorological forcing data for 134 sub-basins in the Rhine basin, performed for different climate change scenarios. Downscaling can be done by a RCM or by the delta method.

3. Resampling of meteorological forcing data to 1000 (when possible 10,000) years of daily precipitation and temperature values in 134 sub-basins.

4. Generation of a series of 1000 (when possible 10,000) years of daily discharge using a semi-distributed conceptual hydrological model. Long time series decrease the statistical uncertainty when simulating low-probability peak events.

5. Implementation of a hydrodynamic model to simulate routing processes of flood peaks, upstream flooding, and the impact of flood management measures.

In Chapter 2 we found that conceptual model HBV performs better than the more complex land-surface model VIC for the hydrological simulation of climate change scenarios in the Rhine basin, since it models the peak discharges well. In addition, HBV has very short calculation times compared to VIC, making it suitable for the generation of long time series of daily discharge.

In Chapter 3 we concluded that for downscaling climate data, bias-corrected direct RCM output performs better than the delta method, since this method can describe spatial and temporal variation in meteorological events that are relevant for the planning of flood management measures. The HBV model, forced by RCM output, transforms the changed characteristics and extremes in the atmospheric system into physically plausible responses of extreme discharges.

The results in Chapter 3 further indicate that there is a substantial increase in flood-peak probability in 2050 throughout the Rhine basin, when compared to the control climate period of 1961–1995, due to increased predicted precipitation under climate change. The increase in yearly maximum peak discharge varied considerably throughout the basin and between RCM transformation methods, ranging from 6% to 40%. At Lobith, the probability of flooding (currently 1/1250 per year) is expected to be three to five times as high in 2050 as it is today. Increasing the length of the climate data series to 1000 years reduced the statistical uncertainty when estimating low-probability (1/200 per year, or less) flood peak discharges, from ±13% to ±3%. The statistical uncertainty is illustrated here by the 95% confidence intervals around an extreme value distribution (GEV, see Appendix C.

Chapter 4 provided estimates of future flood risk, which is defined here as the product of a probability and a consequence. We estimated that the annual expected loss in the Rhine basin may increase between 54% and 230% in 2030 compared to 2000, of which ~three-quarters of the increase can be attributed to climate change, and the remaining part to socio-economic developments. Results further showed that the area
with the highest flood risk numbers is located in the Lower Rhine in North Rhine-Westphalia in Germany, and not in the Netherlands as previously believed (ICPR, 2005b).

Chapter 5 evaluated the effectiveness of flood management measures for their ability to reduce peak water levels and the probability of flooding. In the current situation, safety levels vary throughout the Rhine basin, and decrease in the upstream direction. Consequently, flooding is more likely upstream in Germany and France, while dikes prevent the Rhine from flooding in the Netherlands. It was found that upstream flooding in Germany has a profound decreasing effect on the simulated peak water levels and discharges along the main Rhine branch and downstream in the Netherlands. For example, an event that results in \(16,000 \text{ m}^3/\text{s}\) at Lobith when simulated without flooding, will decrease to \(\sim 14,000 \text{ m}^3/\text{s}\) when simulated with upstream flooding.

The mean increase in peak water level along the Rhine due to climate change in 2050 is 50 cm, but varies between several centimeters and 140 cm. The currently implemented and proposed measures in the Action Plan on Floods, as well as most additional measures we evaluated, seem inadequate to cope with increased flood probabilities that are expected in a future climate change scenario. According to my results, the only measure that can prevent the Rhine from flooding is drastic, basin-wide, dike heightening of between 1.30 m and 3.30 m, depending on location, on the assumption that these dikes cannot fail.

6.2 Research questions

6.2.1 Comparing model performance

Does a physically-based land-surface model perform better than a conceptual rainfall-runoff model when simulating the effect of climate change on the discharge regime?

The land-surface model VIC and the conceptual rainfall-runoff model HBV were compared for their performance in predicting climate change effects. Both models were forced with different meteorological data sets and their results compared at both a basin and sub-basin scale using various performance criteria (Appendix A). The comparison was made for daily results over the period 1993–2003. Both models performed less well in the upstream basins but improved at the Rhine basin outlet at Lobith. For all sub basins, HBV performed better than VIC. At Lobith, the HBV model forced with ERA15 performed moderately well \((E=0.62, r^2=0.65)\), whereas the VIC model performed badly \((E=0.31, r^2=0.54)\). For the calibration year 1993 with the model forced with observed CHR data, the HBV performance increased up to a coefficient
of efficiency ($E$) of 0.85 and a coefficient of determination ($r^2$) of 0.97. However, the performance of VIC remained poor when forced with CHR ($E=0.44$, $r^2=0.81$). HBV performed more consistently between the calibration and validation period than did VIC, which indicates that HBV is more robust (Figure 2.6). Overall, these results show that not only does HBV performs better than VIC at the sub-basin scale at the basin outlet, but also that the forcing data to a large extent influences the performance values of both models.

For the most extreme peak flows (above 10 000 m$^3$/s at Lobith), HBV performed best simulating the maximum discharge ($d_{\text{max.}} \ Q_{\text{sim.}}$ HBV 1–17%, $d_{\text{max.}} \ Q_{\text{sim.}}$ VIC 2–27%). HBV was also able to accurately predict the timing of flood peaks, whereas VIC tended to delay the flood peaks, some of them up to six days.

Overall, the semi-distributed conceptual HBV model performed much better than the distributed land surface model VIC. This is in contrast to the general idea that more complex distributed models are better at predicting observed discharges than simple conceptual models (Reggiani and Schellekens, 2003; Refsgaard, 1996). Even for a well documented river basin such as the Rhine, more complex modeling does not automatically lead to better results (Booij, 2003; Uhlenbrook, 2003).

For the Rhine basin thus, the HBV model is the preferred hydrological model for use in climate scenario studies, since it has better overall performance and appears to be more robust than the VIC model. Also, HBV better simulated extreme events, which may occur more in the future due to climate change. The more realistic representation of evaporation processes within VIC than HBV did not improve VICs performance even in the dry periods, when evaporation is a substantial component of the water balance. The final advantage of HBV over VIC is that HBV has short computational times, making it suitable for simulating long time series for many different climate scenarios.

### 6.2.2 Simulating climate change

**How can we optimally use climate change scenarios of precipitation and temperature to estimate expected changes in low-probability flood peak events?**

To answer this question, the approach adopted in this thesis used RCM data and a weather generator to create long, resampled time series of climate change scenarios for input to hydrological (daily) and hydrodynamic (hourly) modeling for the Rhine basin. This approach was applied to three parallel modeling methods, each using a different method to transform the climate data of different RCM outputs to the hydrological model input. The three modeling methods were: delta change (method 1), RACMO direct (method 2), and RACMO bias-corrected (method 3). RACMO
refers to a climate scenario that is the output of a one RCM (RACMO2.1), which is forced by the ECHAM5-GCM member 3 output that was forced by the SRES-A1B emission scenario (Lenderink et al., 2003; Meiggaard et al., 2008). The delta change method was applied to the KNMI’06 W-plus scenario. The KNMI’06 scenarios are based on a suit of GCM and RCM simulations, forced by several SRES emission scenarios (Van den Hurk et al., 2006, 2007).

