ESTIMATION OF EXTREME FLOODS IN THE RIVER RHINE BASIN BY COMBINING PRECIPITATION-RUNOFF MODELLING AND A RAINFALL GENERATOR

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SUMMARY

The determination of design discharges from statistical analyses of peak discharges faces various problems. Here an alternative approach is investigated that makes use of precipitation as the source of discharge generation. A stochastic rainfall generator based on nearest neighbour resampling has been developed to produce the daily meteorological input of a hydrological/hydraulic modelling system. In two 1000-year simulations much larger multi-day precipitation amounts are found than in the historical record. With the exception of a slight underestimation of annual maximum peak flows, the HBV precipitation-runoff model satisfactorily reproduces the discharges of the main tributaries of the river Rhine. The methodology is tested further for the Moselle basin using one of the 1000-year precipitation simulations. The largest simulated flood event based on generated precipitation is 20% larger than the 1993 flood event.

Keywords: Flood estimation, rainfall generator, HBV, precipitation-runoff modelling, Rhine basin

1 INTRODUCTION

In the Netherlands, the design discharge for the river Rhine (and the other large rivers) is exceeded on average once every 1250 years (Parmet et al., 1999). Statistical approaches for estimating the design discharge have a number of weaknesses. First, the representativeness of the relatively short discharge record of about 100 years can be questioned. For a number of fitted extreme-value distributions it turned out that the 90% confidence interval is about 2500 m³/s around the estimated 1250-year event. Second, the discharge record is potentially non-homogeneous because of changes in the drainage basin, the river geometry and climate since 1901. A third point of uncertainty concerns the choice of frequency distributions. Furthermore, statistical methods provide no information about the volume and duration of the considered flood event.

Therefore, a new methodology is being developed to provide a better physical basis for the design discharge (Parmet et al., 1999). The development is co-ordinated by RIZA and is carried out so far in co-operation with KNMI and BfG. 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 precipitation-runoff models for the major Rhine tributaries. The final component is a one-dimensional hydrodynamic model that routes the runoff from the hydrological models. In this way, the generated rainfall is transformed into a homogeneous discharge series thereby tackling the problem of the short, non-homogeneous historical discharge record. The coupling with the hydrodynamic model in order to simulate discharge of the whole river Rhine basin has not yet been realised.

An additional advantage is that the new methodology may give a better insight into the shape and duration of the design flood, because meteorological conditions and catchment responses are explicitly taken into account. Furthermore, it can potentially assess the effects of future developments like climate change and upstream interventions such as retention-basins and dike-relocations. The latter are incorporated in the hydrodynamic model (Lammersen et al., 2002).

In section 2 the rainfall generator for the complete Rhine basin is presented. Section 3 describes the HBV modelling for the major tributaries downstream of Basel and in section 4 both models are combined for the Moselle basin. The conclusions are given in section 5.

2 STOCHASTIC RAINFALL GENERATOR

Daily rainfall and temperature are simultaneously simulated at 36 stations in the Rhine basin using nearest-neighbour resampling. A major advantage of a non-parametric resampling technique is that it preserves both the spatial association of daily rainfall over the drainage basin and the dependence between daily rainfall and temperature without making assumptions about the underlying joint distributions.

2.1 Nearest-neighbour resampling

In the nearest-neighbour method weather variables like precipitation and temperature are sampled simultaneously with replacement from the historical data. To incorporate autocorrelation, one first searches the days in the historical record that have characteristics similar to those of the previously simulated day. One of these 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 t. A feature vector $\mathbf{D}_t$ is used to find the nearest neighbours in the historical record. $\mathbf{D}_t$ is formed out of the standardised weather variables generated for day t-1. The nearest neighbours of $\mathbf{D}_t$ are selected in terms of a weighted Euclidean distance. In this study a decreasing kernel is used to select randomly one of five nearest neighbours.

