Rijkswaterstaat

Generator of Rainfall And Discharge Extremes (GRADE) for the Rhine and Meuse basins

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Contents

Abstract

In 1996 Rijkswaterstaat RIZA (Institute for Inland Water Management and Waste Water Treatment) and KNMI (Royal Netherlands Meteorological Institute) started to work together on a new methodology to provide a better physical basis for the estimation of the design discharge of the main Dutch rivers. The first component of this new methodology is a stochastic multivariate weather generator, which generates long simultaneous records of daily rainfall and temperature over the basin. The second component consists of hydrological and hydraulic models, which transform the generated rainfall and temperature records into synthetic discharge series. Altogether this new methodology is indicated as GRADE: Generator of Rainfall And Discharge Extremes. This report gives an overview of the development of GRADE and presents preliminary results for the Rhine and Meuse rivers. The applicability of the methodology is discussed and an overview of further research needs is given.

1 Introduction

Protection against flooding is a point of continuous concern in the Netherlands. Flood protection along the coast and main rivers is based on design water levels with a given probability of exceedance. Along the embanked part of the Dutch Rhine branches and Meuse, an average annual exceedance frequency of once every 1250 years holds for the design discharge and the corresponding design water levels. In 1996 the Flood Protection Act was established. This act prescribes the evaluation of the flood protection situation every five years, including an evaluation of the design water levels along the Meuse and Rhine branches.

The determination of the design water levels along the Meuse and Rhine branches is first of all based on the determination of design discharges of the Rhine at Lobith (German/Dutch border) and the Meuse at Borgharen (near the Belgian/Dutch border). The determination of design discharges from statistical analyses of the measured peak discharges faces various problems. The estimation of the 1250-year discharge event from statistical information in a discharge record of about 100 years involves a strong extrapolation, which is quite uncertain. Firstly, it is unknown how representative the relatively short measured discharge records are. Secondly, the discharge record is potentially non-homogeneous because of changes in the upstream basin, the river geometry and climate. Thirdly, the choice of frequency distributions is also a point of uncertainty. Also the extrapolation does not take into account the physical properties of the river basin.

In 1996 Rijkswaterstaat RIZA (Institute for Inland Water Management and Waste Water Treatment) and KNMI (Royal Netherlands Meteorological Institute) started to work together on a new methodology to provide a better physical basis for the estimation of the design discharge of the main Dutch rivers. The first component of this new methodology is a stochastic multivariate weather generator, which generates long simultaneous records of daily rainfall and temperature over the basin. The second component consists of hydrological and hydraulic models, which transform the generated rainfall and temperature records into discharge series. Altogether this new methodology is indicated as GRADE: Generator of Rainfall And Discharge Extremes (see Figure 1.1). Advantages of the proposed methodology are that i) long (e.g. 10^3-10^4 years) discharge records can be simulated, ii) meteorological conditions and basin characteristics can be taken into account, iii) the shape and duration of the flood can be analysed, and iv) it can potentially assess the effects of future developments like climate change and upstream interventions such as retention basins and dike relocations. However, also this new methodology has a number of statistical and modelling limitations. This motivates the need to test the proposed methodology and to discuss its applicability for the determination of design discharges for the Rhine and Meuse rivers.

Since 1996 several reports and papers have been written about the development of GRADE for the Rhine and Meuse basins (see Appendix 1). This report gives an overview of the work that has been performed so far. Firstly, the presently used methodology to determine the design discharges of the Rhine and Meuse is briefly outlined (Chapter 2). Next the methodology and results of GRADE for the Rhine and Meuse basins are presented (Chapters 3 to 9). Finally the applicability of the methodology is discussed and an overview of further research needs is given (Chapters 10 to 13).

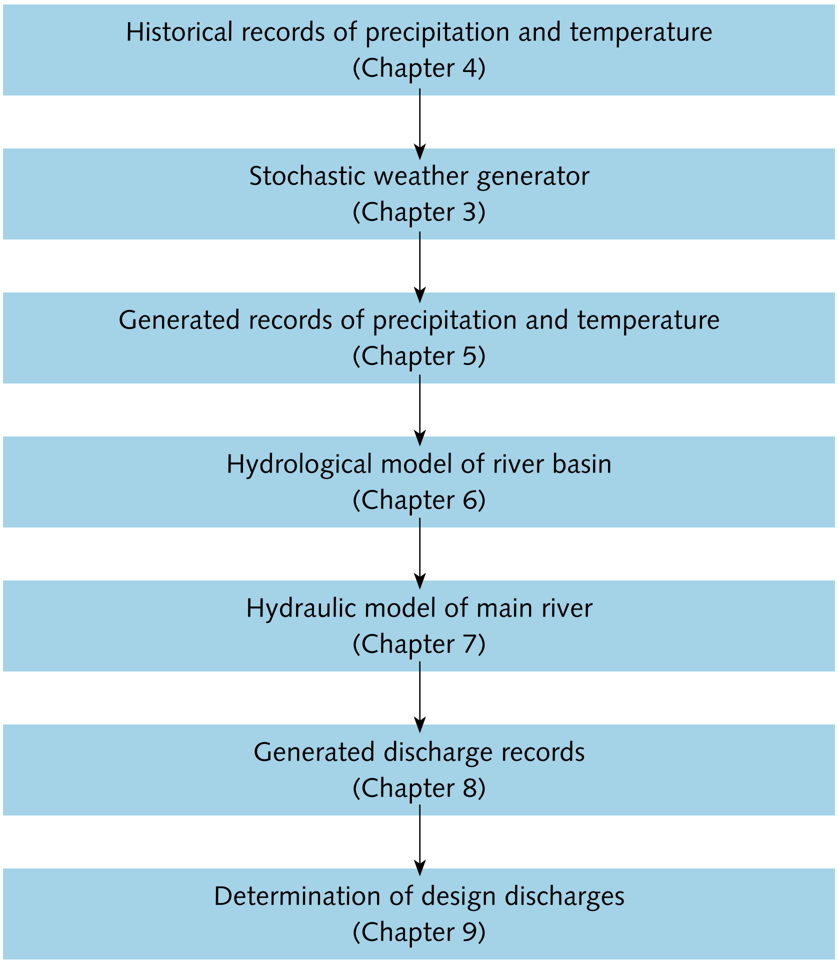


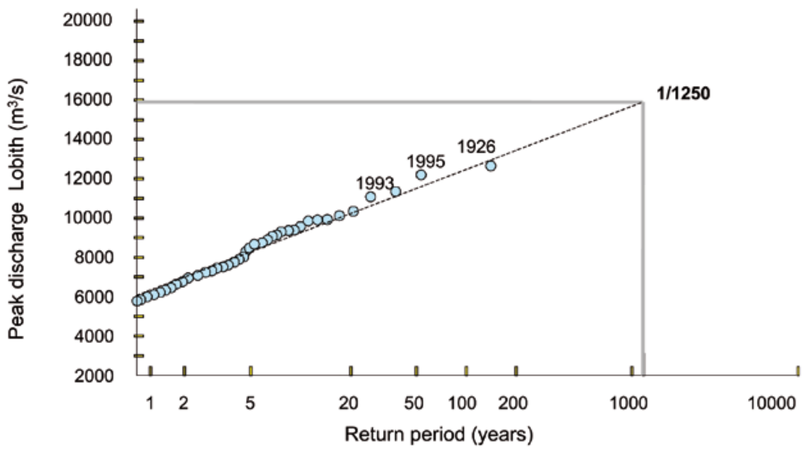
Figure 1.1 Components of GRADE.

2 Present methodology to determine design discharges

The design discharge is obtained by analysing annual maximum discharges and peak over threshold data. This analysis is based on measured discharges with records starting from 1901 for the Rhine at Lobith and from 1911 for the Meuse at Borgharen. These records have been homogenised in order to account for past changes in the upstream basin. Several theoretical distribution functions have been fitted to the annual maximum discharges. These distribution functions have been used to make an extrapolation to the required exceedance frequency. This results in a range of possible outcomes. The calculation of the design discharge is based on a combination of the different distribution functions, where the weights are determined by Bayesian analysis (see Chbab et al., 2006). Finally the determined value is rounded because of the limited accuracy of the methodology.

Figure 2.1 Distribution of extreme discharges of the Rhine at Lobith.

The dots are the observations. The line is based on the combination of different distribution functions.



The design discharges that have been determined in 1996, 2001 and 2006 are presented in Table 2.1. The increase of these values for 1996, 2001 and 2006 (for the Meuse) are mainly the result of the extension of the observed records with a relatively wet period of five years. This illustrates the sensitivity of the analysis. A more detailed description of the procedure used in 2006 is given in Diermanse (2004a and 2004b).

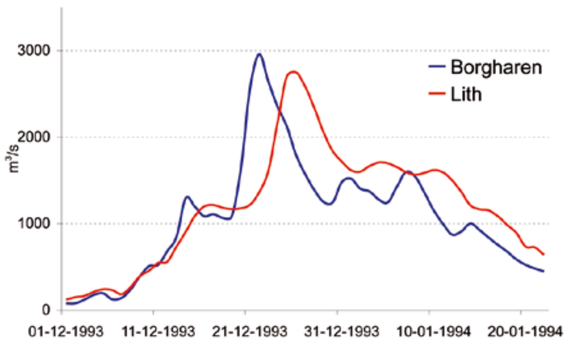
Table 2.1 Design peak discharges (Q1250) for the Rhine and Meuse.

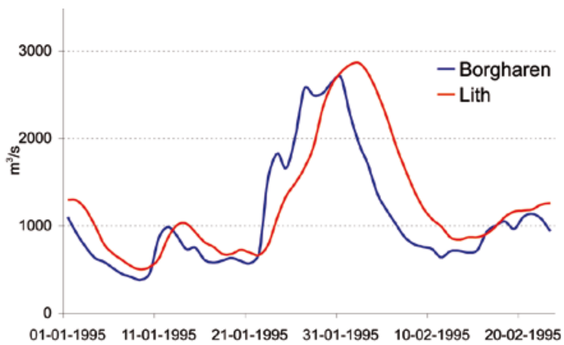
Station	1996 (m^3/s)	2001 (m^3/s)	2006 (m^3/s)	95% confidence interval in 2006 (m^3/s)
Lobith	1500	16000	16000	13060-18370
Borgharen	3650	3800	4000	3250-4705

Above-mentioned methodology only includes the determination of the design peak discharge. In order to calculate the design water levels downstream along the Dutch Meuse and Rhine branches also the shape of the design flood wave at Lobith and Borgharen needs to be determined (e.g. Figure 2.2). This is done by multiplying the hydrographs of selected historical flood waves with the ratio between the design discharge and the observed peak discharge (Wijbenga and Stijnen, 2004). The characteristics of these scaled waves have been used to determine the shape of the design flood wave.

Figure 2.2 Hydrographs of the 1993 and 1995 Meuse floods at Borgharen and Lith.

The peak discharge at Borgharen was larger during the flood of December 1993 than during the flood of January 1995. Nonetheless, the peak discharge (and water level) in the downstream-embanked part of the Dutch Meuse (e.g. at Lith) was larger during the 1995 flood. This example illustrates that water levels in the embanked part of the Meuse not only depend on the peak discharge at Borgharen, but also on the shape/ volume of the flood wave at Borgharen.





3 Stochastic weather generator

The weather generator is based on a nonparametric resampling technique. Daily rainfall amounts are resampled from the historical record with replacement. Although this does not give new information about the distribution of the 1-day rainfall amounts, different temporal patterns are generated. Therefore, multi-day rainfall amounts can take values that are not observed in the historical data (Figure 3.1).

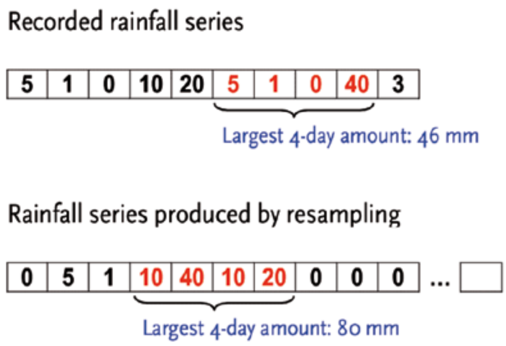
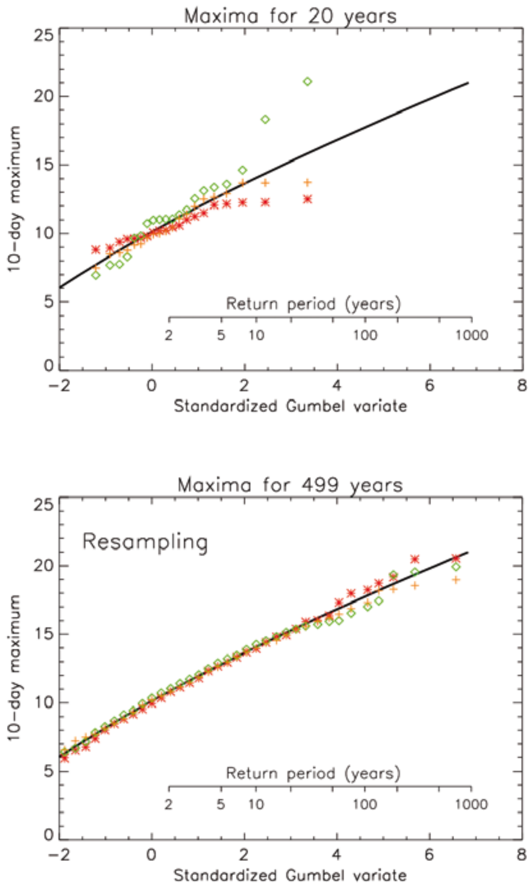


Figure 3.1 Schematic representation of resampling. The multi-day values in the generated sequences can take values that are not observed in the historical sequence, due to the reordering of historical days. Single-day values in the generated sequences do not exceed the observed values in the historical record.

With the weather generator it is possible to simulate long records of daily weather data. This enables a more accurate estimation of the statistical properties of the multi-day extreme events. The following example illustrates this. Synthetic sequences were generated from a stochastic rainfall model assuming that the probability of a day being wet is 0.5 and that the amount of rainfall on a wet day comes from a known (exponential) distribution. There is no temporal correlation in this simple stochastic model. Figure 3.2 (upper panel) presents Gumbel probability plots of the 10-day annual maxima for three 20-year simulations with the stochastic rainfall model. For short and moderate return periods there is little difference between the three 20-year simulations. The ordered maxima almost fall on the line representing the true distribution. The largest values in the three simulations, however, strongly differ. This shows that it is not possible to get a reliable estimate of the 10-day rainfall amount that is exceeded on average once in 100 years from a sample of only 20 years. Therefore, from each 20-year simulation a new series of 499 years was generated by resampling with replacement. The ordered 10-day annual maximum amounts from these series are shown in Figure 3.2 (lower panel).
In contrast to the upper panel, each 499-year simulation seems to describe the upper tail of the distribution quite well, illustrating the fact that a 20-year record of daily rainfall amounts contains much more information about the distribution of the 10-day annual maximum amounts than the 20 individual annual maxima alone.

Figure 3.2 Gumbel plots of the 10-day annual maximum rainfall amounts in three 20-year simulations with a simple stochastic rainfall model (upper panel), and in 499-year resampled sequences from the data of the 20-year simulations (lower panel). After Buishand (2007). The solid curve represents the true 10-day maximum distribution for the underlying rainfall model.



The weather generators for the Rhine and Meuse basins do not generate rainfall at a single site but rainfall and temperature at multiple locations simultaneously. A major advantage of resampling historical days is that both the spatial association of daily rainfall over the drainage basin and the dependence of daily rainfall and temperature are preserved without making assumptions about the underlying joint distributions. To incorporate autocorrelation, one first searches the days in the historical record with similar characteristics as those of the previously simulated day, i.e. the nearest neighbours. One of the k nearest neighbours is randomly selected and the observed values for the day subsequent to that nearest neighbour are adopted as the simulated values for the next day. A feature vector is used to find the nearest neighbours in the historical record. This vector is determined for each day and typically contains the mean (standardised) temperature and precipitation over the basin and some information of the spatial variation of the precipitation field. The effect of seasonal variation is reduced by standardising the daily precipitation amounts and temperatures and by restricting the search for nearest neighbours to days within a moving window, centred on the calendar day of interest. Standardisation mainly eliminates the annual cycle in the mean but not the seasonal variation in the dependencies between variables (e.g., relatively strong spatial correlation of precipitation in winter and weak spatial correlation in summer).

