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

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Abstract

Climate change increases flood probabilities in the Rhine river basin, which complicates long-term flood management planning. This paper 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 (APF) 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 APF, as well as most additional measures, seem inadequate to cope with the increased flood probabilities that are expected in the future climate change scenario.

Introduction

Over the last decades, the number of fatalities and economic damage caused by river floods worldwide has increased considerably (e.g. Kron, 2008; Munich Re, 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 northwest 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 the mean winter discharges are expected to increase by 5–30% and the mean summer discharge to decrease by 0–45% by 2050 (compared with the current climate), using a range of climate change scenarios and hydrological modelling methods (Buishand & 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 m^3/s at present to between 16 500 and 19 500 m^3/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 [International Commission on the Protection of the Rhine (ICPR), 2005a]. Implemented and planned measures include dike relocation, the allocation of retention basins and land-use change to store water in head watersheds. 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 the 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

(~110 years) and extrapolation of these data may introduce large uncertainties (Klemeš, 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 (Lammersen, 2004).

This paper 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 the 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 paper is organized as follows: the second section describes the Rhine basin and briefly reviews its long history of flooding and flood management practice. In the third section, the method and models are explained. The fourth section summarizes the results of the evaluation of flood management measures. Finally, the last section presents the discussion and conclusions and the outlook for further research.

Rhine basin

General description

The Rhine is a cross-boundary river located in northwest 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 1). The Rhine basin comprises an area of ca. 185 000 km^2. 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 harbours, 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, 2005b).

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). Before 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 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, because urbanization in flood-prone areas increases 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

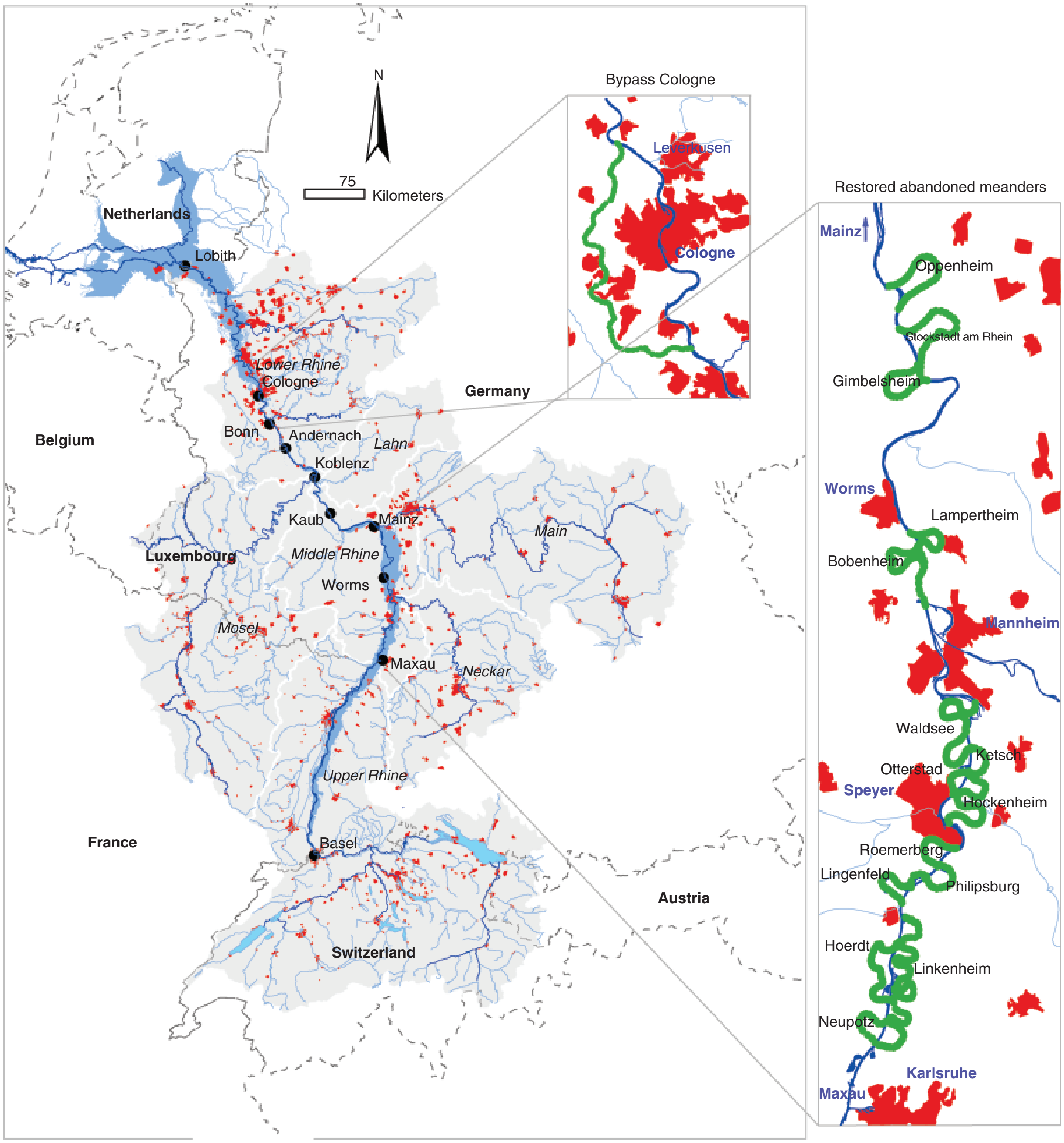

Figure 1 Rhine basin: The flood-prone areas of the Rhine are displayed in light blue and were derived from the Rhine Atlas (ICPR, 2001). The measures 'Cologne Bypass' and 'Restored abandoned meanders Upper Rhine' are enlarged.

for the design discharge of 16 000 m^3/s (the maximum discharges for which flood protection measures are designed) (Silva, 2003). Because of 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).