On the basis of numerous 1000-year model simulations for the Rhine, the results suggest a basin-wide increase in peak discharge in 2050 of 8 to 17%, for probabilities between 1/10 and 1/1250 per year. For the 1/1250 per year discharge of 16 000 m$^3$/s at Lobith, this implies an increase to 17 280 m$^3$/s or 18 725 m$^3$/s. Furthermore, the results show that the statistical uncertainty when estimating low probability flood-peak events can be reduced from ±13% (at 16 000 m$^3$/s this corresponds to ±2100 m$^3$/s and ±70 cm) to ±3% (at 16 000 m$^3$/s this corresponds to ±500 m$^3$/s and ±15 cm) by increasing the length of the climate data series using a weather generator.

The flood frequency is expected to increase as a result of climate change (Figure 3.10). The calculated parameters from the Generalized Extreme Value (GEV) distribution through the yearly maximum discharges were used to calculate the projected shifts in the probability of extreme events. According to the bias-corrected RACMO scenario (method 3), in 2050, a discharge with a return period of 1250 years in the control climate would occur once every 460 years. This is equivalent to an increased probability by a factor of 2.7. The RACMO (method 2) scenario projects that the 1250-year discharge will increase in frequency to once every 510 years (a factor of 2.5), and the Wp (method 1) scenario projects an increased frequency of once every 265 years (a factor of 4.7).

When creating future climate scenarios, the delta change approach is more transparent than the bias-corrected RCM output. The delta change approach is also robust, allowing the use of climate model output even if they inaccurately represent the control climate (Graham et al., 2007). However, it can be concluded that the use of bias-corrected RCM output is preferred in a climate change analysis, since that method incorporates projections of geographical differentiation, and includes changes to the variance of temperature, the coefficient of variation of precipitation, and the number of precipitation days. When identifying future problem areas and potential adaptation measures, it is of paramount importance to estimate spatial differences in flood-peak probabilities. However, the bias correction method has still room for improvement, in particular for extreme events. In addition, the use of a weather generator in combination with hydrological and hydrodynamic modeling is recommended when simulating low probability peak discharges under climate change.
6.2.3 Future flood risk

What is the present basin-wide flood risk, how will it change up to 2030, and what is the relative contribution of climate and socio-economic change to this risk?

Current flood risk in the Rhine basin (taking 2000 as reference year) was calculated by estimating both the flood probability and consequence of a flood event, expressed in potential direct damage. Future flood risk was simulated using scenarios to assess changes in flood probability due to climate change and by using land-use change scenarios for calculating changes in potential damage. These data combined provided different projections for future flood risk in 2030 for the entire Rhine basin. The projected change in land-use value put at risk by flooding is based on two different socio-economic scenarios derived from a land-use model. Potential damage is calculated by a damage model, and changes in flood probabilities were derived from two climate scenarios and hydrological modeling.

It was found that, in absolute terms, potential flood losses are highest in the Dutch Delta region (G), namely €110 billion, compared to €80 billion of the second highest value in the Lower Rhine region (E) (for locations of the regions, see Figure 4.5). Flood risk (damage × probability) is, on the other hand, much higher in other regions, most notably in the Lower Rhine region (E) (€350 million per year) and the Upper Rhine (C) (€290 million per year), whereas the Dutch Delta region only reaches €87 million per year.

This thesis further projected that flood risk in the Rhine basin will not be stationary and might considerably increase over a period of several decades. Expected annual losses in the entire Rhine basin may increase by between 54% and 230%, due to socio-economic and climate change. The results displayed large variations in current risk and flood-risk projections between regions along the Rhine. The increase in flood risk can mainly be attributed to increasing probabilities of flood peaks due to climate change (43–160%, which is ~ 6/8 of the total risk increase), whereas socio-economic change accounts for 7.5–27% increase, which is ~ 1/8 of the total risk increase (Figure 4.6).

The method in this thesis provides a more comprehensive assessment of basin-wide flood risk than was previously possible for the Rhine, and is based on 13 land-use classes and sophisticated damage functions derived from the Damage Scanner (Klijn et al., 2007; Aerts et al., 2008b; Bouwer et al., 2010). Furthermore, the method integrates a land-use model with a damage model at a spatial resolution of 250 m, which enables basin-wide scenario projections for future land use and potential loss. However, both the land-use model and the damage scanner contain uncertainties that need further quantification.
6.2.4 Effectiveness of flood management measures

Which flood management measures are most effective in reducing flood stages and flood frequency on a basin-wide scale?

As explained above, climate change may increase flood probabilities, which may strongly influence the expected annual losses. Therefore, it is important to test whether the implementation of flood defense measures, such as retention basins and dike heightening, might prevent the increase of flood probabilities due to climate change, and thus the flood risk.

We evaluated the effectiveness of flood management measures included in the Action Plan on Floods (ICPR, 2005a), and additional measures at different return periods along the Rhine, assuming the relatively extreme W-plus climate change scenario for 2050 (Van den Hurk et al., 2006). These alternative measures include reforestation, restoration of abandoned meanders, implementation of extra retention polders, and a bypass around Cologne. All measures are aimed at reducing flood-peak probability and flood stages at a basin-wide scale.

It was found that upstream flooding in the Upper and Lower Rhine in Germany has a profound diminishing effect on the peak water levels and peak discharges along the main Rhine branch and downstream in the Netherlands. The decrease varied between 2–13% in control climate conditions and 10–19% in the W-plus climate change scenario. Hence, upstream floods in Germany are favorable for reducing flood risk in the downstream areas of the Netherlands. However, it is possible that future flood policies in Germany will aim at raising their dikes, especially in a scenario with increased flood probabilities due to climate change. This may increase peak discharges and water levels downstream (e.g. in the Netherlands).

The mean increase in peak water level along the Rhine due to climate change in 2050 is 50 cm, but varies between several centimeters and 137 cm. The currently implemented and proposed measures in the Action Plan on Floods, as well as most additional measures we evaluated reduce peak water levels by 5 cm to 13 cm over medium return periods (between 50 and 100 years) for the control climate. These simulations included the effects of potential upstream floods. As a result, these measures may be inadequate to cope with the increased flood probabilities that are expected in future climate scenarios. According to my results, the only measure that can prevent the Rhine from flooding in 2050 is drastic dike, basin-wide, heightening of between 1.30 m and 3.30 m, depending on location, with the assumption that these dikes cannot fail.
6.3 Implications and recommendations

Below I will reflect on the implications of these results, mainly focused on the Netherlands. Since the geography and dike system of the Lower Rhine in Germany is very much alike, although maintained under a different law system, many remarks may also be relevant in that area. Recommendations are made for further work and for potential applications of the modeling approach. I discuss the consequences of ignoring the uncertainties in available data and methods on flood defense management decision making, and plead for a shift toward flood risk management that include uncertainties.

6.3.1 The consequences of ignoring the uncertainty of the design discharge

Although we have been able to decrease the statistical uncertainty in estimations of low-probability flood peak events, a residual uncertainty remains. For example, the impact of upstream flooding and climate change add to the lack of predictability of extremes. Estimating extreme events at high safety levels (i.e. at probabilities lower than 1/200 per year) requires either statistical or hydrological modeling far outside the calibrated range of those models. This introduces an unknown error and thus will always entail uncertainty. Increasing safety levels to reduce the probability of flooding will therefore inevitably go together with increased uncertainty in the estimation of accompanying peak discharge, no matter how far models have improved.