The composition of the feature vector and the number k of nearest neighbours are important elements of the resampling procedure. Their impact on the simulated rainfall sequences is demonstrated in Chapter 5. Other points are the width of the moving window, the choice of a metric that measures the similarity of the potential nearest neighbours, and the probability distribution used for selecting one of the nearest neighbours.

For three sub-basins of the river Meuse (Ourthe at Hamoir, Amblève and Vesdre) the simulation of 6-hourly values of precipitation and temperature was studied (Wójcik and Buishand, 2001). Disaggregation of the simulated daily values into 6-hourly values turned out to be superior to straightforward resampling of 6-hourly values.

Further details about the nearest-neighbour resampling procedures used can be found in the reports and papers presented in Appendix 1.

4 Historical records of precipitation and temperature

For the Rhine basin the simulations were based on station records for the period 1961-1995. Two sets of simulations were performed for the Meuse basin, simulations using observed station data for the period 1961-1998 (hereinafter referred to as Sim61) and simulations based on the period 1930-1998 (Sim30). The number of stations used for the procedure (i.e. for the derivation of the feature vector) is listed in Table 4.1. The station positions are shown in Figures 4.1 and 4.2.

For each selected historical day in the simulation algorithm it is possible to deliver variables that do not contribute to the feature vector.
In this way the generated station rainfall data were supplemented with the area-average rainfall amounts over the sub-basins of the rivers (134 for the Rhine and 15 for the Meuse, see Chapter 6). For the Meuse simulation Sim30 this required an additional nearest-neighbour search because the area-average rainfalls for the sub-basins were only available from 1961 onwards (see Leander and Buishand, 2004c; Leander et al., 2005). The daily area-average rainfall amounts for the sub-basins were derived from interpolated station values on a regular grid. The number of stations used for these gridded values is much larger than that mentioned in Table 4.1 (e.g. 63 stations for the French part of the Meuse basin). The method of interpolation and the grid size used depends on the country of origin (see Appendix 2).

Table 4.1 Number of stations used for the resampling procedure (see also Figures 4.1 and 4.2).

Basin	Period	Precipitation	Temperature	Source
Rhine	1961-1995	34	34	Deutscher Wetter Dienst (DWD), Service de la météorologie et de l'hydrologie de Luxembourg, Météo France and MeteoSwiss via the Commission for the Hydrology of the Rhine basin (CHR/KHR)
Meuse	1961-1998	7	4	Météo France, Royal Meteorological Institute of Belgium (RMIB), Deutscher Wetter Dienst (DWD)
Meuse	1930-1998	7	2	Météo France, Royal Meteorological Institute of Belgium (RMIB), Deutscher Wetter Dienst (DWD)

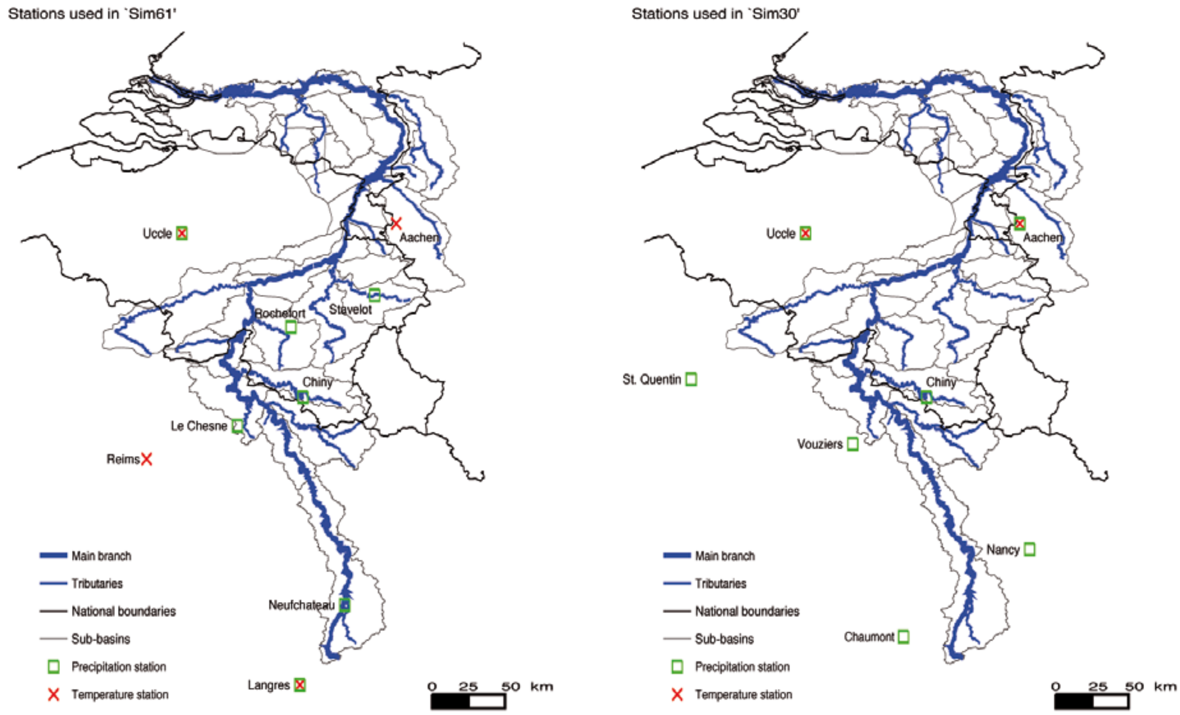
The daily temperatures for the sub-basins of the Rhine were generated in a similar way as their area-average rainfall amounts. For the Meuse basin, an additional nearest-neighbour search was performed to obtain temperature data for 11 locations, instead of two (Sim30) or four (Sim61), using data from additional stations for the period 1968-1998. The simulated temperatures at these 11 locations were then converted to areal values for the 15 sub-basins of the Meuse (Appendix 2).

The simulation of 6-hourly values for the three sub-basins of the Meuse was based on sub-basin area-average rainfall and temperature at St. Hubert. The 6-hourly sub-basin rainfall data were obtained by disaggregating the daily area-average rainfall amounts using hourly station records. Hourly precipitation and temperature were only available for the Belgian part of the Meuse basin (period 1967-1998) and were obtained from the Royal Meteorological Institute of Belgium.

The collection and screening of the historical data have been very laborious. A meaningful enlargement and improvement will require an enormous effort.

Figure 4.1 Locations of precipitation and temperature stations in the Rhine basin.

Figure 4.2 Locations of precipitation and temperature stations in the Meuse basin for Sim61 (left) and Sim30 (right).



5 Generated meteorological records

The analysis of the generated rainfall sequences was focussed on the reproduction of the autocorrelation of daily rainfall and the extreme-value distributions of multi-day rainfall, in particular for the 10-day rainfall amounts. Large multi-day rainfall amounts in the winter half-year (October – March) are in general the cause of floods in the Rhine and Meuse rivers. It was found that the autocorrelation of daily rainfall is best reproduced with a small number ($k = 2$ or $k = 5$) of nearest neighbours in the resampling scheme, but even then there is a slight underestimation of the lag 1 and lag 2 autocorrelation coefficients. This bias tends to increase if $k > 10$. As a result of the bias in the autocorrelation, the variability of the generated multi-day rainfall amounts is somewhat too low.

Table 5.1 The largest value (MAX) and the 50-year events of N-day winter (October-March) precipitation (mm) in 1000-year simulations, averaged over 25 German stations in the Rhine basin and averaged over 3 simulation runs of 1000 years each. After Buishand and Brandsma (2001). The figures in the bottom line refer to the averages of the largest N-day winter precipitation amount (mm) in each of the 35-year historical records.

Experiment	Resampling scheme		MAX			50-year event		
	q	k	N = 4	N = 10	N = 20	N = 4	N = 10	N = 20
1	3	2	115	176	239	91	129	178
2	3	5	119	179	237	90	131	178
3	3	20	125	182	244	91	130	180
4	3	50	126	178	237	90	129	177
5	9	2	119	222	285	92	135	182
6	9	5	121	175	235	90	129	176
7	9	20	120	178	227	89	127	173
8	9	50	120	171	228	87	125	171
Historical (35 years)			96	137	190			

Table 5.1 compares two characteristics of the extreme multi-day rainfall amounts in simulated 1000-year sequences from a number of resampling experiments for the German part of Rhine basin (25 stations). Both the number of nearest neighbours (k) and the composition of the feature vector (q denotes its dimension) were varied. In the experiments with $q = 3$, the feature vector contains the average of the standardised daily rainfall and temperature of the 25 stations, and the fraction of stations with precipitation.

The feature vector in the experiments with q = 9 contains more detailed information of the rainfall field and three indices for the atmospheric circulation. For all durations, the largest values in the 1000-year generated sequences are considerably larger (on average about 20%) than the largest historical values. The averages of the latter are comparable with the 50-year event, which is in accordance with statistical theory about the expected value of the largest order statistic. The results for Experiments 3, 4, 7 and 8 with a relatively large value of k are not much different from those for Experiments 1, 2 and 6 with a small value of k, suggesting that the effect of the larger bias in the autocorrelation for large k is small. The largest 10-day and 20-day values in Experiment 5 (k=2) are much larger than the corresponding values in the other experiments. Exceptionally large 10-day and 20-day values were found in this experiment due to repetitive sampling of the same historical days with large rainfall in a short time period. The likelihood of this artefact decreases with increasing k and increasing width of the window from which the data are resampled.

The reproduction of the second order moments of temperature worsens with increasing k and increasing q. The standard deviation of the monthly temperature is underestimated by 5% in Experiment 1 (k=2, q=3) in Table 5.1, by 11% in Experiment 4 (k=50, q=3) and by 26% in Experiment 8 (k=50, q=9).

For the Meuse basin the mean standardised rainfall amount for the four days preceding the last simulated day was entered in the feature vector. The inclusion of this “memory” element improves the reproduction of the autocorrelation. This leads to the simulation of more extreme multi-day winter rainfalls as is shown in the upper panel of Figure 5.1 for the winter maxima of 10-day basin-average rainfall. At long return periods, the Gumbel plot for the Sim61 simulation with memory element is clearly above the plot for the Sim61 simulation without memory element. The lower panel of Figure 5.1 presents the Gumbel plot for a Sim30 simulation with memory element. This plot is somewhat below that of Sim61, which can be ascribed to the fact that the winter half-year is on average drier for the period 1930-1960 than for the years 1961-1998.

The Gumbel plot for the 10-day winter maximum amounts from the Sim61 simulation with memory element is close to the corresponding plot of the historical data, except for the two largest historical extremes. These extremes correspond to the Meuse floods of December 1993 and January 1995. By splitting the 12,000 - year Sim61 simulation into segments of the same length as the historical series it can be shown that the deviations between the plots for that simulation and the historical maxima are not statistically significant (Leander et al., 2005). Note further from Figure 3.2 (upper panel) that it is not unlikely that the largest values from a sample strongly deviate from the line of their theoretical distribution.

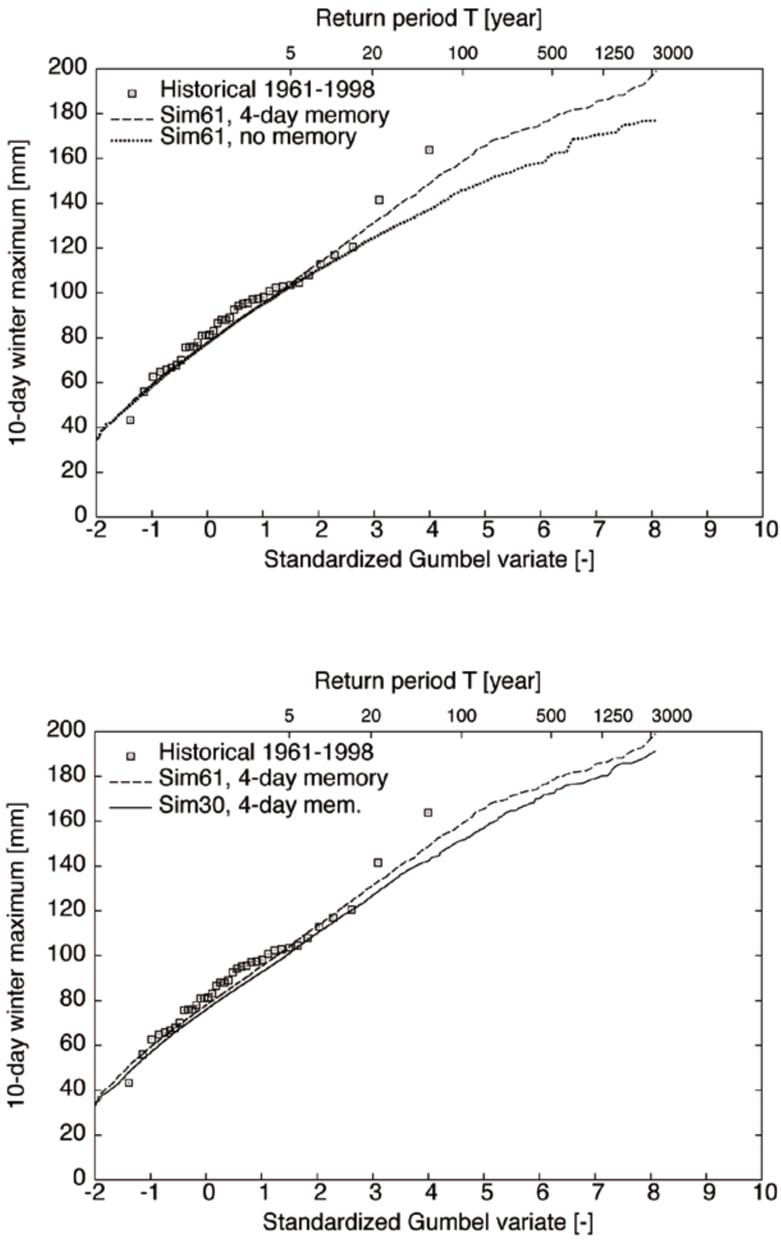


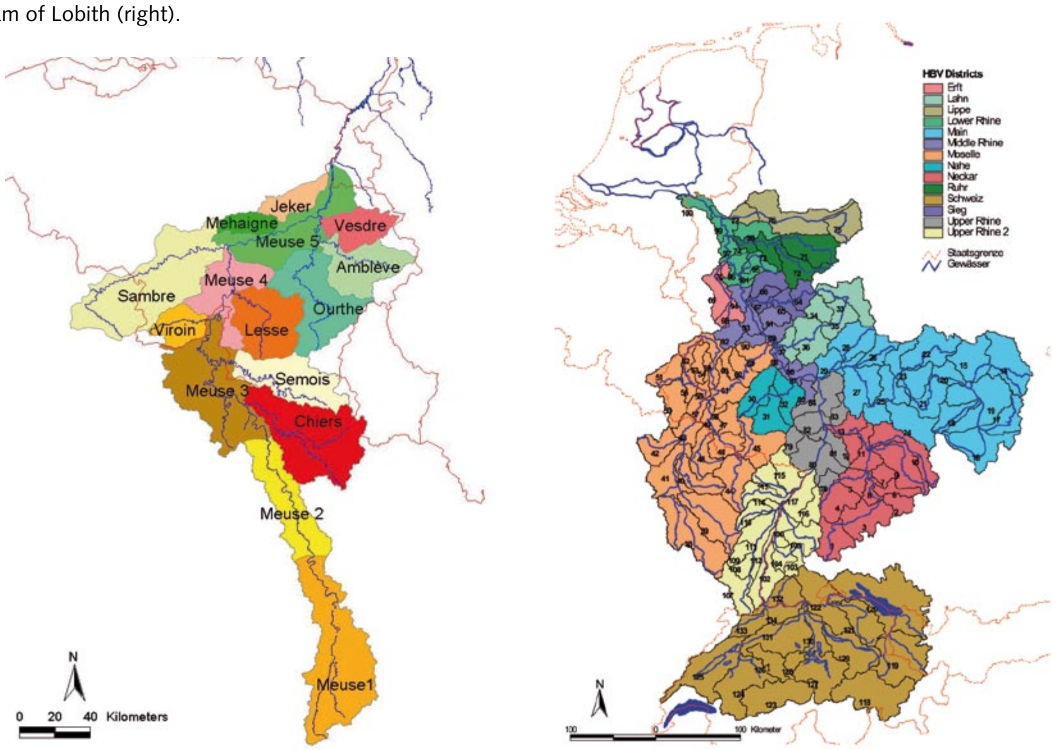
Figure 5.1 Gumbel plots of 10-day winter maxima of the average rainfall over the Meuse basin from historical data and from 12,000-year simulations (average plot of four 3000-year segments). After Leander et al. (2005). The upper panel shows the effect of including a 4-day memory element in the feature vector. The lower panel compares a simulation based on historical data for the period 1961-1998 (Sim61) with a simulation based on the period 1930-1998 (Sim30).