Methods

Let us assume that T equals $1/P$, where P represents the 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 that an event will occur once

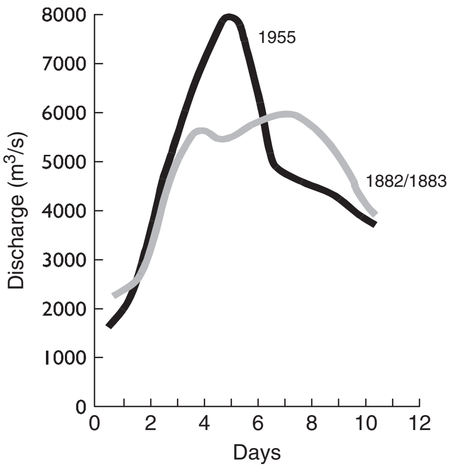

Figure 2 Discharge wave at Worms before and after canalization of the Upper Rhine. Both waves result from heavy rains in the southern part of the basin and have comparable volumes. Adapted from Silva *et al.* (2001).

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 paper, we will therefore use return periods when discussing low-probability peak events.

The different steps of the research approach in this paper are displayed in Figure 3. Steps 1–3 focus on simulating long discharge series using resampled meteorological data and the hydrological model HBV ('Hydrological modeling').

Because of 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 the 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 return periods, at four locations, resulting in 16 flood waves that can be used for the evaluation of flood measures.

Finally, Steps 6–8 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 ('Hydraulic modeling'). The results were analysed at the gauging stations at Lobith, Cologne, Andernach, Kaub, Worms and Maxau.

Hydrological modelling

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 (e.g. Nash and 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 modelling 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 modelling package that is based on the one-dimensional (1D) St Venant equations (Chow, 1959) 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.

Simulating long discharge series (Steps 1–3)

We used a weather generator to create 10 000 years of daily precipitation and temperature data [Figure 3 (Step 1)] for 134 sub-basins in 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 described thoroughly 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

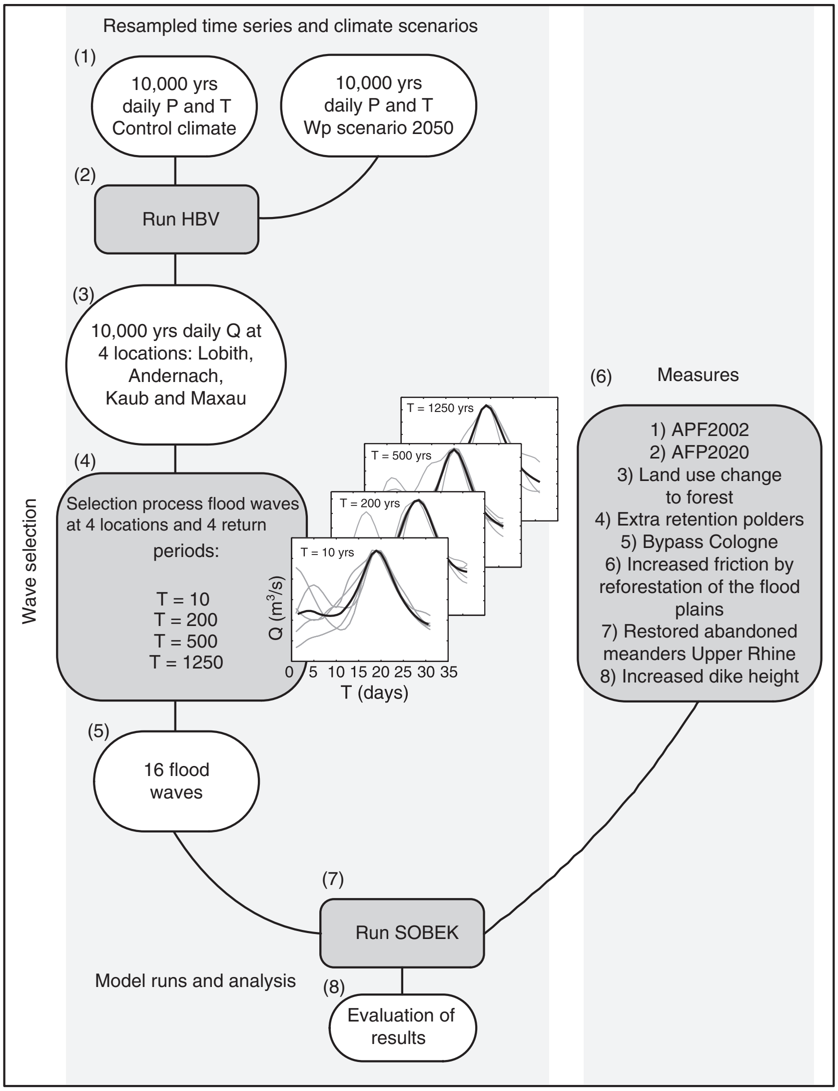

Figure 3 Flowchart describing all the steps of the method. APF2002 are existing measures implemented in the framework of the Action Plan on Floods (ICPR, 2005a). APF2020 are planned measures for 2020.

Rhine region following Te Linde *et al*. (2010). W-plus is an extreme climate scenario, based on combined global climate model and regional climate model (RCM) outputs, with an annual mean temperature increase of 2.5 °C, an increase in the mean monthly winter rainfall of 14%, and a decrease in the mean monthly summer rainfall of − 19% (Van den Hurk *et al*., 2006). The W-plus scenario of projected climate in 2050 was obtained using 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 the changed climate in 2050 [Figure 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 using the delta change approach with direct RCM output. They concluded that bias-corrected direct RCM output is to be preferred over the delta change approach because it provides an insight into 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.

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 1) and at four return periods ($T = 10$, 200, 500 and 1250), resulting in 16 flood waves. These four 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 carried out both for the control climate and for changed climate in 2050. To obtain results for the additional locations Worms and Cologne, we used flood events that culminate to flood waves that were selected for relatively nearby locations. These locations showed comparable peak flow characteristics when we analysed 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 the 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 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 3, Step 4). More details on the selection process are available in Te Linde (2009).

Hydraulic modelling and description of measures (Steps 6 and 7)

We used the 16 selected flood waves as boundary conditions for the hydrodynamic model SOBEK (Figure 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 kilometres upstream of their mouth to the Rhine. The model contains the 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 3.892 Mio m^3 (Eberle *et al.*, 2004).