For each day the simulated values (i.e. the observed data of the selected day) may also include the observed data of the selected day from stations that are not used in the feature vector or include the area-average precipitation data from subcatchments of the selected day. The simulation of such additional data is designated as *passive* simulation. More details about nearest-neighbour resampling can be found in Rajagopalan and Lall (1999), Wójcik et al. (2000) and Buishand and Brandsma (2001).

2.2 Data

Daily temperature and precipitation data for the 35-year period 1961-1995 were made available for 36 stations in the Rhine basin: 25 in Germany, 1 in Luxembourg, 4 in France and 6 in Switzerland. Because precipitation P and temperature T depend on the atmospheric flow, three daily circulation indices are also considered: (i) relative vorticity Z, (ii) strength of the westerly flow W and (iii) strength of the southerly flow S. These circulation indices were computed from daily mean sea-level pressure data on a regular 5° latitude and 10° longitude grid.

Before resampling the data were deseasonalised through standardisation. The effect of seasonal variation is reduced further by restricting the search for nearest neighbours to days within a moving window, centred on the calendar day of interest. The width of this window was 61 days. To keep the dimension of the feature vector low, a small number of summary statistics was calculated from the observed data at 34 of the 36 stations (two Swiss mountain stations were excluded). Both for P and T the arithmetic mean of the standardised daily values was used. In addition, the fraction F of stations with $P \geq 0.1$ mm was considered. F helps to distinguish between large-scale and convective precipitation.

2.3 Performance of the rainfall generator

The performance of the rainfall generator was mainly studied for the winter half-year (October-March) because most extreme river discharges in the lower part of the Rhine basin occur during that season. Twenty-eight runs of 35 years were generated to investigate the reproduction of standard deviations and autocorrelation coefficients. Both the standard deviations of the daily values and the monthly values (totals for precipitation and averages for temperature) were considered. Table 2-1 presents the differences between the standard deviations and the autocorrelation coefficients of the simulated and historical data for a model with a 3-dimensional feature vector and for a model with a 6-dimensional feature vector.

Table 2-1: Percentage differences between the mean standard deviations of monthly and daily values, $\bar{s}_{\mathrm{M}}$ and $\bar{s}_{\mathrm{D}}$ respectively, and absolute differences between the mean lag 1 and 2 autocorrelation coefficients $\bar{r}\,(1)$ and $\bar{r}\,(2)$ in the simulated time series (twenty-eight runs of 35 years) and the historical records (1961-1995) in winter (October-March), averaged over 34 stations. Bottom lines: average historical estimates (standard deviations in mm for precipitation and in °C for temperature). Values in bold refer to differences more than twice the standard error (se) from the historical estimate. The elements $\tilde{P}$ and $\tilde{T}$ in the feature vector $\mathbf{D}_t$ refer to the average standardised precipitation and temperature of 34 stations, F refers to the fraction of stations with precipitation and $\tilde{Z}$, $\tilde{W}$ and $\tilde{S}$ are standardised atmospheric circulation indices.

		$\Delta\bar{s}_{\mathrm{M}}$ (%)		$\Delta\bar{s}_{\mathrm{D}}$ (%)		$\Delta\bar{r}(1)$		$\Delta\bar{r}(2)$	
Model	Elements of $\mathbf{D}_t$	P	T	P	T	P	T	P	T
UE	$\tilde{P}_{t-1}, F_{t-1}, \tilde{T}_{t-1}$	0.3	-1.1	0.2	0.2	**-0.019**	**-0.032**	-0.001	0.006
UEc	$\tilde{Z}_{t-1}, \tilde{W}_{t-1}, \tilde{S}_{t-1}, \tilde{P}_{t-1}, F_{t-1}, \tilde{T}_{t-1}$	-1.7	-8.2	-1.2	-1.9	**-0.018**	**-0.036**	0.001	-0.020
Historical		35.7	2.1	4.2	4.2	**0.283**	**0.826**	0.144	0.639
se		4.5	6.2	2.5	2.5	**0.008**	**0.007**	0.009	0.015

For the model that incorporates only the large-scale features of the P and T fields (model UE) the precipitation and temperature statistics are well reproduced. A slight, though statistically significant, bias is present in the lag 1 autocorrelation coefficients. Incorporation of the circulation indices into the feature vector (model UEc) generally worsens the reproduction of daily temperature statistics. For precipitation both models give similar results.