6 Hydrological modelling

Based on a model inventory by Passchier (1996) it was decided to use the conceptual hydrological model HBV in GRADE for the Rhine and Meuse basins. HBV was developed at the Swedish Meteorological and Hydrological Institute (SMHI) in the early 1970s and has been applied to many river basins all over the world (Lindström et al., 1997). HBV describes the most important runoff generating processes with simple and robust algorithms. In the "snow routine" storage of precipitation as snow and snow melt are determined according to the temperature. The "soil routine" controls which part of the rainfall and melt water forms excess water and how much is evaporated or stored in the soil. The "runoff generation routine" consists of one upper, non-linear reservoir representing fast runoff components and one lower, linear reservoir representing base flow. Flood routing processes are simulated with a simplified Muskingum approach. A flow diagram of the HBV model is given in Appendix 3. In GRADE the Rhine and Meuse basins have been divided into 134 and 15 sub-basins respectively (see Figure 6.1). HBV simulates the rainfall-runoff processes for each sub-basin. The sub-basins are interconnected within the model schematisation and as such HBV can simulate discharges at Lobith and Borgharen.

Figure 6.1 Meuse basin upstream of Borgharen (left) and Rhine basin upstream of Lobith (right).

Both basins have been divided into sub-basins of on average about 1000 km^2. These sub-basins have been used as entity for hydrological modelling.



For the Rhine basin HBV has been calibrated and validated with daily temperature, potential evapotranspiration, precipitation, and discharge data covering the period 1961-1995 (Mülders et al., 1999; Eberle et al., 2002 and 2005). Discharge data were available for most of the sub-basins schematised by HBV. The calibration of the sub-basins for which no discharge data were available is based on discharge data measured downstream of the sub-basins. For the main branch of the river Rhine it was not possible to correctly simulate the damping of peaks during flood events with the simplified Muskingum approach that is implemented in HBV. This flood routing procedure was adapted to reduce high peaks. Usually a certain percentage of the discharge is lost in this adaptation. The segments of the Rhine where this is implemented are given in Eberle et al. (2005). The adapted flood routing procedure in HBV is only meant for first analyses, for detailed studies more sophisticated flood routing models are used for the river Rhine (see Chapter 7).

Table 6.1 Values of the Nash-Sutcliffe criterion R^2 for HBV modelling of the Rhine basin. Only the results for the main branch and the major tributaries are listed in this table. Source: Eberle et al. (2005)

River	Gauging station	Upstream area (km²)	Period 1961-1995
Aare	Untersiggenthal	17625	0.92
Rhine	Basel	35921	0.92
Rhine	Maxau	50196	0.89
Neckar	Rockenau	12710	0.85
Main	Raunheim	27142	0.88
Nahe	Grolsheim	4013	0.86
Lahn	Kalkofen	5304	0.87
Moselle	Cochem	27088	0.91
Sieg	Menden	2825	0.87
Rhine	Cologne	144232	0.93
Erft	Neubrück	1880	< 0[1]
Ruhr	Hattingen	4118	0.90
Lippe	Schermbeck	4783	0.84
Rhine	Lobith	160800	0.92

[1] The discharge of the Erft is strongly influenced by measures related to browncoal mining. These influences are not included in the HBV model for the Erft.

Table 6.2 Values of the Nash-Sutcliffe criterion R^2 for HBV modelling of the Meuse basin. Only the results for the main branch and the major tributaries are listed in this table. Source: van Deursen (2004)

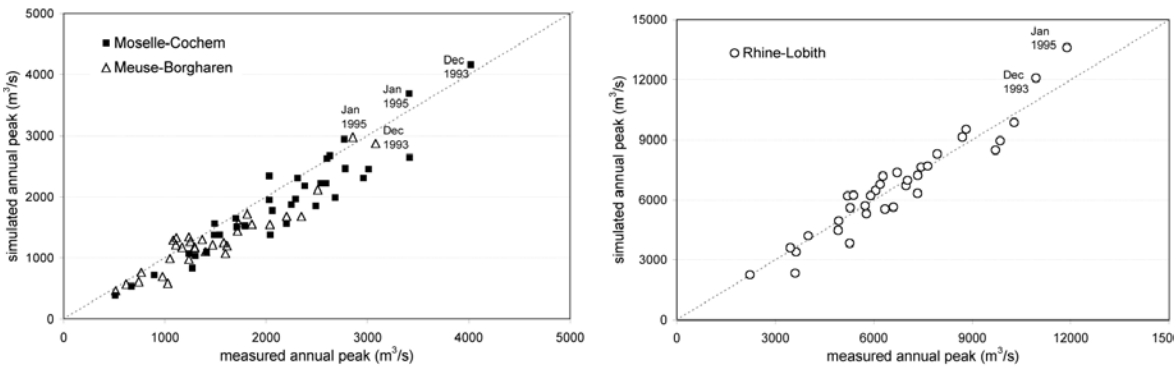
River	Gauging station	Upstream area (km²)	Calibration 1969-1984	Validation 1985-1998
Meuse	Chooz	10120	0.92	0.94
Lesse	Gendron	1314	0.90	0.91
Ourthe	Tabreux	1597	0.87	0.93[1]
Amblève	Martinrive	1044	0.85	0.91
Vesdre	Chaudfontaine	677	0.77	0.82
Meuse	Borgharen	21000	0.91	0.93

[1] Aalders and de Wit (2004) applied HBV for the Ourthe basin with a 6-hour resolution and obtained a value of 0.96.

The HBV simulations for the Meuse basin are based on the work of Booij (2002 and 2005) and van Deursen (2004). Data for the period 1969-1984 have been used for calibration and data for the period 1985-1998 have been used for validation.

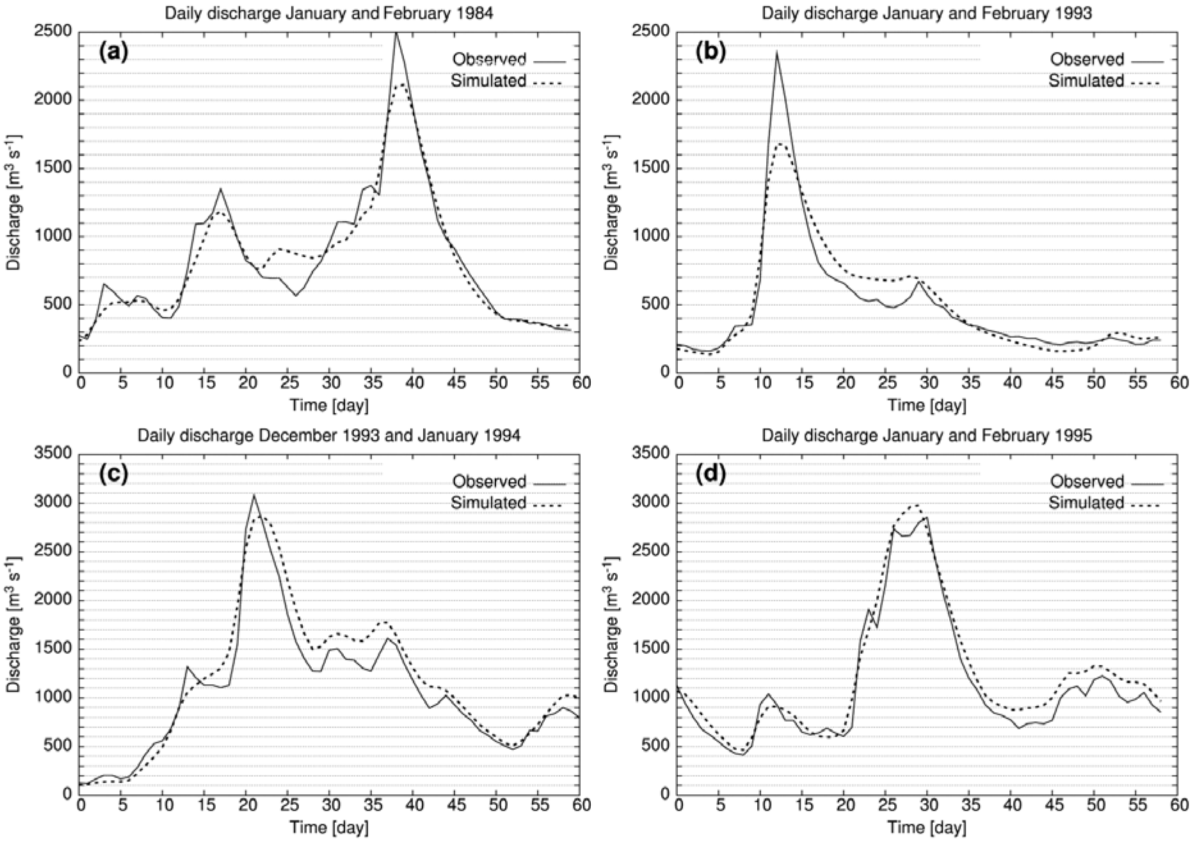
The results have been evaluated in terms of Nash-Sutcliffe R^2 values (Nash and Sutcliffe, 1970) for stations along the Rhine, Meuse and their tributaries. Values around 0.9 were found for both basins, which is a satisfactory result (see Tables 6.1 and 6.2). In particular, the value 0.92 for Basel is surprisingly good considering that the operation of the outflow of the Swiss lakes is not included in the model. It is further noted that for the Meuse basin the values of R^2 for the validation period are larger than those for the calibration period. Possible explanations for this phenomenon are differences in the variability of the discharges in the two periods or an improved quality of the data in the validation period.

Figure 6.2 Scatter plot of the measured and simulated (HBV) annual maxima of the daily discharges of the Rhine, Meuse and Moselle. For the Rhine the flood routing procedure in HBV has been adapted (Eberle et al., 2005).



A comparison between observed and simulated annual maximum discharges is given in Figures 6.2 and 6.3. The mean of the annual maximum discharges appears to be underestimated for the Meuse and Moselle (left panel of Figure 6.2), whereas the maximum discharges of the largest flood waves (December 1993 and January 1995) are reasonably simulated (left panel of Figure 6.2 and bottom panels of Figure 6.3). For the Rhine at Lobith the maximum discharges of December 1993 and January 1995 are overestimated by HBV. As a result of the deviations between observed and simulated flood waves there are significant differences between the extreme-value distributions from the observed and simulated data. The discrepancies between the observed and simulated extreme-value distributions for the Meuse basin become less if the 10-day average maximum discharges are considered (Leander et al., 2005). This indicates that HBV is able to provide reliable estimates of the volumes of extreme floods in the Meuse.

Figure 6.3 Observed and simulated (with HBV) discharges for a number of flood events in the Meuse (Leander et al., 2005).



7 Flood routing

Within the HBV model the sub-basins are linked together with a simplified Muskingum approach to simulate flood routing processes (see also Chapter 6 and Appendix 3). As such discharge records at the outlet of the entire basin can be simulated. This simplified approach generally works quite well in rivers with large gradient and limited floodplain retention. However, especially along the downstream part of the river Rhine there are specific conditions of the floodplain that require a more detailed approach. Therefore HBV Rhine has been linked with flood routing models. This implies that HBV is used only to simulate the rainfall-runoff processes in the tributaries. The output of the sub-basins (discharge volumes) is used as input for the flood routing models for the main river. The flood waves in the stretch between Basel and Maxau have been simulated with SYNHP. The flood waves in the stretch between Maxau and Lobith as well as the downstream stretch of the Moselle have been simulated with SOBEK. The choice of these two models is motivated by their use by local water authorities in the specific stretches. These models allow for a more detailed description of the processes in the river and its floodplain (e.g. retention). As a result the simulation of the flood wave is more reliable than the simplified Muskingum flood routing module within HBV. Moreover, these models allow for a simulation of changes within the floodplain.

It appeared that for the observed flood events (1961-1995) the flood peaks at Lobith were systematically overestimated with the combined HBV/SOBEK/SYNHP model. The sum of the flood volumes at the tributaries exceeded the flood volume at Lobith. A possible explanation is that high water levels in the main branch of the Rhine obstruct the discharge of the tributaries near their confluence with the Rhine. Ideally, flood routing models of the downstream parts of the tributaries should be linked with the flood routing model of the Rhine to account for this phenomenon. As a first approximation the simulated (with HBV) discharges of the tributaries have systematically been reduced with five percent (personal communication Hendrik Buiteveld, Rijkswaterstaat RIZA) for the entire record. The correction of the discharges of the tributaries has also been applied to the discharge records that result from the HBV simulation with generated meteorological records. This is an imperfection of the methodology and implies that the preliminary results of GRADE Rhine should be interpreted with care.

The simulation of discharges at Lobith with a combined HBV/SOBEK/SYNHP model instrument demands far more computation time than the simulation based on a hydrological model only. The weather generator and hydrological model have been operated at a daily time step. The flood routing models operate with an hourly time step and therefore the output of the hydrological simulation has been transferred to hourly sequences. To limit the computation time the combined HBV/SOBEK/SYNHP instrument has only been used to simulate annual maximum discharge events. Both SOBEK and SYNHP use 1-dimensional profiles of the riverbed. For specific applications 2-dimensional hydraulic models have been used for selected parts of the river (see Chapter 10).

There is also a SOBEK schematisation available for the Meuse between Chooz (French/Belgian border) and Borgharen. However, for the Meuse basin GRADE has (so far) only been run with HBV. Incorporation of the SOBEK schematisation in GRADE of the Meuse is a possible improvement of the instrument. It should however be noted that i) the geometry of the Meuse floodplain between Charleville-Mézières and Borgharen is relatively simple and it is likely that a more detailed flood routing model of this stretch of the river Meuse has limited added value (see also de Wit et al., 2002), and ii) detailed information about the geometry of the Walloon Meuse is not (yet) readily available for this project.

Figure 7.1 The filling of the floodplain attenuates the flood wave.
Photo: Martijn Antheunisse

Figure 7.2 The Meuse is captured in its own valley. Flood waves in the Meuse are hardly attenuated in the stretch between Charleville-Mézières and Borgharen.
Photo: Marcel de Wit

8 Generated discharge records

The generated records of rainfall and temperature (see Chapter 5) were used to simulate discharge records of 10^3-10^4 years at Lobith and Borgharen with the models described in Chapters 6 and 7. Tables 8.1 and 8.2 compare some statistics derived from observed records and generated records. For the Meuse the mean value of the Sim30 records is lower than that of the Sim61 records. This reflects that the 1961-1998 period is a wetter base period than the 1930-1998 period. The mean annual maximum discharge is lower for the simulated records than for the observed records. This can be partly attributed to the systematic underestimation of the maximum discharges of the Meuse by HBV as shown in Figure 6.2. The absolute maxima in the generated records exceed the largest value in the observed record as well as the largest value in the simulation with observed precipitation and temperature data, which is expected since the generated records are much longer.

To limit the computation time the combined hydrological/hydraulic instrument for the Rhine has only been used to simulate the annual maximum discharge events. The ten 1000-year HBV runs were used only to select these events. As a result no mean and standard deviation for the 1000-year records could be derived from the HBV/SOBEK/SYNHP simulations. The mean annual maximum discharge is a little bit lower (≈ 3%) for the records based on generated precipitation and temperature data than that for the record based on observed precipitation and temperature data. Figure 8.1 compares the hydrographs of the three largest observed floods and one generated flood event.