In addition to implementing measures from the APF (nos. 1 and 2 in Step 6, Figure 3), we developed six flood management measures (nos. 3–8 in Step 6, Figure 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.

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

The APF measures are listed in Table 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 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 1, and are based on Raadgever *et al.* (2008). The total additional volume is 140 Mio m^3/s. The operational rules for these retention polders to start inundating at a defined water level or discharge were derived from the 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 Bárdossy, 2004). The effectiveness, however, of reforestation seems to depend on scale and reduces with increasing basin size (FAO, 2005; Bronstert *et al.*, 2007) and

Table 1 Measures along the Rhine, where RP is retention polder and DR is dike relocation

Rhine kilometres	Name	Type	Volume ($10^6\,m^3/s$)	APF2002	Measure APF2020	Additional retention
160	*Basel*					
235	Breisach/Burkheim	RP	6.5		v	v
246	Wyhl/Weiswel	RP	7.7		v	v
253.5	Mouth of the Elz	RP	5.3		v	v
275	Erstein	RP	7.8		v	v
276	Ichenheim/Meisenheim	RP	5.8		v	v
280	Altenheim	RP	17.6		v	v
308	Freistett	RP	9		v	v
321	Söllingen/Grefferen	RP	12	v	v	v
330	Moder	RP	5.6		v	v
359	Daxlander Au	RP	5.1	v	v	v
360	*Maxau*					
368	Neupotzh/Wörth	DR+RP	16.2		v	v
381.3–383.0	Elisabethenwörth	RP	11.9		v	v
384	Near Germersheim	RP	40			*
388.4	Mechtersheim	RP	7.4		v	v
390.4	Rheinschanzinsel	RP	6.2		v	v
392.6	Flotsgrün	RP	5	v	v	v
409.9	Kollerinsel	RP	6.1	v	v	v
411.5	Waldsee/Altrip/Neuhofen	DR+RP	9.1		v	v
436	Petersau/Bannen	DR	1.4		v	v
438	*Worms*					
438	Worms Bürgerweide	DR	3.4	v	v	v
440	Mittlerer Busch	DR	2.3		v	v
488	Near Darmstadt	RP	40			*
490	Bodenheim/Laubenheim	RP	6.4		v	v
517	Ingelheim	RP	3.8		v	v
546	*Kaub*					
614	*Andernach*					
660	Upstream Cologne	RP	50			*
668.5–673.5	Cologne-Langel	RP	4.5	v	v	v
688	*Cologne*					
705.5–708.5	Worringer Bruch	RP	29.5	v	v	v
707.5–713.5	Monheim	DR	8		v	v
723.5–727.5	Itter-Himmelgeist	DR	2		v	v
750	Downstream Cologne	DR	60			*
750.5–754.5	Ilvericher Bruch	RP	8.4		v	v
760.5–769.5	Mundelheim	DR	3	v	v	v
797.5–803.5	Orsoy Land	DR	10	v	v	v
818.5–823.5	Bislicher Insel	DR	17.4	v	v	v
832.5–833.5	Lohrwardt	RP	25	v	v	v
837.5–847.5	Griether Busch	RP	25		v	v
882	*Lobith*					

Displayed are the location and volume of implemented measures in 2002 in the Action Plan on Floods (APF2002) (v) and planned measures for 2020 (APF2020) (v), and the measure 'additional retention polders'. *Highlight the additional retention compared with APF2020).

the discussion continues on the links between deforestation, reforestation and floods (e.g. FAO, 2005; Bruijnzeel, 2008).

HBV distinguishes four land-use classes (forest, nonforest, 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 2), are represented by different factors for infiltration rates and potential evaporation (Eberle *et al.*, 2000). In the reforestation measure, we replaced all nonforest classes in HBV with mixed forest, which results in a 96.2% cover of forest in the entire basin, 2.4% rock and glacier and 1.4% lake.

Cologne bypass

Cologne suffered from flooding in the years 1993 and 1995. The economic damage in 1993 was estimated at €75 million.

Table 2 Current land use and the measure land-use change to forest in the Rhine basin

	Current		Land-use change	
Land-use class	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Forest	62 194	38.7	154 719	96.2
Arable land	36 304	22.6	0	0
Grassland	45 294	28.2	0	0
Built-up areas	7930	5	0	0
Rock and glacier	3797	2.4	3797	2.4
Lakes	2284	1.4	2284	1.4
Other	2996	1.9	0	0
Total	160 800	100	160 800	100

However, in spite of improved disaster management after the 1993 and 1995 floods, the city remains at a high risk, as 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, 2002).

To lower the water levels around Cologne during extreme floods, a bypass is proposed. A potential location for this bypass is shown in Figure 1. Because 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 kilometre (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, 2006). Our hypothesis, though, is that reducing the 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 to be > 3 m. According to the literature, 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.

Table 3 Properties of the measure restored abandoned meanders

Location	Length (km)	Width (m)	rkm
Neupotz	7.5	400	367.5
Linkenheim	3.9	300	367.5
Hoerdt	13.2	200	373
Lingenfeld	14.8	200	385
Philipsburg	7	200	389
Roermerberg	7.6	200	391
Hockenheim	17.8	200	399
Otterstad	4.2	200	403
Ketsch	5.6	150	406
Waldsee	18.1	150	409
Bobenheim	11.3	150	436
Lampertheim	8.6	150	438
Gimbelsheim	11.3	400	466
Stockstadt am Rhein	16.9	300	467.5
Oppenheim	17.8	300	476
Total length	200.7		

The location names are displayed in Figure 1. Maxau is located at Rhine kilometre (rkm) 360 and Worms at rkm 438.

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 3 and displayed in Figure 1.

Increased dike height

We increased the dike height in our SOBEK model along all the branches to such an extent (several meters) that the 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.