In the Netherlands, flood management measures are designed to prevent coastal and fluvial flooding up to flood stages with a very low probability of occurrence. Safety standards vary between 1/10 000 per year in the low-lying coastal zones, to 1/1250 per year in the higher areas which are only threatened by fluvial flooding. These norms were established by the first Delta Committee in 1960 (Van Dantzig, 1956). However, the actual probability of flooding does not necessarily agree with these norms; it might be higher with higher failure probabilities, or lower if the dikes are taller than design level and do not fail.

The design discharge associated with a safety standard of 1/1250 per year at Lobith is estimated to be 16 000 m$^3$/s. The related maximum water level determines the dike heights along the major rivers in the Netherlands (Ministry of Transport, Public Works and Water Management, 2006b). This discharge volume, however, is very uncertain, for three reasons. First, current methods to estimate extreme discharges only use a statistical extrapolation of 100 years of historical data for an event that happens once every 1250 years. Second, climate change and altered river geometry contribute to the non-stationarity of the system. Third, the impact of upstream
flooding is not considered in this extrapolation. These uncertainties are largely ignored in the Netherlands’ current flood management strategy and they are explained in more detail below.

1. Statistical extrapolation of historical data

Substantial uncertainties are introduced when the design discharge is estimated only with historical data. The 95% confidence interval spans 13% more or less than the estimated design discharge (Figure 3.10), i.e., a 70 cm higher or lower maximum water level at Lobith. Although this uncertainty band is recognized and has been published previously (Silva et al., 2001, 1.8), the value of 16 000 m$^3$/s is chosen as the best estimate and therefore as the design discharge. Dike heights are derived from design water levels and 50 cm is added to account for wave run-up on dikes. In a guidance on dike design (not a law), the Ministry of Transport, Public Works and Water Management (2007) advises to add a robustness level of 30 cm to the dike height, to account for future changes and uncertainties.

2. Changing conditions

In conjunction with the fact that 100 years of observation data is too brief to estimate the properties of a 1/1250 per year event, fitting an extreme value distribution through a historical data set implies that these data are stationary, i.e., that the physical conditions of the river system did not change. Obviously, over 100 years the geometry of the Rhine has changed and very likely also the meteorological conditions, and the principle of stationarity does not hold. Even after an attempt to ‘normalize’ the data, this adds to the uncertainty. Moreover, discharge behavior is likely to change in the future, as was established in this thesis by the assessment of climate change impact on flood peaks. At Lobith, the 1/1250 per year peak discharge of 16 000 m$^3$/s is projected to increase between 17 280 m$^3$/s ($+ \sim 40$ cm) or 18 725 m$^3$/s ($+ \sim 90$ cm) in 2050.

3. Upstream flooding

One of the most remarkable results of this research is the influence of upstream flooding, adding to the uncertainty of the design discharge. Flooding in Germany and in the Upper Rhine in France lowers the flood stage up to 130 cm at the German-Dutch border, and a peak discharge of 16 000 m$^3$/s tops off to 14 000 m$^3$/s (Figure 5.8a). This effect is completely ignored in estimates of the design discharge at the current safety standard of 1/1250 per year (Ministry of Transport, Public Works and Water Management, 2006b), probably leading to a considerable overestimation. The Second Delta Committee (Deltacommissie, 2008), however, advised to apply a physical maximum discharge at Lobith when considering climate projections, of 18 000 m$^3$/s. The estimates of the physical maximum were provided by Vellinga et al. (2008) that contained some of my
results of Chapter 5, although the Delta Committee reduced the effect upstream flooding to some extent.

A reason to ignore the effect of upstream flooding in Dutch safety policy is that dikes in Germany might be raised in the future (Delta-commissie, 2008). The assumption that Germany will raise their dikes after a flood event is realistic, as was observed in the Elbe basin where flood protection was implemented after the floods in 2002 (Petrow et al., 2006). However, it does not seem realistic that safety standards will be raised from current levels of 1/200 to 1/500 per year up to Dutch standards (1/1250 per year). A costly flood of the Rhine in Germany does not fail the country as a whole, which is the risk in the Netherlands. For France, the flood prone area of the Rhine is even less important. Reasons for this are threefold. First, Germany governs many more large river basins, such as the Weser (substantial flooding in 2003), the Danube (large floods in 1999, 2002, and 2006, although most of the damage occurred in Slovakia, Bulgaria, and Romania), and the Elbe (large floods in 2002, with €2 billion insured damage in Germany) (RMS, 2006). Second, in countries other than the Netherlands, the flood prone areas are surrounded by hills or mountains, so that the maximum extent of even the most extreme flooding is known and will not change in the future. Third, both in Germany and France homeowners and companies can insure their properties for flood damage (Kron, 2009). Therefore, raising the safety levels of the whole Rhine basin up to Dutch standards would probably be a huge over-investment in Germany and France.

If the uncertainty around the estimation of the design discharge is neglected, instead of considering an unusually wet or dry year as part of a natural variation, the design discharge might change in response. This has occurred in the past, for instance shortly after the flood events in 1993 and 1995, the extreme value distribution was ‘lifted’ causing the design discharge to change from 15 000 to 16 000 m$^3$/s at Lobith. This had large implications for the Dutch policy on river management that continues through the present, which I will explain briefly below. If instead uncertainty bands had been taken into account, it would have been recognized that the flood peaks of 1993 and 1995 were well within those bands and one could argue (and maybe engineers and policymakers would have argued) that these two flood peaks do not justify a sudden adjustment of the design discharge and related safety standards for flood defenses and spatial measures.

The 1993 and 1995 events also revealed that 650 km of dike length did not meet the safety standards (of 15 000 m$^3$/s at Lobith) and needed immediate reinforcement. The ‘Deltaplan’ was quickly enacted (Ministry of Transport, Public Works and Water Management, 1995) and has been completed in 2000. Furthermore, it was decided to compensate for the increase of 1000 m$^3$/s in the design discharge by creating extra room for the river wherever possible, avoiding the need for dike heightening (Ministry of Transport, Public Works and Water Management, 2006c). Although I would cri-
ticize the decision for the sudden shift in design discharge, the ‘Room for the River’ concept is a very interesting and daring diversion from the former policies of continuing dike enforcement and heightening. It has been recognized that increased dike heights leads to increased maximum water levels and thus to a potentially larger flood hazard. Therefore, the objective for making room for the river is to lower peak water levels.

The measures under consideration include deepening of low flow channels and flood plains, removing hydraulic structures, dike replacements, and lowering of groins. The impact on the maximum water level of these measures has been studied at a very detailed level, on the order of millimeters (Ministry of Transport, Public Works and Water Management, 2006c). However, it seems contradictory to plan and implement measures accurately to the millimeter based on a fixed design discharge and water level, and to ignore the huge uncertainty in the design water level of \( \pm 70 \) cm due to statistical uncertainty. On top of that, there are the uncertainties related to changing conditions (non-stationarity) and upstream flooding. In my view, the design discharge and accompanying design water levels are wrongly communicated as certain values, fixed for as long as no extreme event occurs, while these two preconditions are in fact very uncertain. As a result, enormous efforts are invested in maintaining and designing the Dutch dike system and landscape according to these uncertain preconditions, while different design values would probably lead to very different decisions.

6.3.2 How to implement uncertainty in the calculations of the design discharge

Acknowledging the uncertainties, and to use them in a sensitivity analysis of the effects and costs of proposed measures and alternative strategies is important. The potential explosion of the number of required simulations by the already very detailed models may however be a constraint. A stochastic modeling setup that considers the uncertainties of various modeling steps, including the effects of upstream flooding, along with a more flexible interpretation of the results, might bring some relief.