Table 8.1 Absolute maximum and the mean of the annual maxima of the simulated and historical daily discharges of the Rhine.

	Nr. of years (-)	**abs. max. (m^3/s)**	**mean ann. max (m^3/s)**
Recorded discharge 1961-1995	35	11885	6629
HBV/SOBEK/SYNHP with 1961-1995 P, T data	35	13108	6577
HBV/SOBEK/SYNHP with generated P, T data	1000		
Sim_1		17158	6349
Sim_2		16912	6347
Sim_3		16036	6450
Sim_4		17607	6394
Sim_5		14306	6439
Sim_6		15765	6388
Sim_7		16853	6436
Sim_8		17039	6375
Sim_9		18244	6467
Sim_{10}		15796	6364

Table 8.2 Mean, standard deviation, absolute maximum and the mean of the annual maxima of the simulated and historical daily discharges of the Meuse (based on data from Aalders et al., 2004).

	Nr. of years (-)	mean (m^3/s)	stand. dev. (m^3/s)	abs. max. (m^3/s)	mean ann. max (m^3/s)
Recorded discharge 1968-1998	31	267	269	3080	1474
HBV with 1968-1998 P, T data	31	277	286	2976	1288
HBV with generated P, T data	3000				
$Sim30_1$		238	250	3599	1148
$Sim30_2$		240	252	4113	1166
$Sim30_3$		238	249	3543	1155
$Sim30_4$		240	253	3352	1163
$Sim30_5$		247	251	3621	1178
$Sim30_6$		250	253	3306	1179
$Sim60_1$		256	270	3914	1232
$Sim60_2$		257	269	3921	1245
$Sim60_3$		255	264	4340	1224
$Sim60_4$		254	265	4464	1222

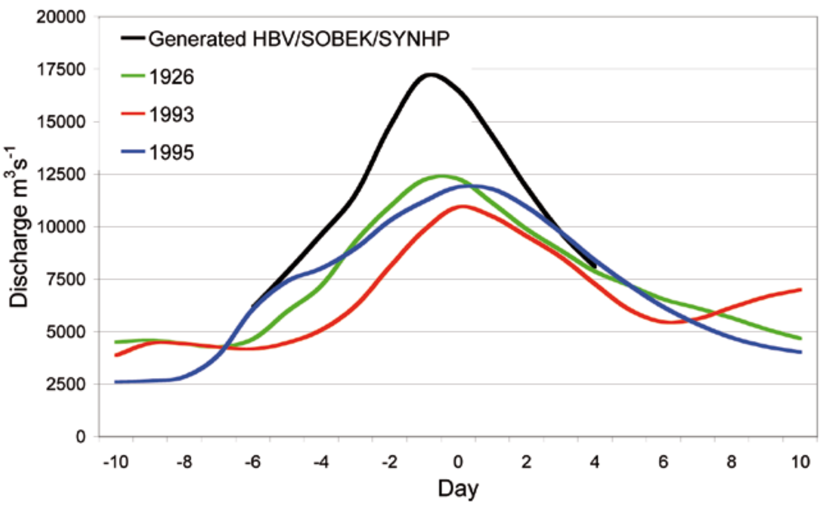
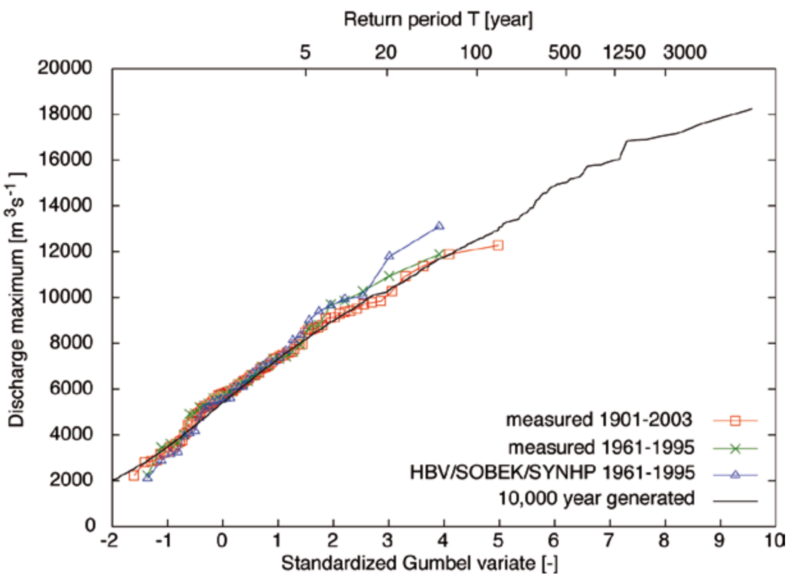


Figure 8.1 Hydrograph Lobith. Observed flood events and one extreme generated flood event (Sim_1 abs. max. Table 8.1).

9 Determination of design discharges

Probability distributions can be derived from the generated discharge data. An example of such a distribution is given for the Rhine in Figure 9.1 and for the Meuse in Figure 9.2. Despite the discrepancies shown in Figure 6.2 and Table 8.1, the distributions of the generated and observed daily annual maxima correspond well for the Rhine. Several corrections have been applied within the hydrological/ hydraulic instrument for the Rhine (e.g. Chapter 7). It is possible that remaining errors or errors associated with these corrections are partly compensated by some shortcoming of the rainfall generator regarding the simulation of very rare events. For the Meuse the annual maxima of the generated daily discharges tend to be lower than the observed maxima. Figure 6.2 shows that HBV systematically underestimates the annual maxima for the period 1968-1998. This deviation of HBV may (partly) explain the relatively low values of the ordered annual maxima for the Sim30 and Sim61 simulations in Figure 9.2. Leander et al. (2005) found that this underestimation also shows up in the daily winter maxima but not in the 10-day average winter maxima. The distribution of these 10-day average maxima is well reproduced by the hydrological simulations with the generated daily rainfall and temperature data. Sim30 is somewhat below Sim61, which can be ascribed to the fact that the winters in the period 1930-1960 are on average drier than those for the years 1961-1998 (see also Figure 5.1).

Figure 9.1 Annual maxima of the observed daily discharge at Lobith (1961–1995 and 1901-2003), the simulated daily discharge based on the historical meteorological data for 1961–1995, and the generated 10,000-year discharge record based on resampled meteorological data. Note that dike overflows have not (yet) been included in these calculations.



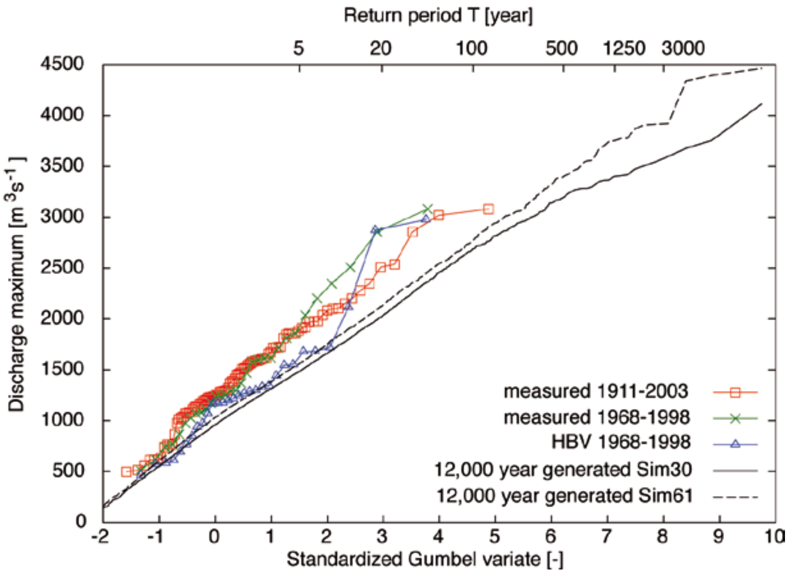


Figure 9.2 Annual maxima of the observed daily discharge at Borgharen (1968–1998 and 1911-2003) and the simulated daily discharge based on the historical meteorological data for 1968–1998, and the generated 12,000-year discharge record based on Sim30 and Sim61, respectively.

Figures 9.3 (Rhine) and 9.4 (Meuse) compare the shape of the design flood waves used for HR2001 and HR2006 and the shape of a number of extreme generated flood waves. In Figure 9.3 the eight largest flood waves out of the 10,000-year generated record for the Rhine are shown. The GRADE waves in Figure 9.3 are based on the combined HBV/SOBEK/SYNHP calculations. In Figure 9.4 the fourteen largest flood waves out of the 18,000 year generated record (sim 30_1,..., sim 30_6, see Table 8.2) the Meuse are presented. Also the average of these generated flood waves is shown. This wave is denoted as GRADEavg. HR2001 and HR2006 are the design flood waves that have been determined in 2001 and 2006 (see also Chapter 2). The difference between HR2001 and HR2006 is partly caused by the extension of the discharge record and partly by a different application of the method to derive a design flood wave (Wijbenga and Stijnen, 2004). From the comparison it appears that for the Rhine at Lobith the GRADE waves are sharper than the HR waves. For the Meuse at Borgharen the GRADE waves are smoother than the HR waves.

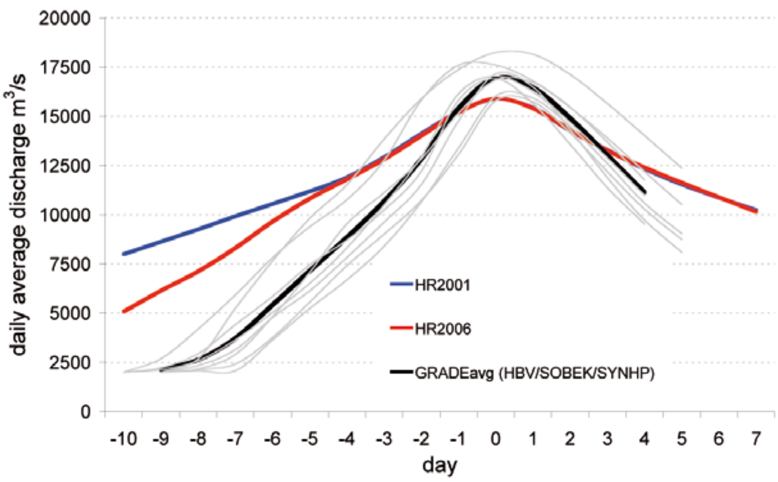
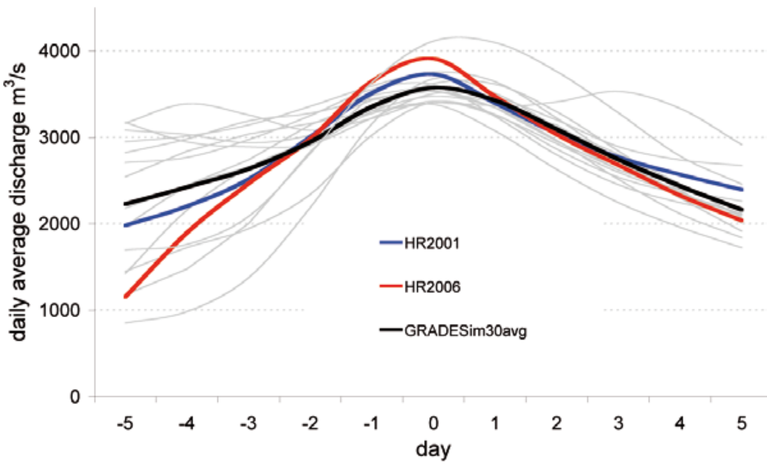


Figure 9.3 Comparison between the design flood waves derived for HR2001 and HR2006 and the temporal evolution of the eight largest floods in the 10,000-year GRADE record for the Rhine at Lobith.

Figure 9.4 Comparison between the design flood waves derived for HR2001 and HR2006 and the temporal evolution of the fourteen largest floods in the 18,000-year GRADE record for the Meuse at Borgharen.



10 An application of GRADE in the Rhine basin

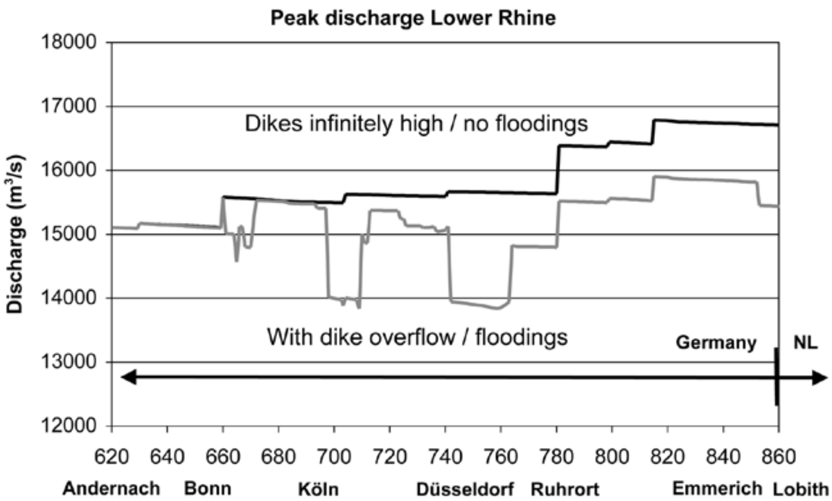
After the Rhine floods in 1993 and 1995, the Province of Gelderland (The Netherlands), The Ministry of Public Works and Water Management (The Netherlands) and the Ministry of Environment, Nature Conservation, Agriculture and Consumer Protection in Northrhine-Westfalia (Germany) signed a declaration for cooperation in flood control. As part of the cooperation, the project "Effects of extreme floods along the Lower Rhine (Niederrhein, Rhine downstream of Andernach)" was carried out to investigate the effects of extreme floods along the Rhine in Northrhine-Westfalia (NRW) and Gelderland. The aim of the project was to i) increase knowledge of the occurrence and behavior of extreme floods in the Rhine basin, ii) to indicate areas vulnerable to flooding in NRW and Gelderland, and iii) to develop techniques and tools for the evaluation of flood reduction measures. Lammersen (2004) reports the results of the Lower Rhine study.

GRADE has been used to generate a 1000-year discharge record for the river Rhine (Werner and Reggiani, 2002). The generated precipitation and temperature time series were based on Beersma (2002). A selection was made of the 16 most extreme events, based on the HBV results at Andernach and Lobith. These 16 extreme events were then put into a 1-dimensional flood routing model to compute 16 extreme discharge waves at Andernach in a more accurate way, taking into account flooding and retention measures along the Rhine upstream of Andernach (for more information see Eberle et al., 2004 and Lammersen, 2004). With the two most extreme discharge waves at Andernach flood simulations have been performed using the 2-dimensional model Delft-FLS. A Delft-FLS simulation was done for the Rhine downstream of Andernach (Rhinekm 642) using a 100 m × 100 m grid on top of a digital terrain model. Dikes and floodwalls are represented as special grid cells. When the water level reaches the dike level a dike collapse occurs. In the case of a floodwall, or a natural levee, the floodwall or levee simply overflows and no collapse is simulated. See Figure 10.1 for an example of a flood simulation. Note that a large inundation occurs at Emmerich near the German/Dutch border.

Figure 10.1 Flooding along the Lower Rhine between Bonn (right) and Arnhem (left). Red arrows indicate the direction of the spreading of the flood. The flooded area is shown in light blue. After Lammersen and Kroekenstoel (2005).

Some of the generated events exceeded the design flood levels of the dikes. This causes inundations along the Lower Rhine, first in the southern part, later also in the middle part (see Figure 10.1). Inundation of these parts of the Lower Rhine reduces the peak discharge in the northern part of the Lower Rhine and in The Netherlands (Figure 10.2). The Lower Rhine study illustrates that the relation between peak discharges and return period (e.g. Figure 2.1, Chapter 2) depends on specific conditions upstream and evolves stepwise. Note that the results presented for the river Rhine in Chapters 8 and 9 do not allow for dike overflows between Andernach and Lobith.