2.4 Long-duration simulations

With the two models 1000-year simulations have been performed. Figure 2-1 shows Gumbel plots of the 10-day winter precipitation maxima for the area average precipitation of the 34 stations used in the feature vector.

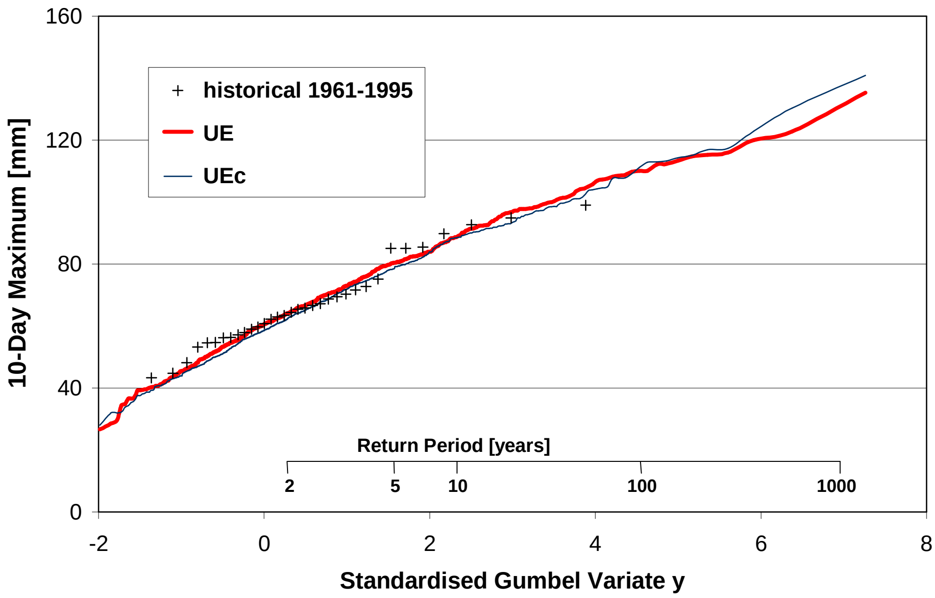

Figure 2-1: Gumbel plots of 10-day winter precipitation maxima for observed and simulated data (runs of 1000 years)

The figure shows that there is a good correspondence between the historical and simulated distributions. Realistic multi-day precipitation amounts much larger than the largest historical precipitation amounts are found in these simulations, which is particularly interesting from the viewpoint of precipitation-runoff modelling. Figure 2-1 shows e.g. that the largest 10-day precipitation amounts in the simulations are up to 40% larger than in the historical record. The 1000-year simulation with the UE model serves as input for precipitation-runoff modelling of the river Moselle. The simulated daily temperatures of 8 stations in the Moselle basin are used as well as passively simulated daily area average precipitation amounts of 42 subcatchments (see section 4).

3 PRECIPITATION-RUNOFF MODELLING OF THE RIVER RHINE BASIN

3.1 HBV modelling of the major river Rhine tributaries

The major tributaries of the river Rhine downstream of Basel (Figure 3-1) are modelled with the precipitation-runoff model HBV on a daily basis. Discharge formation of the remaining (white) areas along the river Rhine is less important concerning floods at Lobith - however, they will be considered in the future. In addition, it will be necessary to incorporate precipitation-runoff modelling for the Swiss part of the basin.

HBV is a conceptual semi-distributed precipitation-runoff model. It was developed at the Swedish Meteorological and Hydrological Institute (SMHI) in the early 1970s and has been applied in more than 30 countries with only small adjustments (Lindström et al., 1997 - e.g. Lidén, Harlin, 2000 and Eberle et al., 2001). HBV describes the most important runoff generating processes with simple and robust structures. 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.