Results

Figures 4 and 5 summarize the modelling 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

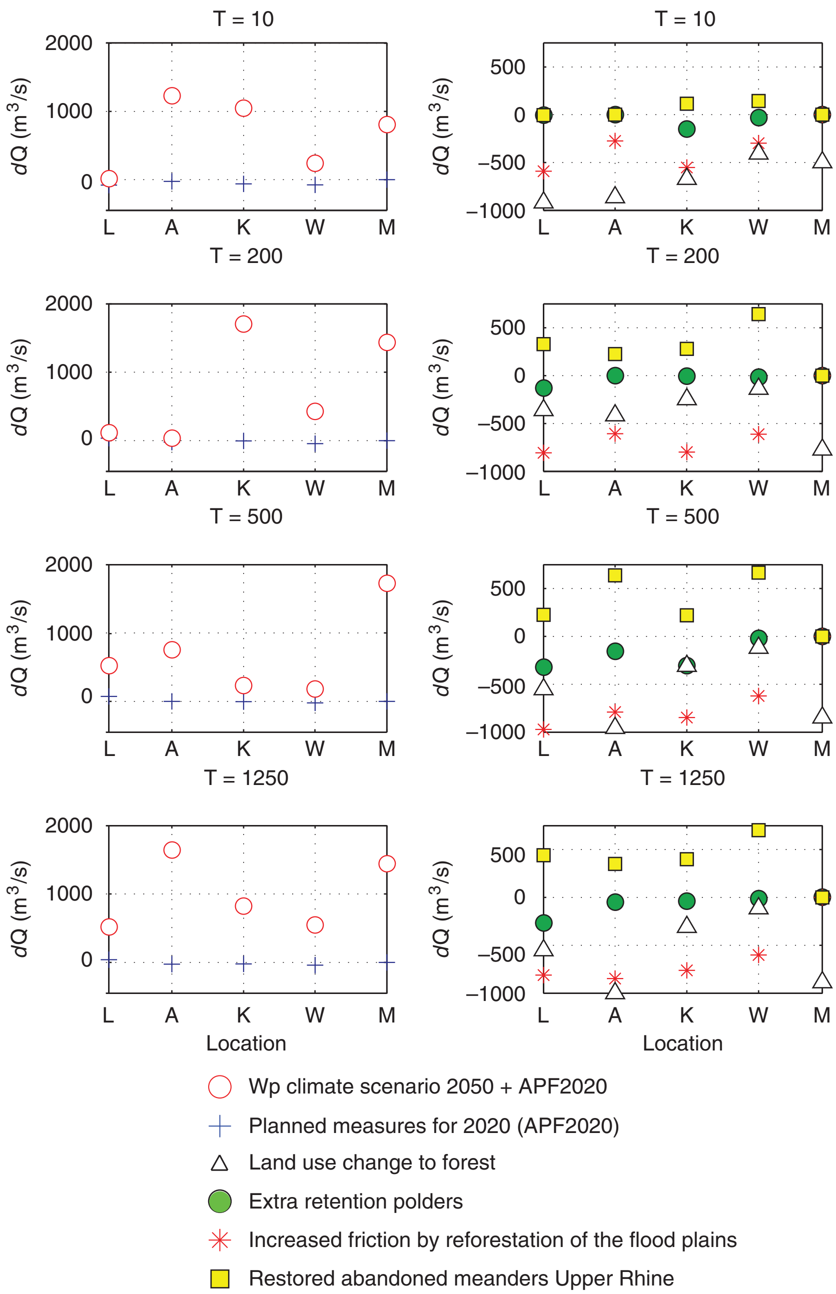

Figure 4 Effect of strategies and the W-plus climate change scenario on maximum discharge m^3/s. In the left panels, the APF2002 schematization with control climate boundary conditions is used as a reference. In the right panels, the APF2020 schematization with the climate change boundary conditions is used as a reference (W plus scenario for 2050). All values are displayed in Tables 4 and 6. L, Lobith; A, Andernach; K, Kaub; W, Worms; and M, Maxau.

compared with the reference situation. The circles in the left panels indicate the effect of climate change in 2050 in combination with the APF2020 measures on the maximum water levels, also compared with 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 by different symbols (see the legend). Tables 4–7 contain all the numbers that are shown in Figures 4 and 5.

The effect of dike heightening is relatively large (about a factor 4 larger than the effects of other measures) and hence