Figure 10.2 Maximum discharge with and without dike overflow for one of the generated extreme flood events. After Lammersen and Kroekenstoel (2005).



11 Uncertainties, sensitivities and shortcomings of GRADE

All components of GRADE (Figure 1.1) have uncertain elements. These affect the reliability of the calculated design discharge. A modification of design water levels along the Rhine and Meuse has large impacts and it is therefore necessary to analyse the accuracy of a potentially new methodology to determine design discharges. The potential effects of future climate change and changes in the river basin should also be taken into account.

In Chapter 3 resampling of daily rainfall was introduced as a method to obtain reliable estimates of properties of extreme 10-day rainfall. A demonstration was given based on a simple stochastic daily rainfall model. In that example the benefits of resampling can easily be quantified (Buishand, 2007). A complete evaluation of GRADE for the determination of the design discharges of the rivers Rhine and Meuse is, however, much more complicated. Various uncertainties are encountered, which may seriously limit the gains of resampling. Some of the uncertainties have already been addressed. Others need further attention. An overview of uncertainties is presented in Table 11.1. These uncertainties are discussed below. This chapter concludes with some comments on future change.

Table 11.1 Overview of sources of uncertainties.

Step in the methodology	Sources of Uncertainty
Historical weather data	- Base period
	- Long-term variability (trends)
	- Spatial coverage of the data
	- Homogeneity of the data
Weather Generator	- Boundedness of the largest simulated daily value
	- Different configurations (feature vector, window, etc.)
Hydrological modelling	- Model uncertainties
	- Quality of data used to calibrate/validate the model
Hydraulic modelling	- Model uncertainties
	- Quality of data used to calibrate/validate the model
Frequency analysis of generated discharge records	- Length of the simulation
	- Type of distribution

Historical weather data

Base period
The use of a relatively short base period for resampling (Table 4.1) is an important source of uncertainty. A first impression of this uncertainty was obtained by comparing the Sim30 and Sim61 simulations for the Meuse basin (see Figures 5.1 and 9.2). Further comparisons can be made, e.g. by generating a long sequence from a sub series with relatively wet winters and another long sequence from a sub series with relatively dry winters (Passchier et al., 2004). The length of the simulation runs should be sufficiently long that the differences are mainly due to the choice of the base period and not to random sampling effects. The jackknife and bootstrap are alternatives to quantify the uncertainty due to the base period. These techniques may have practical limitations due to their computational demand. Moreover, the resulting jackknife and bootstrap standard errors can be seriously biased (Beersma and Buishand, 2006).

Long-term variability (trends)
Winter rainfall over large parts of the Rhine basin shows a significant increasing trend over the 20th century (Rapp and Schönwiese, 1995; Widmann and Schär, 1997; Schmidli et al., 2002; Hundecha and Bárdossy, 2005). Tu et al. (2005) report an increase of the maximum precipitation intensities during the winter season for the Meuse basin. The causes of these precipitation trends are not fully understood yet. By conditioning the resampling process on three circulation indices for the period 1891-1995, Beersma and Buishand (1999) found that only a part of the trend in mean winter rainfall over the German part of the Rhine basin could be explained by the atmospheric circulation. Long-term variability is not considered in the determination of design discharges in the Netherlands, which implies that the uncertainty will be underestimated.

Spatial coverage of the data
The feature vector in the resampling process was derived from daily precipitation and temperature at a limited number of stations (see Table 4.1). The use of 7 rainfall stations in the Sim61 simulations for the Meuse basin has been compared with the use of 14 rainfall stations. The differences were small regarding the simulation of extreme multi-day basin-average rainfall (Leander and Buishand, 2004c).

Homogeneity of the data
Changes in the measurement conditions may cause non-homogeneities. The homogeneity of the rainfall records in the Meuse basin has been thoroughly tested (Leander and Buishand, 2004a). Records that failed these tests have been left out. Homogeneity of the Rhine dataset has not been tested in the framework of GRADE. A non-homogeneity in a single record will generally have limited effect on the mean and other statistical properties of the generated rainfall series.

Weather Generator

Boundedness of the largest simulated daily value
The resampling techniques used so far are unable to generate larger daily values than the highest observed daily value. Despite this limitation there is no systematic underestimation of the occurrence of large 10-day rainfalls in the example of Chapter 3. This is because large 10-day rainfalls are generally due to a number of "moderately large" 1-day rainfalls rather than a single 1-day extreme rainfall event. The effect of boundedness of the largest daily value can be explored by replacing the largest values in the resampled sequences by random drawings from the tail of a continuous distribution (Buishand, 2007). An extension of nearest-neighbour resampling that is able to generate larger values than observed is also possible (Prairie et al., 2006). In contrast to the resampling techniques discussed here, this extension also generates different spatial patterns of daily rainfall than those observed. It is, however, computationally more demanding and needs extensive testing regarding the reproduction of the occurrence of extreme 1-day and multi-day rainfalls.

Different configurations
Though nearest-neighbour resampling is a nonparametric technique there are a number of settings in the resampling algorithm that influence the properties of the simulated sequences. The number k of nearest neighbours should be sufficiently large and the moving window sufficiently wide that there is no serious repetition of the same day or days in short periods. Temporal dependence of daily rainfall and temperature is sensitive to k and the composition of the feature vector. Since the reproduction of temporal dependence deteriorates with increasing k, this parameter should be set at the value that is required to avoid spurious multi-day rainfalls as a result of repeated resampling of certain days.

There is a need to study the effect of the use of memory elements in the resampling process on extreme river flows. For the Meuse basin it was necessary to include a 4-day memory element in the feature vector to reproduce the autocorrelation of daily rainfall and to generate sufficient extreme multi-day rainfall amounts. The use of memory elements has not been considered yet for the Rhine basin.

Up to now little attention has been given to the dependence of the spatial patterns of the simulated precipitation fields on successive days. A quantitative measure to explore this is the pattern correlation coefficient (Beersma and Buishand, 2003). The use of feature vector elements that characterise the position of the rain event in the drainage basin (Mehrotra and Sharma, 2005) may improve the reproduction of this measure.

Hydrological modelling

Model uncertainties

The results for the calibration and validation presented in Chapter 6, show that the hydrological model used in GRADE is not perfect. In particular, a tendency to underestimate the mean annual maximum discharge of the Meuse and Moselle were observed (see Figure 6.2). The consequences of model uncertainty may become larger when the model is used for circumstances that are more extreme than those observed. A distinction should be made between model structural uncertainty resulting from simplifications of the complex rainfall-runoff process, and parameter uncertainty due to unknown model parameters. Passchier et al. (2004) discussed the relative uncertainty of the various HBV model parameters. A GLUE analysis was recommended that takes into account the uncertainties of the most influential parameters: alpha, khq and perc. The first two parameters control the fast runoff (see Appendix 3). The GLUE method was proposed by Beven and Binley (1992) and has found widespread use in hydrology (Beven and Freer, 2001). Model structural uncertainty is not taken into account in the standard GLUE method. Weerts and van der Klis (2006) started to explore the application of GLUE for the HBV model applied to the Meuse basin. They observed that the choice of the criteria to select hydrological parameters strongly affects the outcome of the GLUE analysis.

Quality of data used to calibrate/validate the model

River discharges at Lobith and Borgharen are derived from water level measurements and the relation between discharge (Q) and water level (h). This flow rating curve is non-linear and varies over time. It depends on the duration and volume of the flood wave and it is affected by inundations. The flow rating curves for Borgharen and Lobith are regularly validated with direct discharge measurements and hydraulic simulations. Nonetheless, inaccuracies in discharge measurements can be significant, especially during flood events. A comparison between measurements of the Walloon, Flemish and Dutch monitoring stations along the Meuse revealed that the difference in measured peak discharges amounts 200 to 300 m^3/s (Maeghe et al., 2006). This is a deviation of about ten percent.

Hydraulic modelling

Model uncertainties

The models that describe the propagation of the flood waves also have uncertain elements. The spatial and temporal resolution of the models is limited. Some processes, such as the interaction with groundwater in the floodplain, are described with simple functions. The quality and appropriate scale of the hydraulic simulation strongly depends on the quality of the available data on the geometry of the riverbed.

During flood events high water levels in the main branch of the Rhine obstruct the discharge of the tributaries near their confluence with the Rhine. Ideally, flood routing models of the downstream parts of the tributaries should be linked with the flood routing model of the Rhine to account for this phenomenon.

Quality of data used for hydraulic modelling
A lot of efforts have been put in the description of the geometry of the floodplains. New techniques, such as laser altimetry have resulted in detailed elevation data with a high spatial resolution. However, small "errors" in these data can have large effects on flood routing. Meaningful interpretations of the outcome of flood routing models require expertise and verification in the field. Another important and difficult to measure variable is the roughness of the riverbed. The parameters that describe the dynamics of riverbed roughness have been derived through calibration of the model using observed water levels.

Frequency analysis of generated discharge records

Length of the simulation
The accuracy of discharge levels with a given return period increases with increasing length of the generated record. Leander (unpublished document, 13 September 2005) gives estimates of the standard deviation of the 1250-year discharge level for the two 12,000-year Sim30 and Sim61 simulations in Figure 5.1 (with 4-day memory element) for the Meuse basin in Chapter 5. The 1250-year discharge level was estimated as the 10th largest value in the simulation. For the Sim30 simulation a standard deviation of 88 m^3/s was found and for Sim61 a standard deviation of 136 m^3/s. These values refer to the finite length of the simulation run only. The uncertainty due to the limited length of the historical data is not accounted for.

Type of distribution
As an alternative to the empirical estimate based on an order statistic of the simulated annual maximum discharges, the design discharge may be obtained by fitting a theoretical probability distribution to these maxima. This will generally lead to a reduction of the standard error. However, there is a risk of bias due to lack-of-fit in the upper tail of the annual maximum distribution. There is little experience with fitting distributions to extreme values in sequences of 10,000 years or more. Censoring should be considered to avoid a large influence of the lower extremes on the 1250-year design level. This leads, however, to the problem of choosing a suitable threshold.

Future Changes

Global warming may have large impacts on river discharges. This is not only because of the direct effect of temperature on evaporation, snowfall and snow melt, but also because the rise in temperature will be accompanied by changes in precipitation. Kwadijk and Rotmans (1995) and Middelkoop (2000) give estimates of the potential changes of the extreme discharges of the Rhine at Lobith by using information from global climate models. More recently data from regional climate models (RCMs) have been used to estimate the changes in the discharge of the Rhine due to global warming (Shabalova et al., 2003; Lenderink et al., 2007). These estimates are very uncertain because only one RCM was considered and because of the relatively short length of the present-day RCM simulations (not more than 30 years). Resampling of the RCM output makes it possible to obtain more accurate estimates of the changes in extreme river discharges. This is at present done by KNMI. Precipitation and temperature records from a number of RCMs are used to generate long records for the present and changed climate in the Meuse basin. Especially the correction needed to tune the RCM control runs to the observed climate should be done with care (Leander and Buishand, 2007).

Another aspect of future change is the changing geometry of the river, partly due to human influences. Theoretically, GRADE can account for these changes. However, the prediction of future measures and developments in the upstream riverbed remains always limited. The capacity of dikes to withstand extreme water levels is another important aspect of uncertainty (see Chapter 10). Changes in land use may also affect the discharge regime of the Rhine and Meuse. However, the impact of land use change on the occurrence of extreme discharges at the outlet of a large river basin is generally assumed to be limited (e.g. Hooijer et al, 2004; Tu, 2006).

12 Towards further application of GRADE

GRADE has no official status yet in Dutch river basin management. Rijkswaterstaat RIZA aims at acceptance of this instrument as an approved method to determine the design discharges for the Rhine and Meuse. In the first instance, i.e. for the hydraulic design conditions of 2011, a combination of GRADE and the current method of statistical extrapolation of discharge measurements is aimed at. To achieve this goal a number of steps still need to be made (see also van der Klis, 2005).

Further improvement of the methodology

- KNMI has planned to develop extensions of nearest-neighbour resampling for the Meuse basin that are able to generate larger daily rainfall amounts than the highest observed daily value. Apart from a potential effect on the distribution of the annual maximum discharges, the influence of this extension on the shape of the flood wave will be studied.
- The systematic underestimation of HBV for average flood peaks in the Meuse (see Figure 6.2) requires further attention. The systematic deviations in the HBV results for the Rhine are presently addressed in a joint study of BfG, WL|Delft Hydraulics and Rijkswaterstaat RIZA (see Mens et al., 2006). Another point of concern is the simulation of snow accumulation and snow melt. The simulation of these quantities is based on temperature (Appendix 3). Apart from simplifications used in the procedure, the quality of the weather generator for low temperature conditions has not been tested in detail yet. The relatively small number of Swiss stations used for the selection of nearest neighbours in the resampling algorithm for the Rhine basin puts limitations on the reproduction of snow accumlation and snow melt in Switzerland.
- Improvements of the hydraulic simulations used in GRADE can be realised with further improved schematisations of the floodplains, including the downstream parts of the tributaries.
- The shape and duration of extreme flood waves requires further study in continuation of the work of Barneveld and Udo (2006) and van Gerven (2006).

Quantification of the uncertainties of the methodology

- Regarding the weather generator, it is recommended to generate a number of long sequences from different sub series of the entire historical record and to compare the resulting extreme discharges. The sensitivity of the design discharge to the inclusion of a memory element in the feature vector needs also to be quantified. For the Rhine basin it is important to study the succession of the spatial patterns of the simulated precipitation fields and its impact on the design discharge.

- The uncertainty resulting from uncertain HBV model parameters will be analysed through the application of the GLUE method (for a first analysis see Weerts and van der Klis, 2006).
- Run GRADE for a number of settings in order to quantify the overall uncertainty in the determination of design discharges for the Rhine and Meuse. This may also include uncertainties in hydraulic modelling.

Communication of the methodology
Several specialists are involved in the determination of design water levels along the Rhine and Meuse. New information about design discharges for the Rhine and Meuse will also interest managers and policy makers since a change of the design discharge can potentially have a large impact on the management of the flood plains. So far the development of GRADE, and especially the development of the weather generator, have mainly been communicated with the scientific community.

Organisation of the application of the methodology
At present the design discharges for the Rhine and Meuse have to be recalculated every five years. So far the methodology is based on historical meteorological records covering a few decades up to 1995 for the Rhine and up to 1998 for the Meuse (see Chapter 4). A necessary condition for the application of GRADE for the determination of design discharges is that the historical precipitation and temperature records are regularly (every five year) extended with new observations. This will need far more efforts than the five-year extension of the discharge record used in the present methodology to determine the design discharges for Rhine and Meuse. Many stations are involved and the data and metadata must be obtained from a number of organisations abroad. A five-year update will also require a new resampling analysis. Such analysis is much more laborious than fitting frequency distributions to observed extreme discharges. The application of GRADE will require a robust structure for the procedures needed to collect the required data and to perform the necessary resampling and modelling exercises.

13 Conclusions

This report gives an overview of the development of GRADE for the Rhine and Meuse basins. The results so far illustrate that the principle of the methodology works: flood events larger than observed are generated based on resampling of observed precipitation and temperature records.

Frequency analyses based on generated discharge records provide additional information to the frequency analyses based on observed discharge records. GRADE also increases our understanding of how an extreme flood wave in the Rhine and Meuse (e.g. the design flood wave) may look like. This report includes a first rough comparison of the design flood waves derived from the present methodology and those derived from GRADE. This comparison shows that GRADE results in sharper flood waves for the Rhine and smoother flood waves for the Meuse compared to the design flood waves presently used.

This report lists a number of statistical and model limitations that affect the output of GRADE. For some of these limitations suggestions for possible improvements are given. Other limitations are inherent to the limited length of the base period of the meteorological records used by GRADE. A number of recommendations are given to quantify the uncertainties of GRADE. It should however be noted that even these uncertainty estimates will be uncertain. A final judgment on the quality of GRADE is therefore difficult to give.

A necessary condition for the application of GRADE for the determination of design discharges is that the historical precipitation and temperature records are regularly (every five year) extended with new observations. This will need far more efforts than the five-year extension of the discharge record used in the present methodology to determine the design discharges for Rhine and Meuse.