Since HBV is a semi-distributed model, the basin of each tributary is subdivided into subbasins (see. Figure 3-1). Inside these subbasins some processes are simulated separately for different elevation zones and forested and non-forested areas. The subbasins are based on catchment boundaries defined for the International Commission for the Hydrology of the river Rhine basin (CHR). Another aspect concerning the delineation of subbasins is the availability of gauging stations that are necessary for calibration. Most of the subbasins cover between 500 and 2000 km². The elevation zones inside the subbasins as well as the area covered with forest within these zones are derived from grid based GIS data, i.e. a land use classification based on Landsat-TM satellite data and the digital elevation model of the U.S. Geological Survey.

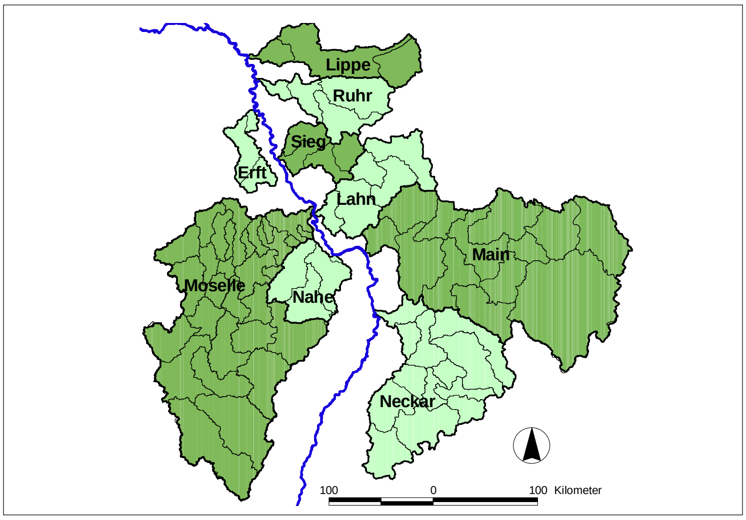

Figure 3-1: Subbasin structure for modelling the major river Rhine tributaries with HBV

Precipitation data for the German part of the Rhine basin are available from the CHR as time series of subbasin average precipitation. For the Moselle basin, which partly belongs to France, Belgium and

Luxembourg, daily gridded precipitation recently calculated at the University of Trier (White, 2001) is taken to calculate areal precipitation time series for the subbasins. Air temperature data from 36 stations are used. For the same stations daily values of reference evapotranspiration are computed from temperature and sunshine duration using the Penman/Wendling approach (Wendling, 1995). However, runoff simulations are also possible with long-term mean monthly values of reference evapotranspiration.

Calibration is done manually by comparison of observed and computed hydrographs and statistical criteria, i.e. the Nash/Sutcliffe criterion R^2 and the accumulated difference of observed and computed discharge. For some HBV parameters, for example the parameter representing the maximum water storage in the soil, values are estimated from the catchment characteristics (e.g. land use and field capacity). The calibration period is 1976 to 1985; it includes both dry and wet years.

Results are satisfactory. As Table 3-1 shows, the Nash/Sutcliffe criterion R^2 generally exceeds 0.85 both in the calibration period and in the validation periods (1986-1990 and 1991-1995). The only basin with poor results is that of the river Erft where discharge dynamics are dominated by technical measures related to brown coal mining. Results tend to be best for the rivers Ruhr, Moselle and Lahn; concerning the river Ruhr, this is rather surprising because the large reservoirs in the river Ruhr basin have not been taken into account explicitly. More information about daily HBV modelling in the river Rhine basin can be found in Mülders et al. (1999).