Instead of assuming that there will be no upstream flooding, it may be better to gain a better understanding of the hydraulic behavior of potential flooding events in the Lower Rhine. Flooded water in the German Lower Rhine might enter the Netherlands via other routes, for example, from Emmerich to Doetinchem, or from Kleve to Nijmegen (Lammersen, 2004; Silva et al., 2006). Due to lower design levels along the German Rhine branch, the probability of flooding via this ‘back door’ seems higher than a riverine flood event in the Netherlands only. More detailed research using well-founded inundation models is necessary to explore ways to cope with such a flood event. Experience from the Dutch compartment study (Asselman et al., 2008) might be beneficially applied to the border area between Germany and the Netherlands.
With cross-boundary cooperation, already existent in the Arbeitsgruppe Hochwasser (Raadgever et al., 2008) and the International Commission for the Protection of the Rhine (ICPR), the development of 2D hydrodynamic models, flooding scenarios and measures can be taken up.

I argued in this thesis that process-based modeling, which considers spatial and temporal meteorological variation and the physical properties of the river basin, is a better method for estimating extreme peak discharges than is the extrapolation of historical data. Resampling and process-based modeling can handle the large variety of flood wave shapes for extreme events, and the modeling results include a description of uncertainty. In addition, the method can simulate upstream flooding, and enables testing and visualization of the effectiveness of measures using a probabilistic approach.

Based on my research the applied modeling method has been partly implemented for the Meuse in a tool named GRADE (De Wit and Buishand, 2007), with the goal of testing an alternative method for estimating design discharges. It also uses long resampled meteorological time series as input for the hydrological model, and a hydrodynamic model to simulate all yearly flood peaks. However, it does not incorporate upstream flooding, the impact of flood management measures, or climate change scenarios.

6.3.3 Lowering peak water levels effective at local scale

Another imperative result of this thesis is that, with the Rhine already heavily embanked and canalized, adding new retention basins will not substantially lower maximum water levels downstream. This is especially true since safety levels that determine dike height and operational rules for retention areas are different throughout the basin. It is therefore not possible for downstream areas, like the Netherlands and the German federal state North Rhine-Westphalia, to derive much benefit from extra retention areas located more than ~ 50 km upstream, let alone in the Upper Rhine. Historical flood events exemplify this observation (Volkskrant, 1995, Becker, personal communication), when the decisions to inundate retention basins were solemnly diverted to local needs in the Upper Rhine.

However, flood management measures, including extra retention basins or land-use changes to detain water in small tributaries, can be beneficial at a local scale. This thesis demonstrated that a bypass around a valuable area, such as a city, can also be very effective (Figure 5.7). In practice, this would mean differentiation at the local scale of flood protection levels. Rural areas will flood, while the city is protected. This relates to the controlled flooding of retention areas. In the Netherlands, the implementation of retention polders Ooijpolder and Rijnstrangen (Commissie Noodoverloopgebieden,
2002) was prevented by the public (Roth et al., 2006), while in Germany, people have been less opposed to controlled flooding (Ouwendijk et al., 2001). Protecting a city using a large bypass might be perceived differently by policy makers and the public than controlled flooding.

### 6.3.4 Risk-based approach can be beneficial basin-wide

According to the calculations in this thesis, the only measure that can prevent the Rhine from flooding from a 1/1250 per year event in 2050 is drastic, basin-wide, dike heightening of between 1.30 m and 3.30 m, depending on location, with the assumption that these dikes cannot fail. However, there are several reasons why such continuous basin-wide dike raise as the solution against potential flooding from the Rhine may not be feasible. First, assuming that a considerable dike raise is not blocked from a landscape value point of view, in many places along the German Rhine it is simply physically impossible (Lammersen, personal communication), since dike heightening implies substantial dike widening.

Second, the risk of a flood hazard can never be ruled out, even when very high safety levels are maintained. A residual risk maintains that an extreme event of a proportion that has not been considered to date might still occur. The historical description of the very extreme and devastating Rhine flood in 1374 exemplifies this, with estimates of peak discharge volume at Cologne ranging from 18,000 to 24,000 m$^3$/s, based on historical descriptions and flood marks on buildings (Sprong, 2009; Herget and Meurs, 2010). This would imply even higher discharges at Lobith, while in this thesis, the most extreme estimated peak discharge for the 1/1250 per year event under 2050 climate conditions reaches 18,725 m$^3$/s at Lobith.

Third, the assumption that dikes, as they are currently designed along the Rhine, cannot fail seems unrealistic, as the FLORIS study demonstrated for the Netherlands (Ministry of Transport, Public Works and Water Management, 2006a). The FLORIS study estimated a substantial number of dikes in the Netherlands that do not meet their design safety standards. To estimate actual risks it is important that dikes are at least able to withstand the water levels they are designed for. A quick scan on ‘unbreakable dikes’, or dikes that can flood, but will not fail due to their substantial width and robust surface material, displayed that the implementation of such dikes seems physically and economically feasible in the Netherlands (Silva and Van Velzen, 2008).

The ability of a river system to recover from floods using controlled flooding and damage reduction is referred to as resilience of the system (Klijn et al., 2004). Instead of indiscriminately raising dikes, they could be designed as ‘unbreachable’ and maintained at levels determined using a flood risk approach that considers the conse-
6.3. Implications and recommendations

sequences of flooding, changing physical properties of the river basin, natural variability and (future) probabilities of meteorological extremes. The advantages of resilience in flood risk management for the Netherlands are explained by De Bruijn (2005) and Vis et al. (2003). Several studies have examined the impacts of flooding, flood risk, and the positive effect of hazard reduction measures in the Netherlands (Ministry of Transport, Public Works and Water Management, 2006a; Aerts et al., 2008b).

Nevertheless, recent findings of the (second) Delta Committee (Deltacommissie, 2008) in the Netherlands have focused mainly on protection against flooding. These findings are formalized into a ‘delta law’, and will form the basis for a new water safety policy. Due to an increase in economic development and potential fatalities since 1960, the Committee has advised an increase in safety standards. Current safety standards are outdated according to the Committee, but as explained in this thesis, increasing safety norms has the effect of increasing uncertainties of the properties of the then lower-probability design events. A combination of flood defense measures, flood hazard mapping and risk zoning, damage reduction, spatial planning, and early warning would be more appropriate.

It has been argued before that an effective climate change adaptation policy in the Netherlands should not only address the reduction of flood probabilities with flood defense measures, but should also consider a wide range of other adaptation options (Aerts et al., 2008b). Damage reduction can be achieved through controlled flooding and measures that reduce the vulnerability of buildings to flooding. In addition, financial arrangements such as insurance can compensate for losses and heighten flood risk awareness (Botzen and Van den Bergh, 2008; Botzen, 2010; Bouwer, 2010). The optimum combination of measures can be evaluated using portfolio theory, as is common in financial services (Aerts et al., 2008a).

The EU Flood Directive (EU, 2007a) (see Chapter 1) might help to force a transition in all member states from a policy of flood control to the acceptance that flood risks, and thus consequences of flooding, should be managed. The considerable potential for damage in flood prone areas in the Rhine basin, coupled with projections for substantial future growth, as calculated in this thesis (Figure 4.7), might help to concentrate more on this aspect of flood risk management, especially in the Lower Rhine and the Netherlands.