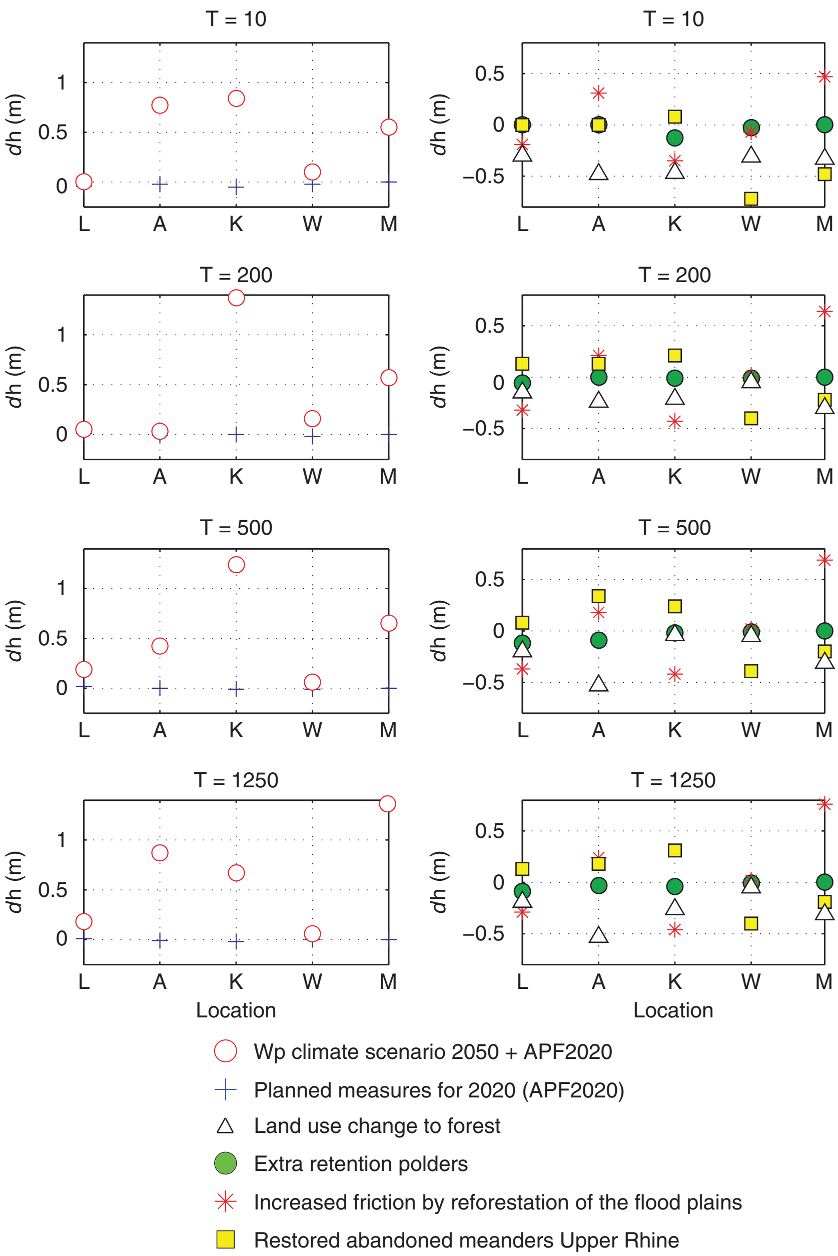

Figure 5 Effect of strategies and the W-plus climate change scenario on the maximum water level. In the left panels, the APF2002 schematization with control climate boundary conditions is used as a reference. In the right panels, the APF2020 schematization with the climate change boundary conditions is used as a reference (W-plus scenario for 2050). All values are displayed in Tables 5 and 7. L, Lobith; A, Andernach; K, Kaub; W, Worms; and M, Maxau.

does not fit well on the vertical scale in the right panels of Figures 4 and 5 (see 'Increased dike height'). Hence, the effect of (extreme) dike heightening to an extent that no flooding occurs is not displayed in Figures 4 and 5.

Furthermore, it should be noted that in the right panels of Figure 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 in which 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 set-up, Maxau is the upstream boundary node, and therefore, no effect on the

Table 4 Effect of planned measures for 2020 and W-plus climate change scenario on peak discharge (m^3/s)

Climate	Control	Control	W-plus 2050
Land use	Current	Current	Current
Dike height	Current	Current	Current
Measures	APF2002	APF2020	APF2020
Return period	*Q*	d*Q*	d*Q*
Lobith			
10	10 491	– 81	9
200	12 022	33	110
500	12 317	70	517
1250	12 827	37	512
Andernach			
10	9017	– 27	1227
200	12 158	– 22	33
500	12 724	– 2	755
1250	13 415	– 27	1638
Kaub			
10	6442	– 64	1047
200	7737	– 5	1702
500	7692	– 4	232
1250	8139	– 25	818
Worms			
10	5313	– 78	236
200	6546	– 44	425
500	6692	– 25	178
1250	6692	– 22	541
Maxau			
10	4729	0	802
200	7160	0	1431
500	7710	0	1727
1250	8421	0	1438

The numbers are plotted in Figure 5, left panels. APF, Action Plan on Floods.

Table 5 Effect of planned measures for 2020 and W-plus climate change scenario on the peak water level (m)

Climate	Control	Control	W-plus 2050
Land use	Current	Current	Current
Dike height	Current	Current	Current
Measures	APF2002	APF2020	APF2020
Return period	*h*	d*h*	d*h*
Lobith			
10	15.99	– 0.04	0
200	16.57	0.01	0.05
500	16.68	0.02	0.19
1250	16.87	0.01	0.18
Andernach			
10	60.84	– 0.02	0.77
200	62.84	– 0.01	0.03
500	63.17	0	0.42
1250	63.55	– 0.01	0.87
Kaub			
10	75.39	– 0.05	0.84
200	76.44	0	1.37
500	76.4	– 0.01	1.24
1250	76.75	– 0.02	0.67
Worms			
10	91.26	– 0.02	0.1
200	92.09	– 0.02	0.16
500	92.15	– 0.01	0.06
1250	92.16	– 0.05	0.06
Maxau			
10	106.79	0	0.55
200	108.11	0	0.57
500	108.33	0	0.65
1250	108.61	0	1.41

The numbers are plotted in Figure 6, left panels. APF, Action Plan on Floods.

discharge is observed at Maxau (Figure 4). The water level, on the other hand, does change between simulations at Maxau (Figure 5).

Land-use change to forest is the only exception, as 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 4. The water level due to land-use change also changes (Figure 5).

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 4, Figure 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 the peak water level is 50 cm, but varies between several centimetres and 137 cm (Table 5, Figure 5, left panels).

Increased dike height

From Tables 6 and 7, we can read that at $T = 10$ in the W-plus climate change scenario, raising dikes hardly has any effect on the 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 set-up 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

Table 6 Effect of additional measures on maximum discharge (m^3/s)

Climate	W-plus 2050	W-plus 2050	W-plus 2050	W-plus 2050	W-plus 2050	W-plus 2050
Land use	Current	Forest	Current	Current	Current	Current
Dike height	Current	Current	Current	Current	Current	No flooding
Measures	APF2020	APF2020	Additional retention	Increased friction	Restored meanders	APF2020
Return period	*Q*	d*Q*	d*Q*	d*Q*	d*Q*	d*Q*
Lobith						
10	10 420	−918	−8	−590	−4	−7
200	12 166	−362	−134	−806	330	3234
500	12 903	−552	−321	−973	224	1238
1250	13 376	−533	−271	−811	439	4378
Andernach						
10	10 217	−864	0	−275	2	0
200	12 169	−415	−3	−608	226	3937
500	13 477	−958	−158	−792	636	3991
1250	15 025	−1012	−50	−849	349	2977
Kaub						
10	7425	−571	−152	−551	116	232
200	9433	−247	−6	−800	280	2691
500	7920	−309	−308	−848	220	4209
1250	8933	−308	−41	−764	400	3848
Worms						
10	5000	−407	−32	−298	145	21
200	6926	−137	−15	−613	642	2950
500	6845	−120	−22	−622	666	3664
1250	6757	−114	−17	−602	701	1459
Maxau						
10	5532	−498	0	0	0	0
200	8591	−773	0	0	0	0
500	9437	−849	0	0	0	0
1250	9859	−887	0	0	0	0