The application of GRADE in the Lower Rhine study illustrates its value for the analysis of extreme flooding conditions. The Lower Rhine study initiated a fruitful cooperation between Germany and the Netherlands and revealed important background information for the determination of the design discharge for the Rhine in the Netherlands. A similar combination of GRADE and inundation modeling for the Walloon/Flemish and Dutch Meuse may improve our understanding on how inundations affect extreme floods in the Meuse.

The development of GRADE has also given an extra push to the development of hydraulic and hydrological models for the Rhine and Meuse basins. These models are used and will be further developed for other applications such as flood forecasting.

Given the uncertainties involved both in the present methodology and GRADE it seems unwise to rashly switch from one method to another. GRADE can however be of use for the determination of the hydraulic design conditions of 2011. It can serve as a reference for the present methodology and in combination with inundation studies it can provide important background information. The results of GRADE can also be used for scenario studies, analysis of the impact of climate change and the development of disaster management strategies.

Samenvatting

Met de invoering van de Wet op de Waterkering wordt iedere vijf jaar een randvoorwaardenboek uitgebracht met daarin de maatgevende hydraulische randvoorwaarden voor alle primaire waterkeringen in Nederland. De maatgevende afvoer voor Rijn en Maas is een belangrijke factor voor het bepalen van de maatgevende waterstanden op onze rivieren. De huidige methodiek om de maatgevende afvoer vast te stellen is gebaseerd op een frequentieanalyse van historische afvoergegevens. Deze methode kent een aantal beperkingen. De beschikbare meetreeks is eigenlijk te kort om uitspraken te doen over de afvoer met een gemiddelde overschrijdingskans van eens in de 1250 jaar. De vraag is hoe representatief de beschikbare meetreeks is. Een andere vraag is met welke verdelingsfunctie een goede extrapolatie naar de maatgevende afvoer gemaakt kan worden. Om te kunnen extrapoleren moet de meetreeks homogeen zijn. Aan deze randvoorwaarde is door de vele ingrepen in het stroomgebied en significante trends in het neerslagklimaat eigenlijk niet voldaan. Een andere beperking van de methode is dat uit de statistische verdelingen alleen de hoogte van de maatgevende afvoer kan worden bepaald. Over de vorm van de afvoergolf of over de genese van de golf geeft de methode geen informatie. Dit laatste aspect is wel van groot belang mede in verband met de effectiviteit van eventuele bovenstroomse maatregelen. Bovenstaande beperkingen hebben aanleiding gegeven tot de ontwikkeling van een nieuw instrumentarium om de maatgevende afvoeren voor Rijn en Maas te bepalen. Dit instrumentarium wordt hier aangeduid als GRADE (Generator of Rainfall And Discharge Extremes). Het streven is om bij de bepaling van de maatgevende afvoeren ten behoeve van de hydraulische randvoorwaarden 2011 GRADE een rol te laten spelen. In dit rapport wordt een overzicht gegeven van de stand van zaken rondom de ontwikkeling van GRADE voor de stroomgebieden van Rijn en Maas.

In plaats van extrapolatie van kansverdelingen op basis van betrekkelijk korte afvoerreeksen worden in GRADE eerst lange (duizenden jaren) neerslag- en temperatuurreeksen gegenereerd met behulp van een resampling techniek. Deze gegenereerde reeksen worden vervolgens doorgerekend met een hydrologisch/hydraulisch model. Voordeel van deze nieuwe methodiek is dat i) zeer lange afvoerreeksen kunnen worden gesimuleerd met daarin gebeurtenissen die extremer zijn dan totnogtoe waargenomen, ii) effecten van veranderingen in eigenschappen van het stroomgebied kunnen worden gesimuleerd, iii) de duur en vorm van de maatgevende golf kunnen worden gesimuleerd, en iv) de invloed van een mogelijke klimaatverandering kan worden gesimuleerd. De methodiek is inmiddels toegepast op het Rijnstroomgebied bovenstrooms van Lobith en het Maasstroomgebied bovenstrooms van Borgharen. Uit de gegenereerde afvoerreeksen

met een lengte van enkele duizenden jaren voor de Rijn bij Lobith en de Maas bij Borgharen kunnen allerlei eigenschappen van extreme afvoergolven worden afgeleid.

In de gegenereerde afvoerreeksen komen dus hoogwaters voor die aanzienlijk hoger zijn dan tot nu toe waargenomen. Voor de Maas komen het gemiddelde en de spreiding van de gegenereerde dagafvoeren goed overeen met die van de gemeten afvoeren. Een duidelijke tekortkoming van GRADE is het onderschatten van de dagextremen (met ongeveer 10%) van de afvoeren voor deze rivier. Bij de maxima van de 10-daagse gemiddelde afvoeren doet deze onderschatting zich niet voor, hetgeen erop duidt dat de volumes van de extreme afvoergolven goed worden weergegeven. Voor de Rijn was er een goede overeenstemming tussen de gemiddelde jaarmaxima van de gegenereerde en gemeten afvoeren na een ruwe correctie op de gesimuleerde afvoeren van de zijrivieren. Een exact vergelijk tussen de bepaling van maatgevende afvoeren volgens de huidige methodiek (extrapolatie op basis van gemeten afvoerreeksen) en GRADE valt nog niet te maken. GRADE genereert vooralsnog gemiddelde dagwaarden voor neerslag en afvoer terwijl bij de huidige methodiek met momentane piekafvoeren wordt gerekend. Daarnaast verschilt de basisperiode van de neerslag- en temperatuurgegevens welke bij GRADE worden gebruikt van de basisperiode van de afvoerreeksen die gebruikt worden bij de huidige methodiek. De dagafvoeren behorend bij een bepaalde terugkeertijd zoals berekend met GRADE vallen ruim binnen de betrouwbaarheidsintervallen van de huidige methodiek. De gemiddelde golfvorm van de extreme hoogwatergolven in GRADE zijn voor de Maas vlakker en voor de Rijn steiler dan de huidige maatgevende hoogwatergolf. De oorzaken van deze verschillen moeten nog nader onderzocht worden.

GRADE bestaat uit een aantal deelmodellen die elk verschillende onzekerheden kennen. Deze onzekerheden zijn in dit rapport geïnventariseerd. Aanbevelingen worden gegeven voor verbeteringen van de deelmodellen en het kwantificeren van de onzekerheden.

Ook met een optimaal werkend GRADE zullen de maatgevende afvoeren voor Rijn en Maas onzeker blijven. Van het ene op het andere moment overstappen van de huidige methodiek op GRADE lijkt derhalve geen verstandige optie. GRADE is recentelijk gebruikt voor het genereren van afvoerscenario's voor een Duits/Nederlandse studie naar de grensoverschrijdende effecten van extreem hoogwater op de Niederrhein. Momenteel wordt de toepassing van GRADE voor het doorrekenen van de effecten van klimaatverandering onderzocht. Daarnaast is er het voornemen om de deelmodellen van GRADE met verschillende instellingen te laten rekenen en zodoende de onzekerheden bij de berekening van de maatgevende afvoer te bepalen. Al deze aanvullende informatie kan helpen bij het maken van een weloverwogen besluit om de maatgevende afvoer voor Rijn en Maas wel of niet aan te passen. De resultaten van GRADE zijn ook bruikbaar als input voor scenariostudies en de ontwikkeling van beheerstrategieën voor overstromingsrampen.

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Appendix 1

Overview of all reports and papers including summaries

Proposing a new methodology (GRADE)
Buishand, T.A. and Brandsma, T., 1996. Rainfall generator for the Rhine catchment: A feasibility study. Technical Report TR-183, KNMI, De Bilt, The Netherlands.

Presents an extensive literature review of statistical methods for generating daily sequences of precipitation and temperature. Much attention is given to the use of the multivariate first-order autoregressive model. It is shown how this model for time series of normally distributed data can be fitted to positively skewed daily rainfall data with a large proportion of zero values. The use of nonparametric resampling techniques is briefly discussed as an alternative. In addition to the simulation of daily precipitation and temperature, the classification and statistical modelling of the atmospheric circulation is discussed in detail.

Passchier, R. H., 1996. Evaluation hydrologic model packages. Report of project Q2044 for RIZA, WL|Delft Hydraulics, The Netherlands.

This report evaluates a number of hydrological models that can be used for the simulation of precipitation-discharge processes in the Rhine and Meuse river basins. HBV turned out to be one of the most suitable candidates.

Parmet, B.W.A.H., Buishand, T.A., Brandsma,T. and Mülders, R., 1999. Design discharge of the large rivers in the Netherlands - towards a new methodology. In: Hydrological Extremes: Understanding, Predicting, Mitigating (L. Gottschalk, J.-C. Olivry, D. Reed and D. Rosbjerg, Eds.), 269-272. IAHS Publication No. 255, IAHS Press, Institute of Hydrology, Wallingford, UK.

The paper considers the estimation of the design discharge of the large rivers in the Netherlands by fitting statistical distributions to the observed peak discharges. The resulting estimates are subject to large uncertainties due to incomplete knowledge of the type of distribution, potential non-homogeneities in the observed discharge record and the relatively short length of this record compared to the required mean recurrence time of 1250 years. The use of a multivariate weather generator in combination with a hydrological/hydraulic model is seen as an instrument to reduce the uncertainty of the design discharge. A Gumbel plot of the 10-day maximum rainfall amounts of Stuttgart from the first 1000-year multi-site simulation is compared with the plot for observed rainfall.

Buishand, T.A., 2003. Estimation of a large quantile of the distribution of multi-day seasonal maximum rainfall: can stochastic simulation be of use? KNMI memorandum KA-03-02. KNMI, De Bilt (unpublished document). Extended version accepted for publication in Climate Research (July 2007).

For synthetic data generated with a simple stochastic model assuming no temporal dependence in the probability and amount of rain, it is demonstrated that resampling by the standard bootstrap provides a much better estimate of a large quantile of the 10-day seasonal (or annual) maximum distribution than the classical method of fitting a Gumbel or GEV distribution to the 10-day seasonal (or annual) maximum rainfall amounts. Using daily rainfall data from Stuttgart (Germany) it is demonstrated that the tail of the distribution of the daily rainfall amounts and temporal dependence strongly influence the distribution of extreme 10-day rainfalls. Nearest-neighbour resampling is employed to reproduce the temporal dependence structure of the Stuttgart data. Particular attention is given to the potential bias in large quantiles of the 10-day seasonal (or annual) maximum distribution due to the inability of a resampling procedure to generate larger daily rainfall amounts than the highest observed daily value. Replacing the largest simulated daily rainfall amounts by random values from the tail of the generalized Pareto distribution suggests that this bias is small.

Leander, R., Buiteveld,H., de Wit, M.J.M. and Buishand, T.A., 2005. Application of a weather generator to simulate extreme river discharges in the Rhine and Meuse basins. In: Proceedings NCR-days 2004, Research for managing rivers: Present and future issues (B. Makaske and A.G. van Os, Eds.), 54,55. NCR report 26-2005, Netherlands Centre for river studies, Delft, The Netherlands.

The paper gives a short impression of the development of the methodology up to 2004.

Chbab, E.H., Buiteveld, H. and Diermanse, F., 2006. Estimating exceedance frequencies of extreme river discharges using statistical methods and physically based approach. Wasser- und Abfallwirtschaft 58: 35-43.

This paper gives an overview of new methodologies to estimate exceedance frequencies of extreme river discharges in the Netherlands. Both GRADE and a new statistical extrapolation method based on a Bayesian approach that accounts for statistical uncertainties, are the subject of this paper.

Rhine basin

Brandsma , T. and. Buishand, T.A, 1997. Rainfall generator for the Rhine basin: Single-site generation of weather variables by nearest-neighbour resampling. KNMI publication 186-I, De Bilt, The Netherlands.

First study of nearest neighbour resampling. Single-site generation of weather variables, both unconditional and conditioned on atmospheric circulation indices, is considered for the stations Essen, Kahler Asten, Trier, Frankfurt, Bamberg, Freudenstadt and Stuttgart in the German part of the Rhine basin. Using the data from Stuttgart, it is shown that the autocorrelation properties of the simulated daily precipitation and temperature sequences are most sensitive to the number k of nearest neighbours in the resampling algorithm and the elements of the feature vector. The need for inclusion of the simulated weather variables for day t–1 in the case of conditional simulation is stressed.

Brandsma, T. and Buishand, T.A., 1998. Simulation of extreme precipitation in the Rhine basin by nearest-neighbour resampling. Hydrology and Earth System Sciences, 2: 195-209.

This paper is based on the work in Brandsma and Buishand (1997) for the seven stations in the German part of the Rhine basin. New single-site simulations are performed. The reproduction of the autocorrelation of daily precipitation and temperature is discussed as well as the reproduction of the distributions of N-day annual maximum rainfall and snowmelt.

Brandsma, T. and Buishand, T.A., 1999. Rainfall generator for the Rhine basin: Multi-site generation of weather variables by nearest-neighbour resampling. KNMI publication 186-II, KNMI, De Bilt, The Netherlands.

First study of multi-site simulation. The joint simulation of daily precipitation and temperature at 25 locations in the German part of the Rhine basin is considered. The search for nearest neighbours is based on summary statistics of the precipitation and temperature fields and (optional) circulation indices. The reproduction of autocorrelation coefficients and the distribution of N-day maximum rainfall in the winter-half year is studied for different values of the number k of nearest neighbours and various compositions of the feature vector. The reproduction of N-day maximum snow melt and the spatial association of N-day maximum rainfall are also explored. The space-time pattern of a number of extreme10-day events in a 1000-year simulation is described in detail and compared with the space-time pattern of the extreme historical 10-day events of December 1982, December 1993 and January 1995.

Buishand, T.A. and Brandsma, T., 2001. Multi-site simulation of daily precipitation and temperature in the Rhine basin by nearest-neighbor resampling. Water Resources Research 37, 2761-2776.

This paper is based on the work of Brandsma and Buishand (1999) for the 25 stations in the German part of the Rhine basin. New unconditional multi-site simulations are performed. The sensitivity of autocorrelation coefficients and the distribution of N-day maximum rainfall to the number k of nearest neighbours and the composition of the feature vector is studied further. The occurrence of spurious multi-day rainfall amounts due to repeated sampling of certain groups of historical days in resampling experiments with k as small as 2 is described.

Beersma, J.J. and Buishand, T.A., 1999. Rainfall generator for the Rhine basin: Nearest-neighbour resampling of daily circulation indices and conditional generation of weather variables. KNMI publication 186-III, KNMI, De Bilt, The Netherlands.

Further study of multi-site conditional simulation of precipitation and temperature for 25 locations in the German part of the Rhine basin. Nearest-neighbour resampling is also used to generate synthetic sequences of daily circulation indices that are needed for long-duration conditional simulations. Conditional simulations are performed to reconstruct precipitation statistics for the period 1891-1995. These simulations explain on average slightly more than 50% of the trends in the mean winter precipitation at five stations for which monthly data during this century were available. The sensitivity of simulated precipitation to changes in circulation indices is studied by performing three simulations conditional on the 1961-1995 circulation indices, in which in each simulation only one of the three circulation indices is systematically changed. These simulations show that the simulated precipitation is most sensitive to changes in the westerly flow index W, followed by changes in the vorticity index Z. The mean precipitation is typically much more sensitive to systematic changes in W and Z than the precipitation extremes. This is because a large part of the change in the mean precipitation is due to a change in the number of wet days, which has less influence on the extremes.

Beersma, J.J. and Buishand, T.A., 2003. Multi-site simulation of daily precipitation and temperature conditional on the atmospheric circulation. Climate Research 25, 121-133.

This paper is based on the work in Beersma and Buishand (1999) for the 25 stations in the German part of the Rhine basin. Several new 980-year multi-site simulations of daily precipitation and temperature were performed conditional on a simulated time series of circulation indices that was obtained with a second resampling model. The models in which the precipitation and temperature of the previously simulated day were taken into account performed best, but even these models somewhat underestimate the quantiles of the distribution of the maximum 10-day area-average precipitation in the winter half-year (October – March). The long-duration simulations demonstrate that nearest-neighbour resampling is capable of producing much larger 10-day area-average precipitation amounts than the historical

maximum. Pattern correlations were used to assess the reproduction of temporal dependence of spatial patterns. Both for precipitation and temperature, the pattern correlations are underestimated.