Available data on direct and indirect damages are literally more down-to-earth than estimates of flood stages and flood probabilities at extremely high protection levels; however, studies of models simulating inundation and damage scenarios reveal that there is still considerable uncertainty associated with flood hazard and risk estimates (e.g. Apel et al., 2004; Merz and Thieken, 2009; De Moel and Aerts, 2010). These uncertainties in flood inundation and damage projections are receiving increasing attention in research (e.g. Merz et al., 2004; Messner et al., 2007; Merz et al., 2010).
6.3.5 Toward communicating uncertainty and adaptive management

Policymakers are positively capable of acting in the face of uncertainty (Pappenberger and Beven, 2006). Unfortunately however, large policy shifts are often reactive (Huitema and Meijerink, 2010), as multiple examples for both natural hazards and human failures show. It seems without doubt that uncertainty will continue to complicate decision-making and policy-making processes in cross-boundary river basin management. Although uncertainty in predictions might appear unsettling, it is an integral component of our understanding, and it aids our advancement to more holistic knowledge (Ivanović and Freer, 2009).

Therefore, known uncertainty should not be hidden by engineers, but communicated clearly and truthfully to policymakers and the general public (Webster, 2003). One option for exploring an uncertain future is scenario testing of management decisions that allows for participatory modeling; engages stakeholders, policy makers, and experts; and improves the dialog between them (Evans et al., 2004; Schanze et al., 2008).

It has been recognized that major floods often trigger policy changes due to public indignation (Samuels et al., 2006). This reactive behavior should be transformed into proactive behavior and strategies of adaptation. Pahl-Wost (2008) explains how iterative learning circles incorporated into overall management are an essential element of adaptive management. An example is the EU Flood Directive, which requires a review, and if necessary an update, of the flood hazard and risk assessment every six years (EU, 2007a).

The future contains inherent uncertainty due to unknown economic growth, political stability, population growth, climate change, etc. The process of decision-making with respect to the uncertain predictions of these aspects is complicated and heavily politicized (Ivanović and Freer, 2009). But since policymakers are capable of acting on uncertainty, they need only start taking action to adapt to projected changes. In adaptive water management, inherent uncertainties are embraced, certainties and risks emphasized, and new management measures continuously reformulated after learning from previous experiences.

6.4 Remaining challenges

This thesis has provided answers to the research questions posed and the described approach is a useful tool for estimating the effects of climate change, socio-economic development, and measures on extreme flood peaks and flood risk in the Rhine basin.
However, during the research process there emerged possible areas for future improvement. These remaining challenges are discussed in this final section of the thesis.

Recent findings show that Alpine temperatures during the past century have increased more than twice the global average (EEA, 2009). This makes Alpine mountains especially vulnerable to changes in the hydrological cycle, and decreases in snow and glacier cover are already occurring. Future research should focus on the timing of flood peaks from the Alps, which seems to advance toward the beginning of the year, in relation to the timing of flood peaks from other tributaries. If these peaks coincide in the future, flood-peak probabilities in the Lower Rhine will further increase.

During the summer, 90% of the river discharge originates from the Alps (Pinter et al., 2006). Drought and low flows deserve more attention in the Rhine basin. The apparent vulnerability of the Alps to climate change underlines these potential problems (EEA, 2009). Low flows can have consequences for shipping, availability of cooling water for power plants, agriculture, and drinking water, and the yearly expected loss can be considerable (Van Beek et al., 2008) when compared to flood risk (Te Linde et al., 2011). Land-surface and atmospheric interactions are more relevant for climate impact modeling on droughts than on floods (Seneviratne et al., 2006). Land-surface models such as applied by Hurkmans (2009) should therefore be further developed to aid research on low flows in the Rhine basin.

To improve the assessment of the impact of flooding, multiple two-dimensional hydrodynamic simulations are required in the Rhine basin. In Lammersen (2004), several 2D inundation runs are described for the Lower Rhine; however, to our knowledge, no 2D inundation model exists for the flood prone areas of the Upper Rhine. Also, future projections of morphological changes in the main Rhine channel and its flood plains require more research, since morphology has a profound effect on flood stages (Van Vuren, 2005).
7.1 English summary

In the past decades, the number of fatalities and the economic loss caused by floods have worldwide increased considerably. The river Rhine in North-West Europe also has a long history of floods that have caused casualties and severe damage. Despite flood defenses improved over time, it is expected that flood risk in the Rhine basin will continue to increase, which can be attributed to both socio-economic developments in flood prone areas, as well as increased flood frequency as a result of climate change. Climate change projections for the Rhine basin show that flood peaks may increase due to increased precipitation and earlier snow melt, and peak discharges are likely to shift from spring to winter and to increase in volume and frequency. Socio-economic projections showing trends in population growth and wealth indicate that the exposure to floods in the Rhine will increase as well. The combination of both trends will increase the flood risk.

Assessing the effect of climate change on flood risk, and maintaining and planning flood management measures are urgent issues for the riparian countries within the Rhine basin. Since safety levels along the Rhine are relatively high (1/200 to 1/1250 per year), the estimation of the size and duration of flood peaks at these low probabilities is very relevant to water managers. However, simulating those low-probability
floods requires extrapolation of only $\sim$110 years of measured data, which introduces large uncertainties. Many methodological challenges remain on simulating the effect of climate change and flood management measures on runoff, particularly when estimating the probability of occurrence of extreme flood peaks. In addition, no future basin-wide flood damage estimates exists to reflect socio-economic and land-use change.

This thesis investigates the combined effect of climate change and socio-economic projections on flood risk in the Rhine basin using improved simulation methods. The focus is on the estimation of low-probability flood events and anticipating to the impacts of these events through the development of cross-boundary flood management measures.

Results show that improvements of the simulation method for the Rhine basin are not as much found in a more detailed description of hydrological processes, but in carefully coupling different methods and models needed to simulate low-probability flood events. For example, it is recommended to improve the estimates of the intensity and duration of extreme meteorological events by applying a weather generator to generate long time series of climate data, and to implement a better description of routing processes in flood peak generation by using a hydraulic model. Furthermore, the impacts of climate change and the alterations in river geometry and land use due to human interventions are parameterized in models, in an attempt to physically describe extreme situations and the consequences of changed conditions. In doing so, I reject the often applied assumption of stationarity of water systems and apply an approach which can be referred to as ‘process-based modeling’.

The thesis compares two hydrological models, and the results show the conceptual model HBV simulates peak discharges best and is therefore preferred over the more complex land-surface model VIC for the hydrological simulation of climate change scenarios in the Rhine basin. As input for the HBV model, a weather generator is used to create long series of resampled meteorological data (up to 10 000 years of daily values), which considerably decreases the statistical uncertainty within extreme value analysis. As a result, for low-probability (1/200 per year, or less) flood peak discharges, the statistical uncertainty (illustrated by the 95% confidence intervals) decreased from $\pm 13\%$ to $\pm 3\%$.

To estimate the impact of climate change on river discharge, the output of Global Climate Models (GCMs) is used as scenario input for HBV. Different downscaling methods were applied to convert data from GCMs to the required regional scale for hydrological modeling in the Rhine basin. From this comparison, it appears that bias-corrected direct Regional Climate Model (RCM) data is preferred over the delta approach, since the first method better describes spatial and temporal variation in the meteorological events, which are relevant for the planning of flood management measures. When using the downscaled data in HBV, the simulation results indicate
7.1. English summary

a substantial increase in flood-peak probability in 2050 throughout the Rhine basin, when compared to the control climate period of 1961–1995. At gauging station Lobith, at the German-Dutch border, the probability of flooding (currently the safety level is set at 1/1250 per year) is expected to be three to five times as high in 2050 as it is today.