The numbers are plotted in Figure 5, right panels. APF, Action Plan on Floods.

maximum water-level increase is 129 cm ($T=1250$) at Lobith, 212 cm ($T=200$) at Andernach, 325 cm ($T=500$) at Kaub and 245 ($T=1250$) at Worms (Table 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 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 $T=10$ increases 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 and 3.25 m, depending on the location, to prevent these areas from flooding.

Land-use change to forest

Land-use change to forest seems to be 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 and 53 cm (Tables 6 and 7, Figures 4 and 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.

Local effects of flood management measures

APF2020

The APF2020 measures result in peak discharge reductions of only -80 m^3/s and water-level reductions of -5 cm both for current climate conditions and for the increased discharges under climate change (Figures 4 and 5, left panels). The minor effectiveness of the APF2020 can be explained by two phenomena that relate to (1) the way in which the retention polders are operated and (2) on whether upstream flooding occurs, both illustrated in Figure 6.

Table 7 Effect of additional measures on the peak water level (m)

Climate	W-plus 2050	W-plus 2050	W-plus 2050	W-plus 2050	W-plus 2050	W-plus 2050
Land use	Current	Forest	Current	Current	Current	Current
Dike height	Current	Current	Current	Current	Current	No flooding
Measures	APF2020	APF2020	Additional retention	Increased friction	Restoredmeanders	APF2020
Return period	*h*	d*h*	d*h*	d*h*	d*h*	d*h*
Lobith						
10	15.99	– 0.3	0	– 0.19	0	0
200	16.62	– 0.15	– 0.06	– 0.32	0.13	1.02
500	16.89	– 0.2	– 0.12	– 0.37	0.08	0.29
1250	17.06	– 0.19	– 0.09	– 0.29	0.13	1.29
Andernach						
10	61.6	– 0.48	0	0.31	0	0
200	62.86	– 0.24	0	0.21	0.13	2.12
500	63.59	– 0.53	– 0.09	0.18	0.34	2.05
1250	64.41	– 0.53	– 0.03	0.24	0.18	1.48
Kaub						
10	76.18	– 0.47	– 0.13	– 0.35	0.08	0.18
200	77.8	– 0.21	– 0.01	– 0.43	0.21	1.88
500	76.34	– 0.04	– 0.02	– 0.42	0.24	3.25
1250	77.4	– 0.26	– 0.04	– 0.46	0.31	2.7
Worms						
10	90.89	– 0.31	– 0.03	– 0.07	– 0.72	0.02
200	92.23	– 0.05	– 0.01	0.01	– 0.4	1.81
500	92.2	– 0.05	– 0.01	0.02	– 0.39	2.17
1250	92.17	– 0.05	– 0.01	0.02	– 0.4	2.45
Maxau						
10	107.34	– 0.33	0	0.47	– 0.48	0
200	108.68	– 0.3	0	0.64	– 0.22	0
500	108.98	– 0.31	0	0.69	– 0.2	0
1250	109.13	– 0.31	0	0.76	– 0.19	0

The numbers are plotted in Figure 6, right panels. APF, Action Plan on Floods.

(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 $T=50$–100 (ICPR 2005). Their volumes are designed for peak events of the 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 6(a), 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 6(b) shows that retention polders become operational at the same discharge as in Figure 6(a) ($\sim$10 500 m^3/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 $>$ 12 000 m^3/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 100 [Figure 6(a) and (b)], no upstream flooding occurs. At $T=200$, though, flooding does occur [Figure 6(c)]. 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 m^3/s, as in Figure 6(a) and (b), and manage to decrease the maximum peak discharge of 13 000 m^3/s by $\sim$100 m^3/s (the dark grey dotted line).

When flooding is simulated, the maximum peak discharge reaches only 12 000 m^3/s [the grey line in Figure 6(c)]. Flooding apparently occurs at 11 500 m^3/s at Lobith and retains a substantial volume, illustrated as the area between the black and the grey lines. The relatively small volume of the APF2020 measures hardly causes extra retention (the dotted line). This further explains why, in Figures 4 and 5, the effects of APF2020 measures are hardly 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 7). The operational

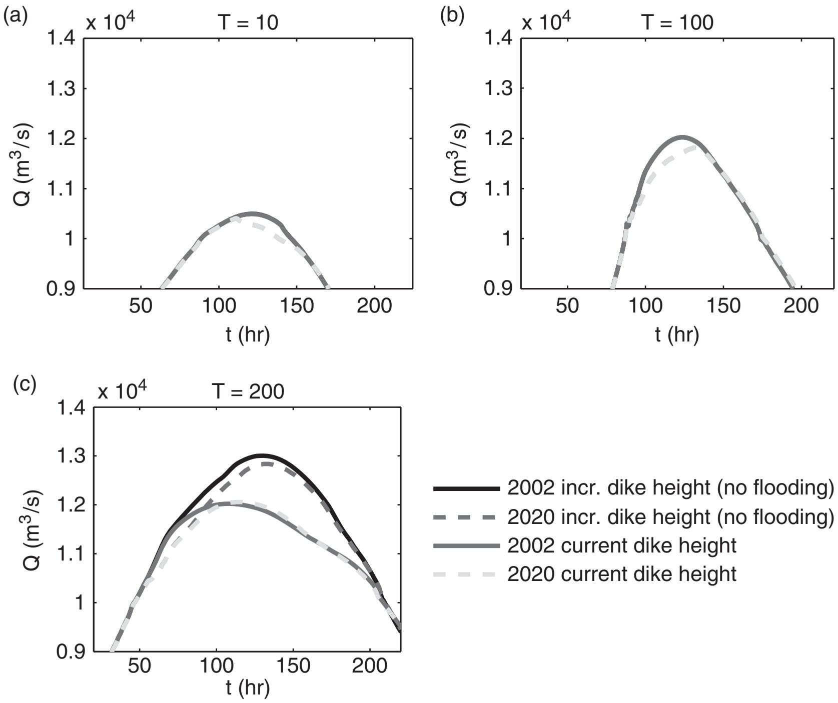

Figure 6 Effect of APF2020 retention measures on flood peaks with different return periods at Lobith, with and without the simulation of flooding. Flooding does not occur at $T = 10$ and 100.