Mülders, R., Parmet, B. and Wilke, K., 1999. Hydrological modelling in the river Rhine basin, final report. Report No. 1215, Bundesanstalt für Gewässerkunde (BfG), Koblenz, Germany.

Report on the first phase of the development of a HBV schematisation for the Rhine basin. It describes the construction of daily models for the major tributaries in the German part of the Rhine basin.

Wójcik, R., Beersma, J.J. and Buishand, T.A., 2000. Rainfall generator for the Rhine basin: Multi-site generation of weather variables for the entire drainage area. KNMI publication 186-IV, KNMI, De Bilt, The Netherlands.

First report on multi-site simulation of daily precipitation and temperature for the whole Rhine basin. Resampling is based on the data from 34 stations in Germany, Luxembourg, France and Switzerland. Three resampling models are considered: two for unconditional simulation and one for conditional simulation. The Mahalanobis distance is introduced as an alternative to the weighted Euclidean distance for measuring the similarity between potential nearest neighbours. The unconditional simulations performed better than the conditional simulations, in particular for temperature and snow melt. For the latter, a significant underestimation (up to 20-30%) of the median and the upper quintile mean of the annual maximum multi-day snowmelt was observed at four of the six high-elevation stations.

Beersma, J.J., Buishand, T.A., and Wójcik, R., 2001. Rainfall generator for the Rhine basin: Multi-site simulation of daily weather variables by nearest-neighbour resampling. In: Generation of Hydrometeorological Reference Conditions for the Assessment of Flood Hazard in Large River basins (P. Krahe and D. Herpertz, Eds.), 69-77. CHR report I-20, International Commission for the Hydrology of the Rhine basin (CHR), Lelystad, The Netherlands.

Paper presented at the international CHR Workshop held in March 2001 in Koblenz (Germany). It is a short version of the report by Wójcik et al. (2000) on multi-site simulation of daily precipitation and temperature for the entire drainage area of the river Rhine.

Eberle, M., Sprokkereef, E., Wilke, K. and Krahe, P., 2001. Hydrological modelling in the river Rhine basin, Part II: Report on hourly modelling. Report No.1338, Bundesanstalt für Gewässerkunde (BfG), Koblenz, Germany.

Report on the second phase of the development of a HBV schematisation for the Rhine basin. The river Rhine basin between

Maxau and Lobith is modelled with the precipitation-runoff model HBV with an hourly time step. The purpose of this is mainly to expand the lead time of reliable flood forecast using available precipitation data and precipitation forecasts.

Eberle, M., Buiteveld, H., Beersma, J., Krahe, P. and Wilke, K., 2002. Estimation of extreme floods in the river Rhine basin by combining precipitation-runoff modelling and a rainfall generator. In: Proceedings International Conference on Flood Estimation, Berne 2002 (M. Spreafico and R. Weingarter, Eds.), 459-468. CHR report II-17, International Commission for the Hydrology of the Rhine basin (CHR), Lelystad, The Netherlands.

Nearest-neighbour resampling is discussed using two 1000-year unconditional simulations from the work of Wójcik et al. (2000). Precipitation-runoff modelling of the major tributaries downstream of Basel is considered. The HBV model satisfactorily reproduces the discharges of these tributaries. A notable exception is an underestimation of the annual maximum peak flows of more than 10% for two sub-basins. The methodology is tested further for the Moselle basin using one of the 1000-year precipitation simulations. The peak discharge during the largest simulated flood event based on generated precipitation is 20% larger than that of the 1993 flood event.

Beersma, J.J., 2002. Rainfall generator for the Rhine basin: Description of 1000-year simulations. KNMI publication 186-V, KNMI, De Bilt, The Netherlands.

In this report ten 1000-year simulations with the rainfall generator for the Rhine basin are described. These simulations serve as input for the hydrological/hydraulic model of the Rhine. One of these simulations is selected as the reference simulation, the other nine simulations give an idea of the statistical spread of the 1000-year simulations. For the winter season the 15 highest basin-average 10-day precipitation amounts are also listed.

Werner, M.G.F. and Reggiani, P., 2002. FEWS Extreme Discharges, phase II: Rhine basin. Report of project Q2967 for RIZA, WL|Delft Hydraulics, The Netherlands.

This report describes the application and development of the instrumentation FEWS Extreme Discharge (FEWS-ED) events for the River Rhine. This second and final phase of the FEWS Extreme Discharges project extends the pilot for the Main catchment to the entire drainage area up to Lobith. Using the 1000-year rainfall and temperature reference simulation from Beersma (2002), runoff is calculated with the HBV models for the Rhine and subsequently routed to Lobith with the applicable SOBEK and SYNHP models.

Eberle, M., Hammer, M., Busch, N., Engel H., Krahe P. and Wilke K., 2004. Effects of extreme floods along the Niederrhein (Lower Rhein), section Extreme floods from the river Rhine basin (in German: ISBN 9036956501 and in Dutch: ISBN 9036956684). Landwirtschaft und Verbraucherschutz des Landes Nordrhein–Westfalen, Düsseldorf, Germany; Provincie Gelderland, Arnhem, The Netherlands; Rijkswaterstaat Directie-Oost, Arnhem, The Netherlands.

An artificial time series of 1000 years of precipitation and temperature based on the reference simulation of Beersma (2002) was put into a rainfall-runoff model of the entire Rhine basin (HBV) in order to simulate discharge. A selection was made of the 16 most extreme events, based on the HBV results at Andernach and Lobith. These 16 extreme events were then put into a 1-dimensional flood routing model to compute the 16 discharge waves at Andernach in a more accurate way, taking into account flooding and retention measures along the Rhine upstream of Andernach. The generated flood waves were used to simulate the trans-boundary effects of extreme floods along the Lower Rhine.

Eberle, M., Buiteveld, H., Krahe, P. and Wilke, K., 2005. Hydrological Modelling in the river Rhine basin, part III: Daily HBV Model for the Rhine basin. Report No. 1451, Bundesanstalt für Gewässerkunde (BfG), Koblenz, Germany.

An HBV model on a daily basis covering the whole river Rhine basin upstream of gauge Lobith on the German-Dutch border has been set up. A simple flood routing procedure for the river Rhine is implemented in the model in order to be able to calculate discharges of the Rhine itself. A consistent set of input time series for the model is available for the period 1961-1995. For this period a detailed validation of the simulation is carried out. It is based on a set of quality criteria and graphs that the project partners have agreed on. Especially when looking at the river Rhine gauges, the simulation results are acceptable. The statistical criteria used for validation were met for most of these gauges. The visual comparison shows a good agreement of simulation and observed discharge as well. However, significant deviations do occur, e.g. the flood peaks in 1993 and 1995 are overestimated by about 10-15%. For the river Rhine gauges only a few minor systematic errors are noticed that might be a starting point for further improvements. One thing that could probably be improved is the flood routing procedure between the gauging stations Basel and Maxau. The analysis of the tributary simulations reveals some systematic problems, especially concerning the simulation of low flows. Concerning the simulation of flood events, annual discharge maxima are underestimated on average except for the river Main. As a result of the validation work in this study some points have been identified where a significant improvement of the model might be possible.

Barneveld, H.J. and Udo, J., 2006. Neerslaggeneratorinstrument Rijn: Gevolgen voor golfvorm Lobith. Rapportage project PR1076 aan RIZA, HKV Lijn in Water, Lelystad.

First study that compares the present design flood wave for the river Rhine with generated flood waves. The latter turned out to be sharper than the design flood wave.

Meuse basin

Wójcik, R. and Buishand, T.A., 2001. Rainfall generator for the Meuse basin: Simulation of 6-hourly rainfall and temperature for the Ourthe catchment. KNMI publication 196-I, KNMI, De Bilt.

This report presents a first study on the development of a stochastic weather generator for the Meuse basin. The study is restricted to the Ourthe basin (3626 km^2). Time series of 6-hourly area-average precipitation of 3 sub-catchments (Ourthe upstream of Tabreux/Hamoir, Amblève and Vesdre) and average 6-hourly temperature at St. Hubert are considered. It appears that straightforward resampling of the historical 6-hourly values does not adequately reproduce a number of second-order statistics of precipitation and temperature. Particularly, the slow decay of the autocorrelation function of 6-hourly area-average rainfall is not preserved. As an alternative, simulation of daily values with disaggregation into 6-hourly values using the method of fragments is studied. With this strategy a reasonable reproduction of the second-order statistics of rainfall and temperature is achieved. Moreover, there is a good correspondence between the historical and simulated distributions of the maximum precipitation amounts in the winter half-year (October – March).

Booij, M.J., 2002. Appropriate modelling of climate change impacts on river flooding. PhD Thesis, University Twente, Enschede, The Netherlands.

The PhD thesis was not part of the GRADE project, but the HBV schematization for the Meuse that resulted from this work has been used for GRADE. As a next step specific aspects of HBV modeling in the Meuse have been addressed by a number of students from the University Twente and Wageningen University (Koen van der Wal, Mirjam Groot Zwaaftink, Paul Aalders, Eefje Dortmans, Menno ten Heggeler, Martin Arends).

Wójcik, R. and Buishand, T.A., 2003. Simulation of 6-hourly rainfall and temperature by two resampling schemes. Journal of Hydrology 273, 69-80.

Paper based on the work of Wójcik and Buishand (2001). Instead of precipitation and temperature for the Ourthe basin, a 6-hourly precipitation and temperature record for Maastricht in the Netherlands is considered.

Vuuren, W., van, 2003. Evaluatie extreme waardenverdelingen voor de afvoeren in het stroomgebied van de Ourthe in de periode 1968-1999 op basis van historische en gegenereerde meteoreeksen. Memo No. 2002.024, Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling (RIZA), Arnhem.

Analysis of the data available for the Ourthe catchment.

Aalders, P., and de Wit, M.J.M., 2004. Rainfall generator for the Meuse basin: Case study Ourthe basin. Report No. 2004.137x, Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling (RIZA), Arnhem, The Netherlands.

This report focuses on the calculation of discharges of the river Ourthe upstream of Tabreux/Hamoir using a 1000-year precipitation and temperature simulation from the work of Wójcik and Buishand (2001). The main aims of the study are to i) test the applicability of the HBV model as a hydrological tool for the rainfall generator, and ii) to compare the frequency distribution of the generated discharges for the Ourthe with the frequency distribution of the observed discharges. It is concluded that the HBV model is a suitable tool to be included in the rainfall generator for the Meuse basin. It appears that the largest generated discharge volumes for the Ourthe basin are less extreme than one would expect from an extrapolation of the frequency distribution of observed discharge volumes. The use of a 6-hour temporal resolution of the meteorological input data was compared with that of a resolution of one day. It is argued that the latter may be detailed enough for the purpose of GRADE Meuse.

Leander, R. and Buishand, T.A., 2004a. Rainfall generator for the Meuse basin: Inventory and homogeneity analysis of long daily precipitation records. KNMI publication 196-II, KNMI, De Bilt, The Netherlands.

This report deals with the homogeneity of the long-term precipitation records from stations in eastern Belgium and north-eastern France. The relative homogeneity of the records was first analysed for the Belgian and French stations separately, using four statistical tests. The tests were then repeated with the most reliable records from the two countries. For the period 1946-1998, 13 of the available 23 records were homogenous. For the period 1928-1998, only 6 of the 18 available records were found to be homogenous. The non-homogeneous ones were not further used for the development of the rainfall generator.

Leander, R. and Buishand, T.A., 2004b. Estimation of areal precipitation from station records. KNMI Memorandum KA-04-01, De Bilt, The Netherlands (unpublished document).

This document describes the calculation of areal precipitation for the French sub-basins of the Meuse for the period 1961-1998. The calculation considers 63 stations of which two are in Belgium. The

station values are interpolated on a 2.5 km × 2.5 km grid using the method of inverse squared distance weighting. The area-average precipitation is then obtained by averaging the interpolated values of all grid points in the sub-basin of interest.
Leander, R. and Buishand, T.A., 2004c. Rainfall generator for the Meuse basin: Development of a multi-site extension for the entire drainage area. KNMI publication 196-III, KNMI, De Bilt, The Netherlands.

First publication on the joint simulation of daily precipitation for 15 sub-basins and temperature for 11 stations in the Belgian and French Meuse basin. Two 3000-year simulations are performed: one based on observed station data for the period 1961-1998 (Sim61) and one based on observed station data for the period 1930-1998 (Sim30). The latter requires an extra nearest-neighbour search because the sub-basin precipitation data were not available over the entire 1930-1998 period. The use of this extra search is extensively tested for the Belgian part of the Meuse basin. It is shown that for a long range of return periods the Gumbel plots of the 4-, 10- and 30-day winter maxima of the basin-average precipitation from the Sim61 simulation are above the corresponding plots for the Sim30 simulation. The distributions of the 4-, 10- and 30-day seasonal maxima of area-average precipitation are well reproduced by the Sim61 simulation, although a rare historical 30-day event was found in July 1980, which was not exceeded in this 3000-year simulation. It is further shown that more extreme multi-day winter rainfalls amounts are generated for the Ourthe basin than in the pilot study of Wójcik and Buishand (2001). This is partly ascribed to the use of a 4-day memory element in the feature vector. For the Sim30 simulation it is noted that the occurrence of spurious multi-day rainfall amounts due repeated resampling of a particular day can be strongly reduced if a moving window of 121 days is used instead of 61 days.

Deursen, W. van, 2004. Afregelen HBV model Maasstroomgebied. Rapportage aan RIZA, Carthago Consultancy, Rotterdam.

This report deals with the calibration of HBV-Meuse. It concerns an update, with more detailed data, of a previous calibration which is reported by Booij (2002). The reported schematisation has been used as the hydrological part of the rainfall generator for the Meuse basin.

Aalders, P, Warmerdam, P.M.M. and Torfs, P.J.J.F., 2004. Rainfall generator for the Meuse basin: 3,000 year discharge simulations in the Meuse basin. Report No. 124, Sub-department Water Resources, Wageningen University, Wageningen, The Netherlands.

The hydrological part of GRADE for the Meuse basin (based on van Deursen, 2004), is described in this report. The main effort is put in the construction of a program which automatically executes the HBV simulations with long-duration synthetic precipitation and temperature data. Ten 3000 year simulations are considered: four Sim61, four Sim30 and two Sim30 simulations with a relatively wide moving window (121 days instead of 61 days). The general results of the 3000 year simulations (average, standard deviation, temporal distribution) are satisfactory. However, the simulations seem to underestimate annual maxima in the middle and highest range. Moreover, Gumbel and GEV fits to the extreme discharges do not give uniform results regarding the value of the 1250-year event. This behaviour is ascribed to random effects during generation of the precipitation and temperature records. Furthermore, the use of a 121-day window for resampling seems to have no significant improvement on the simulation of extreme discharge events. Additionally, the simulations prove that an extreme peak on the Meuse follows from a long period of moderate wet days instead of one or two extreme wet days.

Dortmans, E., 2005. Analysis of extreme floods in sub-basins of the Meuse. MSc thesis, Wageningen University, Wageningen, The Netherlands.

This study deals with simulated flows at Borgharen and those for all sub-basins. One of the four 3000-year synthetic Sim61 sequences of precipitation and temperature is used as input for HBV. The simulated flows for the sub-basins are analysed separately for the most extreme discharge peak event in the 3000 years (3914 m^3/s) at Borgharen. The aim of this study is to investigate whether an analysis of each sub-basin gives more information than looking at the simulated discharge at Borgharen only. A review of the literature of the Meuse basin is part of the study. A hydrological and statistical analysis of the simulated records is presented, in which precipitation, discharge, entropy, lag times, runoff coefficients and water storage of the sub-basins are discussed.

Leander, R., Buishand, T.A., Aalders, P. and de Wit, M.J.M., 2005. Estimation of extreme floods of the river Meuse using a stochastic rainfall generator and a rainfall-runoff model. Hydrological Sciences Journal 50, 1089-1103.