Table 3-1: Values of the Nash/Sutcliffe criterion R^2 for HBV modelling the river Rhine tributaries

River	Gauging station	Catchment Area [km²]	R^2 - Calibration 1976-1985	R^2 - Validation1 1986-1990	R^2 - Validation2 1991-1995
Neckar	Rockenau	14,000	0.86	0.88	0.79
Main	Frankfurt	24,764	0.88	0.87	0.86
Nahe	Grolsheim	4,060	0.87	0.86	0.85
Lahn	Kalkofen	6,000	0.90	0.91	0.94
Moselle	Cochem	27,088	0.92	0.90	0.94
Sieg	Menden	2,880	0.91	0.91	0.91
Erft	Neubrück	1,880	< 0	< 0	< 0
Ruhr	Hattingen	4,500	0.89	0.91	0.94
Lippe	Schermbeck	4,880	0.85	0.91	0.88

3.2 Validation with respect to peak simulation and representation of discharge statistics

Calibration based on the Nash/Sutcliffe criterion R^2 does not focus on peak discharges specifically. Therefore, the simulation of peak discharges and the representation of discharge statistics are examined subsequently.

Table 3-2 shows "peak errors", i.e. the relative deviation between the computed and the observed mean annual discharge maxima for the period with measured discharge data. It has to be kept in mind, that measured and simulated maxima may occur at different times.

Table 3-2: "Peak errors" of simulations for the major Rhine tributaries (relative deviation between computed and observed mean annual discharge maxima)

River	Gauging station	Catchment Area [km²]	Period	Peak error [%]
Neckar	Rockenau	14,000	1970 - 1995	-3.6
Main	Frankfurt	24,764	1970 - 1995	7.8
Nahe	Grolsheim	4,060	1975 - 1995	-4.1
Lahn	Kalkofen	6,000	1970 - 1995	-11.4
Moselle	Cochem	27,088	1961 - 1998	-6.2
Sieg	Menden	2,880	1976 - 1995	-19.3
Erft	Neubrück	1,880	1970 - 1995	-
Ruhr	Hattingen	4,500	1970 - 1995	-5.9
Lippe	Schermbeck	4,880	1970 - 1995	-6.7

Most of the deviations are acceptable. Beside the river Erft, only the simulations for the rivers Sieg and Lahn show a "peak error" of more than 10%. Except for the river Main, there is a tendency for the underestimation of high peaks.
For the Moselle basin, where the new methodology for flood estimation is tested, the simulation of annual discharge maxima and the reproduction of discharge statistics is examined in more detail. Computed and observed annual discharge maxima are compared in Figure 3-2. In contrast to the general underestimation of the annual maxima, the largest two observed discharges are slightly overestimated. Table 3-3 presents standard statistics for measured and simulated discharge.

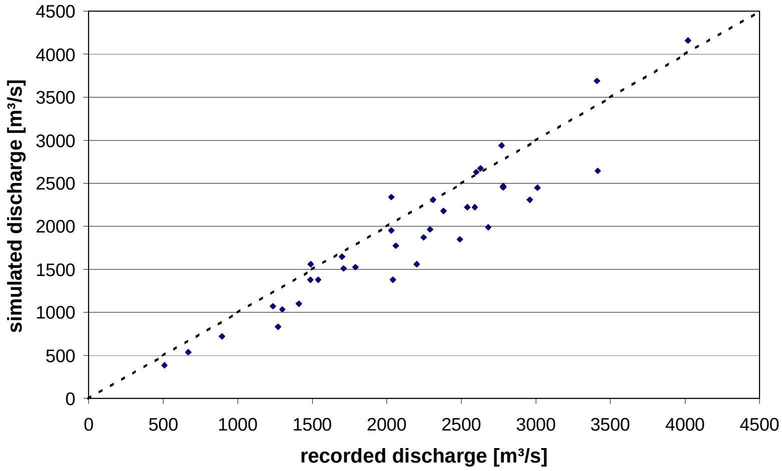

Figure 3-2: Scatter plot of recorded and simulated annual discharge maxima at gauging station Cochem/Moselle 1962-1997

Table 3-3: Standard statistics of recorded and simulated discharge at gauging station Cochem/Moselle (period 1962-1997)

	Mean [m³/s]	median [m³/s]	maximum [m³/s]	minimum [m³/s]	standard deviation of daily values [m³/s]
recorded discharge Cochem	331	207	4020	10	361
HBV simulation Cochem	321	200	4159	19	354

Figure 3-3 shows the discharges for different return periods estimated from measured and simulated data assuming a log Pearson Type III distribution. This distribution is commonly used for calculating design discharge at federal waterways in Germany. Note, that for the recorded data, the computed discharges for certain recurrence periods may differ from the official values because they are based on daily average discharge values during a relatively short period (36 years). The HBV model over-estimates the return periods of discharges smaller than ~3700 m³/s and underestimates the return periods for larger discharges.