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 $T = 50$–100. Furthermore, flooding obscures the dampening effect of these retention measures, in the same way as described above 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 4 and Table 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 at the Lower Rhine (Lobith and Andernach) (Figure 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 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 behaviour (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 4). It appears that because 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 water levels therefore decrease in the Upper Rhine (− 19 to − 72 cm, Table 7), which is a positive result. In the Lower Rhine, on the other hand, water levels increase (up to 34 cm, Table 7) as a result of increased discharge, where there is no change in the flow capacity.

Bypass cologne

The bypass results in a substantial lowering of the peak water level of almost 1 m at Cologne (Table 8) and is thus very effective, but the effect is only local. Twenty per cent 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 8).

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 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 7(a), 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 under the W-plus scenario is higher than that under the current conditions. The range of the decrease is 50–150 cm under current climate conditions and 100–250 cm under climate change in 2050.

In Figure 7(b), 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 the 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 in the peak water levels due to climate change remains, even when flooding is simulated.

Figure 7(c) displays the local effect of the bypass around Cologne (light grey). The basin-wide decrease in the maximum water level as a result of reforestation is also shown (black).

Table 8 Effect of the bypass around Cologne on peak discharge m³/s and peak water level (m)

Climate	W-plus 2050		W-plus 2050	
Land use	Current		Current	
Dike height	Current		Current	
Measures	APF2020		APF2020 and Cologne Bypass	
Return period	*Q*	*h*	d*Q*	d*h*
Cologne				
10	10 542	45.45	− 1939	− 0.96
200	12 258	46.4	− 2240	− 0.99
500	12 786	46.7	− 2320	− 0.97
1250	13 560	47.03	− 3542	− 0.85

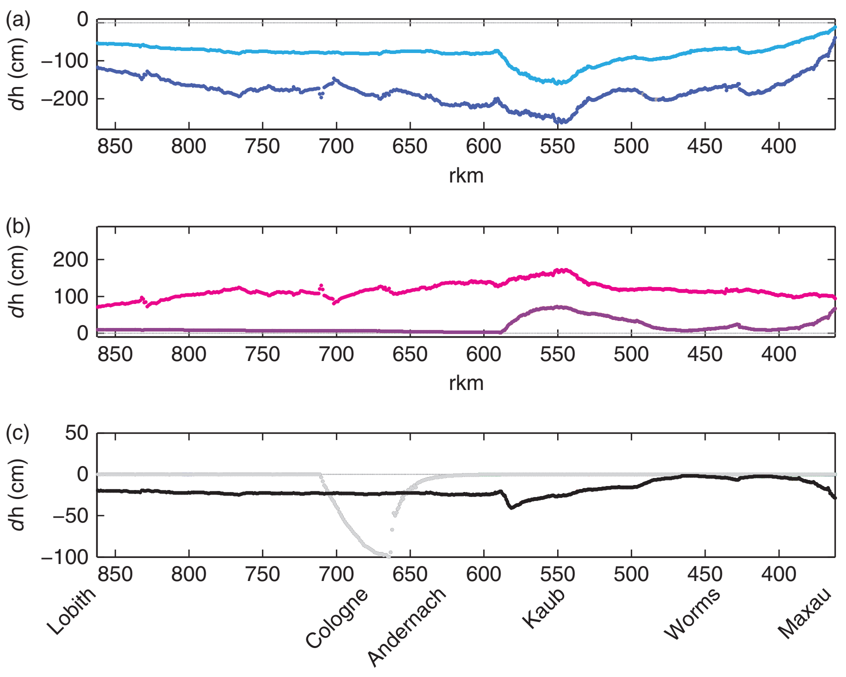

Figure 7 Longitudinal profile of the change in the peak water level (d*h*). The boundary conditions are $T = 200$ at Andernach [see 'Selection of 16 flood waves (Steps 4 and 5)']. Displayed are, (a) the effect of flooding, under control climate conditions (light blue), and under the W-plus scenario in 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).

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 analyse 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 set-up 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 8. According to Figure 8(a) and (b), flood probability will increase by a factor of 4 as a result of the W-plus 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 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% to 19% when upstream flooding does not occur, and from 8% to 11% when upstream flooding is taken into account [Figure 8(a) and (b), Table 9]. The breakpoint due to flooding is at $T = 100$ ($\sim$12 500 m^3/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 8(a) and (b) indicates that there is a physical maximum of the peak discharge that can reach Lobith, due to upstream flooding.

Figure 8(c) and (d) show 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 Figure 8(a–d), it is obvious that the APF2020 cannot restrain the impact of climate change. Finally, Figure 8(e) shows the effect of land-use change in the W-plus climate change scenario. All flood peaks are lowered by $\sim$1000 m^3/s as a result of reforestation to 96% forest in the Rhine basin.

Discussion and conclusions

Methods

The aim of this paper was to explore a method to evaluate the effectiveness of flood management measures that are planned in the APF (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 the dimensions of low-probability flood peaks, because extrapolation of extreme value distribution fits is no longer necessary (e.g. Te Linde *et al.*, 2010). However, the use of a resampling technique to generate extreme events inherits an unknown uncertainty, as it has been trained using a relatively short reference period (35 years) that does not necessarily include such extremes.

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 *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 on extreme events.