Paper based on the reports of Leander and Buishand (2004c) and Aalders et al. (2004). It is shown that the inclusion of a 4-day memory element in the feature vector leads to a better reproduction of the autocorrelation of daily rainfall.

Wit, M.J.M. de, Leander, R. and Buishand, T.A., 2005. Extreme discharges in the Meuse basin. In: Proceedings CHR Workshop Extreme Discharges, Bregenz, Austria, 5-8. International Commission for the Hydrology of the Rhine basin (CHR), Lelystad, The Netherlands.

Paper presented at a workshop on extreme discharges. Part of this paper is based on Leander et al. (2005).

Gerven, L. van, 2006. Onzekerheidsanalyse waterstanden van de Maas bij extreem hoge afvoeren. Werkdocument No. 2006.034x, Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling (RIZA), Arnhem.

First study that compares the present design flood wave for the river Meuse with generated flood waves derived from Leander et al. (2005). This study reveals that the generated flood waves are smoother than the present design flood wave.

Application and further development of GRADE

Stijnen, J.W., 2001. Methoden voor het bepalen van frequenties van extreme afvoeren voor de Rijn. Verslag workshop 13 september 2001. Rapportage project PR480 aan RIZA, HKV Lijn in Water, Lelystad.

Rapportage over een workshop over de methoden voor de bepaling van "maatgevende afvoer".

Passchier, R., Weerts, A. and van der Klis, H., 2004. Baseline study uncertainty in flood quantiles. Report of project Q3827 for RIZA, WL|Delft Hydraulics, Delft, The Netherlands.

The usefulness of the FEWS extreme discharges (FEWS-ED) tool to determine the design discharge needs to be evaluated. Important question to be answered is: How reliable are the calculated discharges at long return periods? This project is a first step in the process to answer this question. This report starts with a short description of FEWS-ED. Followed by an in depth analysis of the uncertainties in the three components (rainfall generator, rainfall-runoff models, routing models) of FEWS-ED. A brief inventory of available uncertainty analysis methods is given. Finally, a two stage research plan is proposed. First, the uncertainty in the separate elements must be determined. Subsequently, these uncertainties must be combined to determine the uncertainty in the design discharge. A workshop has been held at WL|Delft Hydraulics on November 12, 2004, to discuss a draft version of the report. The outcome of this workshop has been used to arrive at the final version of the report.

Leander, R. and Buishand, T.A., 2004d. On the use of the rainfall generator to quantify the effect of climate change on the design discharge. KNMI memorandum KA-04-02, KNMI, De Bilt, The Netherlands (unpublished document).

This memorandum describes a short study on the potential use of nearest-neighbour resampling to estimate the changes in extreme river flows under future climate conditions. Precipitation and temperature from the KNMI regional climate model RACMO are considered for present-day conditions and a future climate (SRES A2-scenario). It is shown that bias correction by simple linear scaling of the simulated daily rainfall overcorrects the extreme daily rainfall amounts. A more sophisticated method of bias correction is therefore needed. For the A2 scenario, a decrease in the coefficient of variation of the 10-day rainfall amounts was found in the winter season. This decrease of the coefficient of variation counterbalances the effect of the increase in mean winter precipitation on the occurrence of large 10-day rainfalls. Three approaches to use nearest neighbour resampling are briefly discussed: i) unconditional resampling of transformed observations, ii) unconditional resampling of bias-corrected regional climate model output, and iii) conditional resampling on atmospheric predictors.

Leander, R. and Buishand, T.A., 2007. Resampling of regional climate model output for the simulation of extreme river flows. Journal of Hydrology, 332: 487-496.

The paper deals with the use of the output of the regional climate model RACMO for simulating extreme flows of the river Meuse. Streamflows are simulated with the semi-distributed HBV rainfall-runoff model. Two RACMO runs are considered: one driven by the global atmospheric model HadAM3H of the UK Meteorological Office for the period 1961-1990 and one driven by ERA40 reanalysis data. Long-duration sequences (3000 yr) of daily rainfall and temperature for the river basin are generated by resampling from the RACMO output using a nearest-neighbour technique. Much attention is given to the bias correction of RACMO rainfall. A relatively simple nonlinear correction was tested and compared to the commonly used linear scaling correction. It was found that the nonlinear correction resulted in a better reproduction of observed extreme daily and multi-day rainfall amounts, which also resulted in more realistic discharge extremes. Different ways of estimating the parameters in the nonlinear correction are compared. The effect of this correction on the autocorrelation of daily rainfall is demonstrated.

Klis, van der, H., 2005. Proposal to implement the rainfall generator methodology in river management. Report of project Q4025 for RIZA, WL|Delft Hydraulics,Delft, The Netherlands.

In order to prepare for the implementation of GRADE in river management, Rijkswaterstaat RIZA has asked WL|Delft Hydraulics to investigate which actions are required in order to actually get GRADE accepted in practice. This report describes the results of this investigation. One of the actions already foreseen is an uncertainty analysis of GRADE. The proposed method by Passchier et al. (2004) is further refined.

Ogink, H.J.M., 2006. Afleiding statistiek van zomerhoogwaters. Rapportage project Q4297aan RIZA, WL|Delft Hydraulics, Delft.

This report describes the derivation of statistics of summer floods in the river Rhine. It includes a comparison between measured and generated (by GRADE) daily discharge maxima on a monthly basis.

Weerts, A. and van der Klis, H., 2006. Reliability of the Generator of Rainfall and Discharge Extremes (GRADE): An exploratory study on uncertainty in the hydrological parameters, a GLUE analysis. Report of project Q4268 for RIZA. WL|Delft Hydraulics, Delft, The Netherlands.
This study concerns some first quantitative steps in the reliability analysis of GRADE: i) the generation of animations of both historical and synthetic rainfall patterns of the Meuse and Rhine river basins (as available on the CD accompanying this report, and ii) the performance of an uncertainty analysis on the hydrological model parameters in GRADE, focusing on the effect on the design discharge of the river Meuse. From the quantitative analysis performed to the uncertainty in the hydrological parameters of GRADE (i.e. a GLUE analysis) the conclusions are: i) the effect of the uncertainty in the hydrological parameters on the flood frequency curve at Borgharen, as a result of GRADE, is small compared to the overall uncertainty in the official design discharge, according to the assumptions made in this study and the criteria applied. This needs further analysis, ii) although the overall uncertainty in the flood frequency curve as computed by GRADE is yet unknown, the influence of the uncertainty in the hydrological parameters is expected to be substantial, iii) the choice of the hydrological parameters has a strong influence on the extreme-value plot of the simulated discharges. Therefore, the choice of the criteria to select hydrological parameter sets is of crucial importance. The results of this study have been discussed in a meeting of specialists of RIZA, KNMI, WL|Delft Hydraulics, HKV and Twente University. A report of this meeting is included in this report.

Appendix 2

Meteorological data in GRADE

Area-average precipitation

The daily area-average precipitation amounts for the sub-basins were obtained by averaging gridded daily precipitation values within the sub-basin of interest. Table A2.1 presents an overview of the grid size used and the method of interpolation. It should be noted, however, that for the Rhine basin the daily average precipitation amounts for the CHR sub-basins were used for the calibration of the HBV model for the major tributaries in the first phase of the project (Mülders et al., 1999) and in the first report on multi-site generation of daily precipitation and temperature (Brandsma and Buishand, 1999). These sub-basins sometimes differ from the HBV sub-basins in Figure 6.1.

Table A2.1 Interpolation of daily precipitation.

Country	Grid size	Method	Reference
Rhine basin			
Switzerland	2 km × 2 km	inverse distance	Dällenbach (2000)
Germany (excluding Moselle basin)	60'' longitudinal 30'' latitudinal	inverse squared distance	DWD[1]
Moselle basin	7 km × 7 km	inverse distance	White (2001)
France (excluding Moselle basin)[2]	-	-	-
Meuse basin			
France	2.5 km × 2.5 km	inverse squared distance	Leander and Buishand (2004b)
Belgium	variable[3]	Thiessen	RMIB[3]

[1] Dr B. Dietzer: Berechnung von Gebietsniederschlagshöhen nach den Verfahren REGNIE (Regionaliserung räumlicher Niederschlagsverteilung), Unpublished document, DWD, Geschäftsbereich Hydrometeotrologie.

[2] The Commission for the Hydrology of the Rhine basin collected data from Météo France (see also Sprokkereef, 2004). These station data were used in HBV to estimate daily precipitation values for the French part of the Rhine basin (excluding Moselle basin). The interpolation method used has not been documented in Eberle et al. (2005).

[3] Daily area-average rainfall is routinely calculated by RMIB for the Belgian sub-basins of the Meuse. These daily averages were made available for the development of GRADE for the Meuse basin. The grid size for spatial interpolation of daily values varies between sub-basins, e.g. 1 km × 1 km for the Vesdre and 2 km × 2 km for the Amblève and Ourthe upstream of Hamoir (Demarée, pers. comm., 2001).

Area average temperature

Rhine basin
The daily temperature values at 49 stations have been transformed to areal values for the sub-basins using the HBV modelling software (Eberle et al., 2005). For each sub-basin, there were user defined input stations and station weights as well as an altitude correction of 6 °C km^{-1} to the mean elevation of the sub-basin as derived from the elevation zones in the HBV model.

Meuse basin
The simulated daily temperatures for the sub-basins were derived from the simulated values at 11 stations. For each sub-basin four station values were used, taking into account a lapse rate of 6 °C km^{-1} to correct for differences in height between the stations and the sub-basins (Aalders et al., 2004).

Potential evapotranspiration (PET)

Rhine basin
For the long-duration simulations mean monthly values of PET were used. These were derived from daily sunshine duration and temperature using the Penman-Wendling approach.
For further details, see Eberle et al. (2001 and 2005).

Meuse basin
For the Belgian sub-basins, sequences of daily PET for the period 1967-1998 were made available by RMIB. For the calibration of HBV in the French part of the basin, PET was set equal to the average PET of the Belgian part. In the long-duration simulations PET was obtained from the simulated daily temperature as (Aalders et al., 2004):

$$PET = \left[1 + \alpha\left(T - \overline{T}\right)\right]\overline{PET}$$

with $\overline{T}$ (°C) and $\overline{PET}$ (mm day^{-1}) being the mean daily temperature and mean monthly PET for the period 1967-1998 and $\alpha = 0.17$ °C^{-1}. In the recent application with regional climate model data (Leander and Buishand, 2007) a seasonally varying value of α based on regression was used.

Appendix 3

HBV model

The following description of the HBV model is taken from Eberle et al. (2005).

For the hydrological modelling of the Rhine and Meuse basins IHMS-HBV 4.5.2 is applied, a commercial version of the model which has been developed at SMHI. As the HBV model is a conceptual model it describes the most important runoff generating processes in a simple and robust way. The following points give a short overview of the three main components in the model together with related parameters:

- Snow Routine
  The precipitation as the initial input into the model is divided into rainfall and snowfall. 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 degree-day relation (snow melt factor cfmax). The snow distribution is computed separately for different elevation and vegetation zones in the basin (see later in this appendix).

- Soil Routine
  The soil routine controls which part of precipitation forms excess water and how much water is evaporated or stored in the soil. The runoff coefficient depends on the ratio of actual soil moisture and the maximum water storage capacity of the soil (parameter fc) as well as an exponent representing drainage dynamics (parameter beta). The parameter lp defines the water storage in the soil at which actual evaporation starts to be equal to potential evaporation. Values of potential evaporation are required as input data and there is a special correction factor for evaporation in forest areas (cevpfo). Interception in forest areas and open land can also be simulated (parameters icfo 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 khq, 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 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 simple filter technique with a triangular distribution of the weights as shown in Figure A3.1 at the bottom on the right.

Figure A3.1 illustrates the general way of discharge formation in the HBV model and gives the main parameters and formulas implemented in the model.

The spatial units of the semi-distributed HBV model are subbasins, which represent real river catchments. These are further divided into zones of different elevation and land cover (forest, non forest, lake and glacier). The zone area is proportional to the occurrence of its characteristic in the subbasin, however, zones cannot be geographically localised.

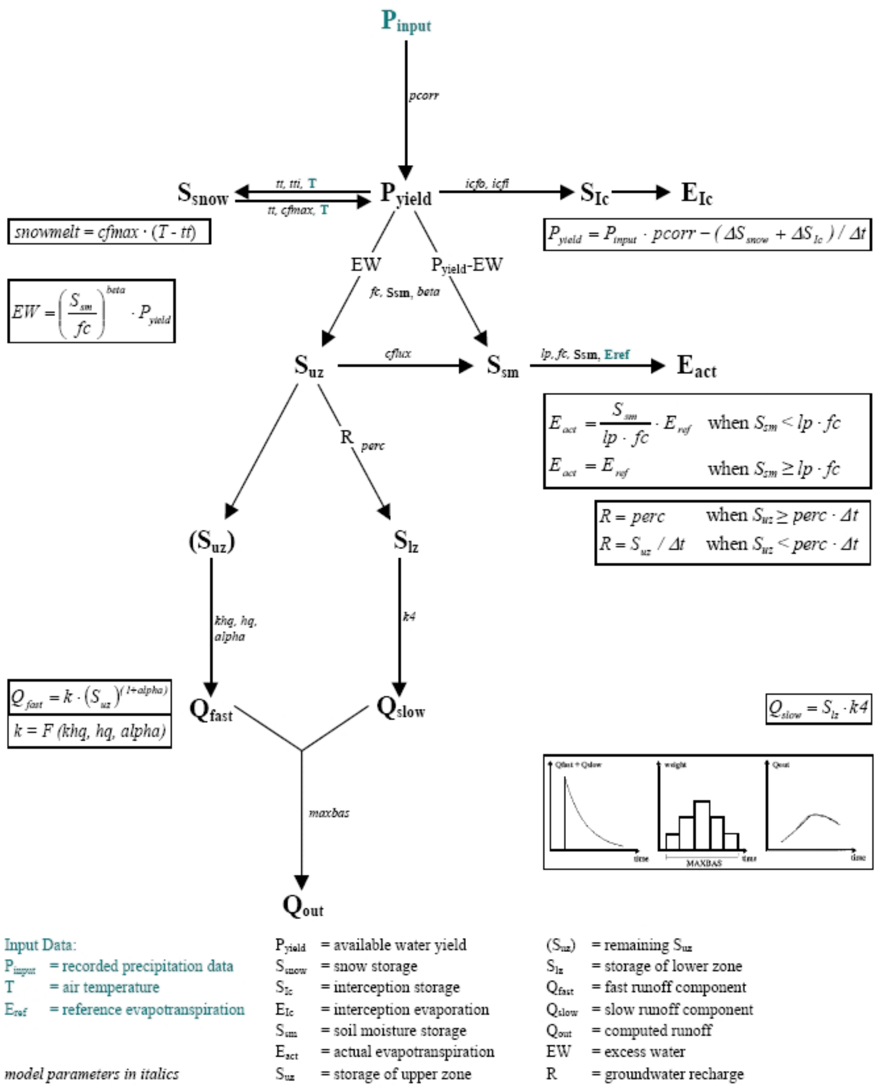
The land cover classes “lake” and “glacier” have only been applied in the part of the Rhine model upstream of Basel. Glacier melt follows a degree-day relation as used for snow melt but with another parameter (gmelt). Since the basin upstream of Basel had to be modelled in a very rough way and little information on the Swiss lakes has been available, lakes have only been implemented concerning runoff formation. Evaporation from lakes is assumed to be equal to the potential evaporation and does not occur as long as there is ice, which is estimated by the model based on air temperature of preceding days (SMHI, 1996).

Lake retention is not implemented yet. Especially concerning the Bodensee this is quite a drastic simplification and an obvious point for further improvement. However, since the simulation results for Basel are of comparable quality as for other major gauging stations and since the main focus of the model applications is on flood events in the Middle and Lower Rhine it was considered to be acceptable for the moment.

The subbasins are linked together with a simplified Muskingum approach to simulate flood routing processes.

For more information about the HBV model see the IHMS user manual (SMHI, 1996).

Figure A3.1 Simplified calculation scheme of the HBV model (Source: Eberle et al., 2005).



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