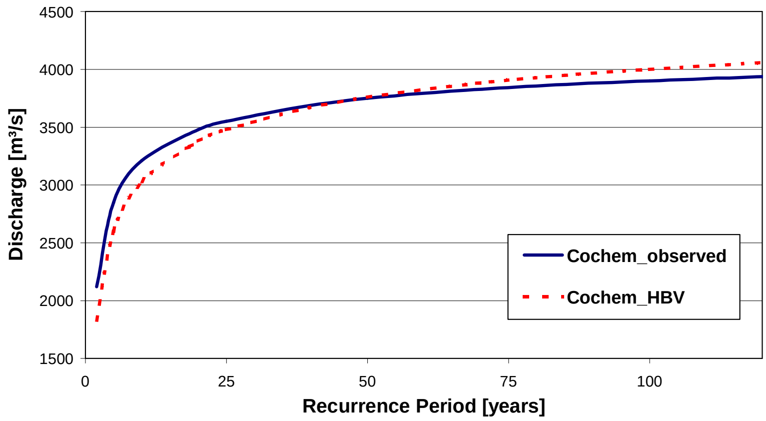

Figure 3-3: Log Pearson Type III distribution estimated with the maximum-likelihood method on the basis of measured and simulated annual peak discharges at gauge Cochem/Moselle 1962-1997

4 APPLICATION OF THE METHODOLOGY FOR THE RIVER MOSELLE BASIN AND ITS COMPARISON WITH THE RESULTS OF STATISTICAL APPROACHES

A 1000-year simulation with the rainfall generator (model UE, see section 2) is taken as input for the HBV model of the river Moselle.
The input data set for the Moselle comprises daily values of temperature at 8 climate stations that are simulated with the rainfall generator and time series of 42 subbasin average precipitation amounts that are generated passively. Evapotranspiration is simulated in the HBV modelling system based on long-term mean monthly values.
Figure 4-1 shows the annual maxima of daily discharges of the simulated 1000 years. The simulated maximum values fit quite well into the range of observed annual maxima during the period from 1962 to 1997 and there is no visible trend. Since there are significantly larger 10-day precipitation amounts in the 1000 years generated precipitation than in the historical record, it is not surprising that some of the simulated floods are considerably higher than the 1993 flood, which marks the maximum of the recorded data. Hydrographs of the 1993 flood event, the maximum peak simulated with generated precipitation and the simulated flood event caused by the maximum generated 30-day precipitation sum are presented in Figure 4-2. The latter flood event is one of the simulated floods with maximal volume.

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Figure 4-1: Annual maximum peaks of 1000 years of simulated discharge at gauging station Cochem/ Moselle based on generated precipitation