Furthermore, a basin-wide flood damage model was developed to estimate current and future potential flood losses. These damage estimates can be combined with flood probability to estimate the annual expected loss (i.e. flood risk) in the Rhine basin. It appears the annual expected loss may increase between 54% and 230% in 2030 compared to 2000, of which ∼ three-quarters of the increase can be attributed to climate change, and the remaining part to socio-economic developments. Results show that the area with the highest flood risk is located in the Lower Rhine in Nordrhein-Westfalen in Germany, and not in the Netherlands as previously believed. This is mainly related to the high safety standards in the Netherlands.

In the current situation, safety levels of dikes and other flood defense structures decrease in upstream direction along the Rhine. The differences result from different flood management policies between countries and are roughly related to economic value in the protected flood prone areas. Consequently, flooding is more likely upstream in Germany and France (where safety levels vary between 1/200 to 1/500 per year), compared to the Netherlands (which has a safety level of 1/1250 per year). It has been shown that flooding in the Upper and Lower Rhine in Germany, upstream of Lobith, has a profound decreasing effect on discharge peaks at Lobith. The decrease varied between 2–13% in control climate conditions and 10–19% in the W-plus climate change scenario, at return periods of 50 years and more.

The mean increase in peak water level along the Rhine due to climate change in 2050 is 50 cm, but varies between several centimeters and 140 cm. These simulations included the effects of potential floods in the Upper and Lower Rhine. Various flood management measures in the Rhine basin have already been developed according to the Action Plan on Floods (APF) that was initiated in the 1990s by the International Commission for the Protection of the Rhine (ICPR). The currently implemented and proposed measures in the APF, as well as most additional measures that were evaluated, such as extra retention areas, reduce peak water levels by only 5 cm to 13 cm over medium return periods (between 50 and 100 years). As a result, these measures seem inadequate to cope with the increased flood levels that are expected in future climate scenarios. According to the results of this thesis, the only measure that can prevent the Rhine from flooding at current safety levels in 2050, is drastic, basin-wide, dike heightening of between 1.30 m and 3.30 m, depending on location, on the assumption that these dikes cannot fail.

Although this research has been able to decrease the statistical uncertainty in estimations of low-probability flood peak events, a residual uncertainty remains. Due to the
too short time series of available discharge measurements (∼110 years), estimating extreme events at high safety levels (1/200 per year or less) requires either statistical or hydrological modeling far outside the calibrated range of those models. This introduces an unknown error and thus will always entail uncertainty. In addition, the impact of upstream flooding and climate change adds to the unpredictability of extremes. Increasing safety levels to reduce the probability of flooding, which is currently considered in the Netherlands, will force engineers to even further stretch their models. This will thus increase uncertainty in the estimation of the accompanying peak discharge, no matter how far models have improved.

Water managers should be more aware of this fact that increasing safety levels will entail increased uncertainty of the related, simulated design discharge. An effective climate change adaptation policy on flood risk management should embrace inherent uncertainties, and not only address flood defense measures, but also consider a wide range of other adaptation options on damage reduction.

7.2 Nederlandse samenvatting

Wereldwijd is de economische schade en het aantal slachtoffers door overstromingen de laatste decennia aanzienlijk gestegen. Ook de Rijn heeft een lange geschiedenis van overstromingen met veel schade en slachtoffers. Bewoners langs de rivier beschermen zich tegen het water door de rivier te kanaliseren en dijken te bouwen, die vaak na een nieuwe overstroming verbeterd werden.

De verwachting is dat het overstromingsrisico in het stroomgebied van de Rijn, dat wil zeggen de kans op een overstroming vermenigvuldigd met het gevolg, zal blijven toenemen. Dit kan worden toegeschreven aan zowel sociaal-economische ontwikkelingen in kwetsbare gebieden, als de toenemende overstromingsfrequentie door klimaatverandering. Klimaatscenario’s voor het stroomgebied van de Rijn laten zien dat de neerslag in de winter zal toenemen, met een hogere afvoer tot gevolg. Door globale opwarming zullen afvoerpieken als gevolg van sneeuwsmelt eerder in het jaar plaats vinden dan dat nu het geval is. Bij elkaar genomen resulteert dit in een hogere frequentie van extreem hoge afvoeren. Daarnaast vertonen sociaal-economische scenario’s voor het Rijnstroomgebied stijgende trends in bevolkingsdichtheid en welvaart, waardoor de kwetsbaarheid van de maatschappij voor overstromingen verder toeneemt.

Voor het ontwikkelen van hoogwaterbeschermende maatregelen is het noodzakelijk om het effect van klimaatverandering op de afvoer van de Rijn goed te kennen. Doordat de veiligheidsniveau’s langs de Rijn relatief hoog zijn (1/200 tot 1/1250 per jaar) is kennis over de grootte en duur van hoogwaterpieken met een dergelijk lage kans van voorkomen relevant voor waterbeheerders. Echter, het schatten van de eigenschappen van deze hoogwaterpieken gebeurt nu door extrapolatie van slechts
7.2. Nederlandse samenvatting

~110 jaar aan beschikbare meetgegevens, wat resulteert in grote onzekerheden. Er zijn nog meer methodologische obstakels wanneer we het effect van klimaatverandering en hoogwaterbeschermende maatregelen op de afvoer willen bepalen, in het bijzonder wanneer het gaat om extreem hoge afvoeren met een zeer lage kans op voorkomen. Zo bestaan er nog geen stroomgebiedsbrede schattingen in het Rijnstroomgebied over hoe de potentiële schade zal toenemen door sociaal-economische ontwikkelingen.

Dit proefschrift onderzoekt het gecombineerde effect van klimaatverandering en sociaal-economische ontwikkelingen op het overstromingsrisico in het stroomgebied van de Rijn met de nadruk op bovenstroomse gebieden, waarbij beschikbare simulatiemethoden waar nodig verbeterd worden. De focus ligt op het simuleren van extreem hoge afvoeren en op het ontwikkelen van grensoverschrijdende, hoogwaterbeschermende maatregelen.

De resultaten laten zien dat het verbeteren van de simulatiemethode niet zozeer zit in een meer gedetailleerde beschrijving van hydrologische processen, maar in het slim combineren van deels nieuwe en bestaande methoden en modellen. Ten eerste wordt geadviseerd om de intensiteit en duur van zeldzame meteorologische situaties, bijvoorbeeld extreem hoge en langdurige neerslag, beter te simuleren. Dit kan met behulp van een zogenaamde weergenerator die op basis van statistische parameters lange synthetische meteorologische reeksen genereert. Ten tweede is het van belang de routing processen van afvoergolven beter te simuleren door een hydraulisch model toe te passen.

Een vaak gebruikte aanname in studies naar extreme afvoeren is dat riviersystemen stationair zijn. Deze aanname wijst af en ik pas een methode toe die beschreven kan worden als ‘proces-georiënteerd modelleren’. In deze verbeterde simulatiemethode wordt zowel de invloed van klimaatverandering als de door de mens veroorzaakte veranderingen in het landgebruik en de geometrie van de hoofdgeul, geparameteriseerd in modellen. Op deze manier kan het effect van deze veranderingen op het afvoergedrag van de Rijn door de tijd heen gesimuleerd worden.