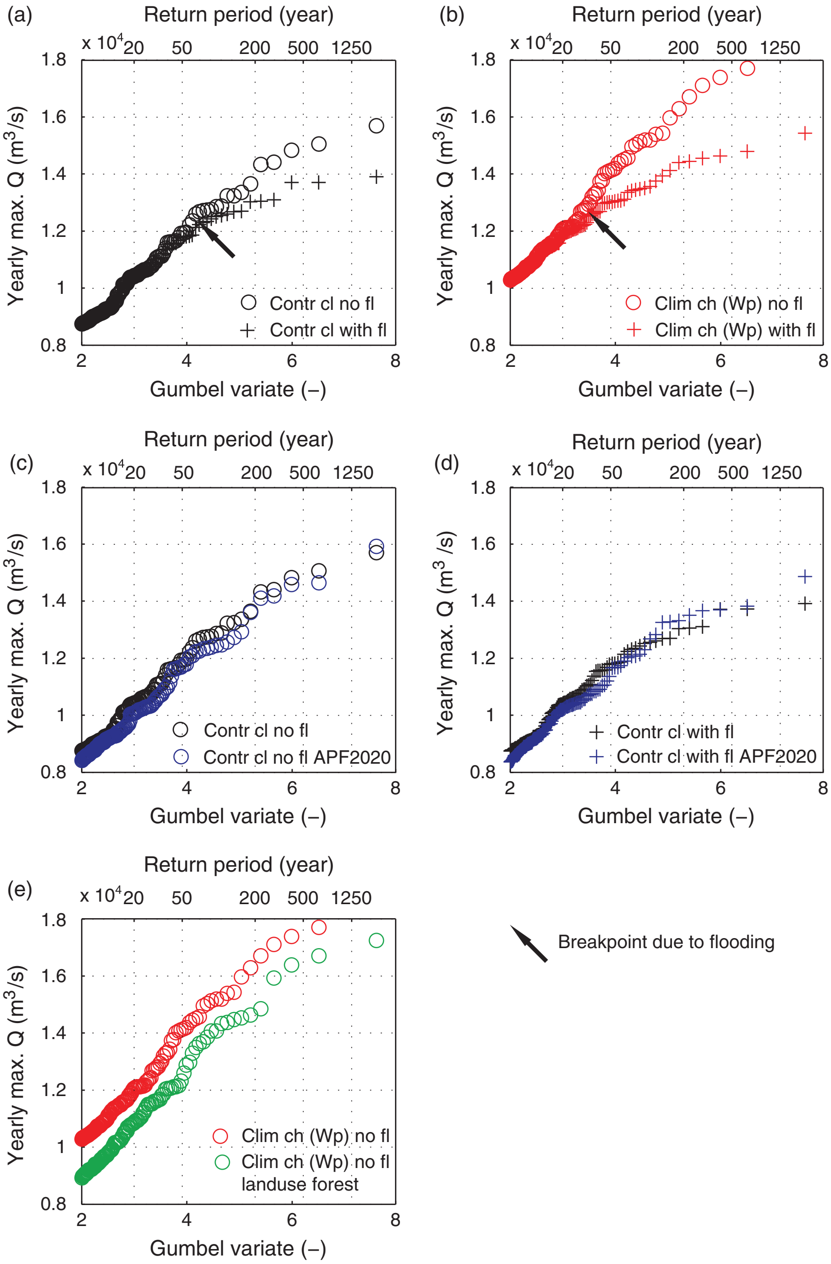

Figure 8 Extreme value plots for the yearly discharge maxima at Lobith for different climate conditions and measures. Contr cl, control climate; fl, flooding; clim ch (W-plus), is the W-plus climate change scenario for 2050.

Table 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

Rank	Return period (year)	Control climate Without upstream flooding (m^3/s)	W-plus (2050) Without upstream flooding (m^3/s) (%)	Control climate with upstream flooding (m^3/s)	W-plus (2050) with upstream flooding (m^3/s) (%)
1	1000	15 694	18 215 (16.1)	13 918	15 445 (11.0)
2	500	15 047	17 696 (17.6)	13 719	14 809 (7.9)
5	200	14 321	16 704 (16.6)	13 052	14 457 (10.8)
10	100	12 880	15 186 (17.9)	12 554	13 576 (8.1)
20	50	11 938	14 147 (18.5)	11 807	13 025 (10.3)

The second methodological issue was the necessity to include hydrodynamic modelling 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% and 13% under control climate conditions and 10–19% in the W-plus climate change scenario. The curve in Figure 8(a) and (b) indicates that there is a physical maximum of the peak discharge that can reach Lobith, due to upstream flooding.

Hence, upstream floods in Germany are favourable 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).

Effectiveness of measures

The mean increase in the peak water level due to climate change in 2050 is 50 cm, but varies between several centimetres and 137 cm (Table 5, Figure 5, left panels). Currently implemented and proposed measures in the APF, as well as most of the 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 the location, on the assumption that these dikes cannot fail.

The APF2020 measures, as well as additional retention polders, reduce the peak water levels by 5–13 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 in which 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 the grey lines in Figure 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 decimetres. 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 the water levels at a local scale. Restoration of abandoned measures in the Upper Rhine was also very effective in reducing the water levels locally, but resulted in increased water levels in the Lower Rhine.

Land-use change to forest decreased maximum water levels between 4 and 53 cm. The range in the percentage of decrease in discharge is between 2% and 9%. However, modelling land-use change with conceptual models, such as HBV and RhineFlow (Van Deursen and Middelkoop, 2001), has limitations, as 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 cause 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 the 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) point 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 with earlier work. The only exception is a study by Hundecha and Bárdossy (2004), who used the HBV model in a similar simulation set-up for the Rhine basin. They found reduced peak discharges of 10–19% 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 an efficient option to reduce flood probability on a basin-wide scale in the Rhine basin.

Further work

In this paper, 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 that do not seem to be very effective in water-level reduction), we are inclined to support the conclusions made by Hooijer *et al.* (2004) and the APF (ICPR, 2005a) that more could be gained from damage reduction and spatial planning than from flood defence 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 modelling 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 the modelling 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.

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