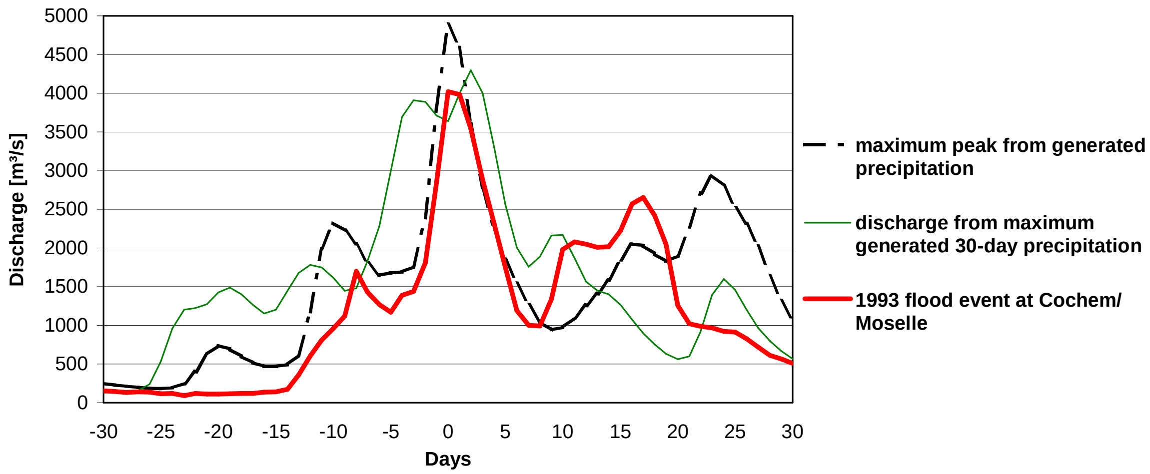

Figure 4-2 Hydrographs of the 1993 flood event and simulated floods based on generated precipitation at gauging station Cochem/Moselle

Figure 4-3 compares the ranked recorded and simulated annual discharge maxima. Fitted log Pearson Type III distributions on the basis of the recorded and simulated discharge are added to facilitate a comparison.

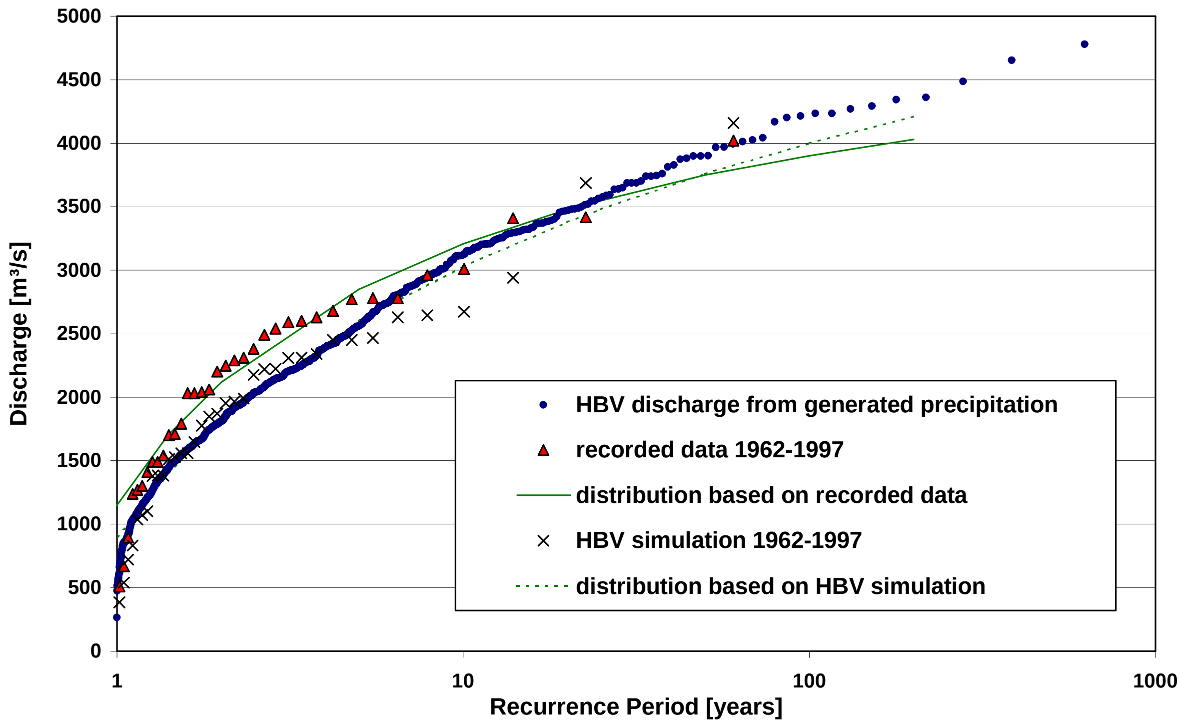

Figure 4-3: Frequency distributions of annual discharge maxima from a HBV simulation based on generated precipitation, a HBV simulation based on recorded precipitation and recorded discharge data

The HBV simulation based on generated precipitation of 1000 years results in other design discharges than by using the statistical approach. However, the deviation is within the range that could be expected when applying different distributions as well. Especially concerning discharges of longer return periods there is a good agreement with the measured values. For smaller peaks the results of the 1000-year simulation show a similar underestimation as that for the HBV simulation with historic rainfall.