Een modelvergelijking laat zien dat het conceptuele hydrologische model HBV piekafvoeren van de Rijn beter beschrijft dan het meer complexe model VIC, en daarom is HBV gebruikt als hydrologisch model in dit proefschrift. De lange meteorologische tijddrieksen uit de weergenerator (tot 10 000 jaar dagwaarden) worden in het HBV model ingevoerd, dat vervolgens 10 000 jaar afvoerdatal simulation uitgevoerd. Als gevolg hiervan wordt de extreme waarden analyse nauwkeuriger dan wanneer alleen de 110 jaar aan historische gegevens gebruikt wordt. Dat de statistische onzekerheid (aangegeven door het 95% betrouwbaarheidsinterval) bij het schatten van extreme waarden met een lage kans van voorkomen (1/200 per jaar of lager) wordt hierdoor verlaagd van ±13% naar ±3%.
Om het effect van klimaatverandering op de afvoer te berekenen, is uitvoer van globale klimaatmodellen (GCMs) gebruikt als invoer voor HBV. Om de meteorologische gegevens van GCMs terug te brengen naar de vereiste regionale schaal, prefereer ik het gebruik van directe uitvoer na bias-correctie van regionale klimaatmodellen (RCMs) boven de zogenaamde ‘delta methode’. RCM uitvoer geeft namelijk beter inzicht in ruimtelijke en temporele variatie van het klimaatsignaal, wat relevant is voor het plannen van hoogwaterbeschermende maatregelen. De simulatie resultaten wijzen op een aanzienlijke toename van de overstroomsksans in 2050 in het gehele stroomgebied van de Rijn, vergeleken met de referentieperiode van 1961–1995. Op de Duits-Nederlandse grens, bij Lobith, is de huidige overschrijdingsnorm 1/1250 per jaar. Deze kans zal naar verwachting in 2050 drie tot vijf keer zo hoog zijn.

Voorts wordt geraamd dat de jaarlijks verwachte schade (oftewel het overstromingsrisico) in het stroomgebied van de Rijn tussen de 54% en 230% toeneemt in 2030 ten opzichte van 2000. Hiervan kan ongeveer driekwart van de toename toegeschreven worden aan het effect van klimaatverandering (toenemende overstromingskans), en de rest is het gevolg van sociaal-economische ontwikkelingen, zoals verstedelijking. Resultaten tonen aan dat het gebied met het hoogste overstromingsrisico gelegen is in de Benedenrijn in Nordrhein-Westfalen in Duitsland, en niet in Nederland zoals vaak wordt gedacht. Dit is vooral het gevolg van verschillende veiligheidsnormen van de waterkeringen in beide gebieden: in Nederland is deze norm relatief hoog waardoor het risico laag is.

In de huidige situatie neemt het veiligheidsniveau van de dijken en andere kunstwerken af langs de Rijn in stroomopwaartse richting. De verschillen vloeiend voort uit verschillen in waterbeheers tussen verschillende landen en Duitse Bundesländer, en zijn grofweg gerelateerd aan de economische waarde in overstroombare gebieden achter de dijken. Het resultaat is dat de kans op overstroomen in Duitsland en Frankrijk (waar de veiligheidsniveaus geschat worden op 1/200 tot 1/500 per jaar) hoger is dan in Nederland (waar de veiligheidsnorm in het bovenrivierengebied 1/1250 per jaar is). Als gevolg hiervan vinden er overstromingen plaats in Frankrijk en Duitsland, bij een afvoer die lager is dan de ontwerpaanvoer in Nederland. Dit heeft een vergaand verlagend effect op de piekafvoeren bij Lobith. De afname van de piekafvoer varieert tussen 2–13% in de referentie situatie en tussen 10–19% in het W-plus klimaatscenario in 2050, bij herhalingstijden van 50 jaar en hoger.

De gemiddelde verhoging van de maximale waterstand tijdens piekafvoeren langs de Rijn in 2050 is 50 cm als gevolg van klimaatverandering, maar varieert tussen enkele centimeters en 137 cm. In deze simulaties is het effect van bovenstroomse overstroomingen in de Boven- en Benedenrijn in Frankrijk en Duitsland meegenomen. Het in de jaren '90 door de ICBR (Internationale Commissie ter Bescherming van de Rijn) geïnitieerde Actieplan Hoogwater bevat verschillende hoogwaterbeschermende maatregelen die momenteel worden uitgevoerd en gepland zijn tot aan 2020. De
resultaten in dit proefschrift laten zien dat zowel de maatregelen in het Actieplan Hoogwater als verscheidene extra maatregelen, zoals meer retentiegebieden, de maximale waterstanden met slechts 5 cm tot 13 cm verlagen voor hoogwatersituaties met middelgrote herhalingstijden tussen de 50 en 100 jaar. De conclusie is dat deze maatregelen ontevreden lijken om te voorkomen dat de kans op overstromen als gevolg van klimaatverandering toeneemt. Volgens de resultaten in dit proefschrift is de enige maatregel die kan voorkomen dat de Rijn vaker overstroomt in de toekomst een drastische dijkverhoging tussen de 1,30 m en 3,30 m, afhankelijk van de locatie, in de veronderstelling dat deze dijken niet kunnen falen.

Hoewel door dit onderzoek de statistische onzekerheid verlaagd is bij het schatten van dergelijke piekafvoeren, zal er altijd een restonzekerheid door overige factoren zijn. Doordat de afvoer meetreeksen te kort zijn (~110 jaar) vereist het schatten van extreme gebeurtenissen (1/200 per jaar of lager) hetzij statistische, hetzij hydrologische modellering ver buiten het gekalibreerde bereik van deze modellen. Dit introduceert een onbekende fout en zal dus altijd een bepaalde onzekerheid bevatten. Daarnaast draagt het effect van bovenstroomse overstromingen en klimaatverandering bij aan de onvoorspelbaarheid van extreem hoge afvoeren. Het verhogen van de veiligheidsnormen om de overstromingskans te verlagen, zoals nu wordt overwogen in Nederland, zal ingenieurs dwingen om hun modellen nog verder op te rekken. Dit verhoogt dus de onzekerheid omtrent het schatten van de bijbehorende ontwerpafvoer, ongeacht hoe goed de gebruikte modellen zijn.

Waterbeheerders moeten zich meer bewust zijn van dit feit dat het verhogen van de veiligheidsnormen inhoudt dat de onzekerheid van de gesimuleerde maatgevende omstandigheden toeneemt. Een effectief klimaatadaptief beleid omtrent overstroomingsrisicobeheer zal de inherente onzekerheden moeten omarmen, en niet alleen hoogwaterbeschermende maatregelen moeten overwegen, maar ook een breed scala aan adaptatiemaatregelen die de potentiële schade van overstroomingen beperken.
Appendix A

The HBV model

The HBV model is a conceptual semi-distributed model, which is developed by Bergström in the early 70s (Bergström, 1976). HBV describes the most important runoff generation processes in a simple and robust way. The model requires precipitation, temperature and potential evaporation as input data, and consists of three routines:

- Snow routine
  Initial precipitation is divided into rainfall and snowfall, depending on temperature. This process is ruled by a threshold temperature (parameter $tt$) below which precipitation is supposed to be snow. The transition from rain to snow can be realised continuously over a temperature interval (parameter $tti$). Snow melt computations are based on a day-degree relation (snow melt factor $cf_{max}$). The snow distribution is computed separately for different elevation and vegetation zones in the basin.

- Soil routine
  The soil routine controls how much water evaporates and which part of the precipitation is direct runoff, or is stored in the soil. The runoff coefficient depends on the ratio of actual soil moisture, the maximum water storage capacity of the soil (parameter $fc$), and an exponent representing drainage dynamics (parameter $beta$). The parameter $lp$ defines the water storage in the soil at which
actual evaporation becomes equal to potential evaporation. There is a special correction factor for evaporation in forest areas \((cev\text{fo})\). Interception in forest areas and open land are also simulated \((icfo\text{ and icfi})\).

- Runoff generation routine
  This routine is the response function which transforms excess water from the soil routine to runoff. The routine consists of one upper, non-linear reservoir \((parameters khg, hq and alpha)\) and one lower, linear reservoir \((recession coefficient k4)\). The upper one represents direct runoff. The lower reservoir represents the base flow which is fed by groundwater. Groundwater recharge is ruled by a maximum amount of water that is able to penetrate from the soil to groundwater \((parameter perc)\). Timing and distribution of the resulting runoff is further modified in a transformation function by means of a retention parameter \((maxbas)\). This routine is a filter technique with a triangular distribution of the weights as shown in Figure A.1 at the bottom on the right \((Bergström, 1992)\).
Figure A.1: Illustration of discharge formation in the HBV model.
SOBEK is a one-dimensional dynamic numerical modeling system for open-channel networks. It can be used to simulate unsteady and steady flow, salt intrusion, sediment transport, morphology and water quality. The model can be applied for flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, ground-water level control, river morphology, salt intrusion and surface water quality. SOBEK is developed by WL | Delft Hydraulics (now Deltares) and the Institute for Inland Water Management and Waste Water Treatment (RIZA) (now Waterdienst), in the Netherlands (Delft Hydraulics, 2005).

The water flow is computed by solving the 1-D cross-sectionally integrated shallow-water equations (St. Venant equations), representing the conservation of cross-sectionally integrated mass and momentum. These equations are:

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_{\text{lateral}} \tag{B.1}
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \alpha_b \frac{Q^2}{A_t} \right) + gA_t \frac{\partial (h + z_b)}{\partial x} + A_t \frac{\tau_b}{\rho R} = 0 \tag{B.2}
\]

where \(A\) is the total cross-sectional area (m\(^2\)), \(A_t\) the cross-sectional flow area (m\(^2\)), \(Q\) the discharge (m\(^3\)/s), \(q_{\text{lateral}}\) the discharge added to the river per unit length (m\(^2\)/s),
\( \alpha_b \) the Boussinesq constant (\(-\)), \( g \) the acceleration due to gravity (m/s\(^2\)), \( h \) the water depth (m), \( z_b \) the bed level [m], \( \rho \) the mass density of water (kg/m\(^3\)), \( \tau_b \) the bed-shear stress (kg/m/s\(^2\)) and \( R \) the hydraulic radius (m). Time and space are represented by \( t \) and \( x \), respectively.

The bed-shear stress \( \tau_b \) is expressed by the Chézy formula:

\[
\frac{\tau_b}{\rho} = \frac{gQ|Q|}{C^2 A_f^2} \tag{B.3}
\]

where \( C \) the Chézy coefficient (m\(^{1/2}\)/s).
The GEV distribution

The generalized extreme value (GEV) distribution is the distribution of normalized maxima of a sequence of independent and identically distributed random variables. Because of this, the GEV distribution can be used as an approximation to model the maxima of long sequences of random variables. Three types of extreme value distribution functions \( F(x) \) are combined into the GEV distribution:

\[
F(x) = \exp \left\{ - \left( 1 + \beta \frac{x - \gamma}{\delta} \right)^{\frac{1}{\beta}} \right\}
\]  

(C.1)

where \( \gamma \) is the location parameter, \( \delta \) is the scale parameter, and \( \beta \) is the shape parameter. The shape parameter governs the tail behavior of the distribution. When \( \beta = 0 \), the GEV corresponds to the type I (Gumbel) distribution; \( \beta < 0 \) corresponds to the type II (Fréchet) distribution; and \( \beta > 0 \) corresponds to the type III (Weibull) distribution.
Appendix D

Performance indicators

Coefficient of efficiency ($E$)

The efficiency $E$ proposed by Nash and Sutcliffe (1970) is defined as one minus the sum of the absolute squared differences between the predicted and observed values, normalized by the variance of the observed values during the period under investigation. It is calculated as:

$$E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2}$$

with $O$ observed and $P$ predicted values.

The range of $E$ lies between 1 (perfect fit) and $-\infty$. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model.
Coefficient of determination ($r^2$)

The coefficient of determination ($r^2$) is defined as the squared value of the coefficient of correlation. It is calculated as:

$$r^2 = \left( \frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2 \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2}}} \right)^2$$  \hspace{1cm} (D.2)

The range of $r^2$ lies between 0 and 1 which describes how much of the observed dispersion is explained by the prediction. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation. The fact that only the dispersion is quantified is one of the major drawbacks of $r^2$ if it is considered alone. A model which systematically over- or underpredicts all the time will still result in good $r^2$ values close to 1.0 even if all predictions were wrong.

Volume error ($VE$)

The relative volume error ($VE$) is calculated as:

$$VE = \frac{\sum_{i=1}^{n} (O_i - P_i)}{\sum_{i=1}^{n} O_i}$$  \hspace{1cm} (D.3)


IPCC (2007a). The 4th assessment report by IPCC. Intergovernmental Panel on Climate Change.


Dankwoord

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Daarna volgden een paar jaar advies- en onderzoekswerk bij WL/Delft Hydraulics, waarbij het gehate wekelijkse tijdschrijven inzicht gaf in mijn eigen effectiviteit. Noodzakelijke competenties als budgetteren en plannen werden in deze tijd diep verankerd, en hebben zeker bijgedragen aan de succesvolle afronding van dit proefschrift. Tijdens mijn promotie ging het WL op in Deltares, dat zich ontwikkelde tot een prachtig onderzoeksinstuut. Er zijn veel WL en Deltares collega’s waarvan ik werk heb gebruikt of die mij hebben geïnspireerd, maar ik wil een aantal mensen in het bijzonder be-
Dankwoord


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Publications related to this thesis

Peer-reviewed articles:


Poster presentations:


Book chapters:


Technological reports:

Te Linde, A.H., 2009. Modeling the effect of flood management strategies in the Rhine basin. Institute for Environmental Studies, VU University, Amsterdam, the Netherlands.


Other publications:


Aline te Linde was born on 21 April 1977 in Deventer, the Netherlands. She attended high school at the Baudartius College in Zutphen and received her VWO diploma in 1995.


After graduation, she joined WL | Delft Hydraulics in 2002 where she worked as a hydrologist on various scales. Projects ranged from water management assignments for Dutch waterboards and the National Government, to international projects on cross-boundary river basin management. In October 2005, Aline started her PhD-research on climate change and adaptative capacity to extreme events in the Rhine basin, part-time, at the Institute for Environmental Studies (IVM), VU University Amsterdam. She arranged a co-operation between WL | Delft Hydraulics (now Deltares) and the IVM, in which both institutes supported her research and which allowed Aline to combine her research with project management and advisory work at Deltares. This resulted in the present thesis.