5 CONCLUSIONS AND DISCUSSION

In order to reduce the uncertainties in the estimation of the design discharge for the Rhine basin, a new methodology is being developed in which a stochastic rainfall generator and precipitation-runoff models are coupled. Promising results have been obtained for the Moselle basin, the largest tributary of the Rhine. The largest shortcoming is an underestimation of the annual maximum discharges by the HBV model. An underestimation of peak discharges is also found for most other subbasins of the Rhine. There is, therefore, some need to reconsider the calibration of the HBV model using other statistical criteria than the Nash/Sutcliffe criterion R^2. Another option for improving HBV results might be to simulate considered flood events on an hourly basis, hence, simulating the actual peak discharges instead of daily average discharges. Concerning the rainfall generator, the good correspondence between the HBV simulation based on observed precipitation data and the HBV simulation based on the precipitation input from the rainfall generator suggests that the effects of possible errors in the statistics of the simulated extreme precipitation are negligible. Nevertheless, it should be noticed that the nearest-neighbour resampling method does not simulate *daily* precipitation values higher than those in the historical precipitation record. Generally, uncertainty is introduced by the relatively short length of the observed precipitation record on which the rainfall generator is based (35 years) and by the limited period with data that is available for the calibration of the HBV model in the Rhine basin.

There are various options for using the long simulation runs of discharges. The design discharge can be derived with or without fitting a distribution to the simulated annual maxima. A first impression of the uncertainty can be obtained from an ensemble of 1000-year generated discharges.
A major advantage of the new method is that it provides information about the shape of the hydrograph, including volume and duration of the floods. A potentially useful application is that the simulated hydrographs can be used as model-floods in other studies.

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7 REFERENCES

Buishand, T.A., Brandsma, T. (2001): Multi-site simulation of daily precipitation and temperature in the Rhine basin by nearest-neighbor resampling. Water Resour. Res., 37: 2761-2776. American Geophysical Union (AGU). Washington.

Eberle, M., Sprokkereef, E., Wilke, K., Krahe, P. (2001): Hydrological Modelling in the River Rhine Basin, Part II. Report on Hourly Modelling. BfG - 1338. Bundesanstalt für Gewässerkunde. Koblenz.

Lammersen, R., Buiteveld, H., Ritter, N., Disse, M., Engel, H. (2002): Simulating the effect of flood reducing measures on the flood conditions of the river Rhine. Draft December 2001. To be published in the proceedings of the International Conference on Flood Estimation in Berne, March 6-8, 2002. CHR. Lelystad.

Lidén, R., Harlin, J. (2000): Analysis of conceptual rainfall-runoff modelling performance in different climates. Journal of Hydrology, 238, 231-247. Elsevier Science. Amsterdam.

Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S. (1997): Development and test of the distributed HBV-96 hydrological model. Journal of Hydrology, 201, 272-288. Elsevier Science. Amsterdam.

Mülders, R., Parmet, B., Wilke, K. (1999): Hydrological Modelling in the River Rhine Basin. Final Report. BfG - 1215. Bundesanstalt für Gewässerkunde. Koblenz.

Parmet, B., Buishand, T.A., Brandsma, T., Mülders, R. (1999): Design discharge of the large rivers in The Netherlands - towards a new methodology. In: Hydrological Extremes: Understanding, Predicting, Mitigating. Proceedings of IUGG 99 Symposium HS1. L. Gottschalk, J.-C. Olivry, D. Reed and D. Rosbjerg (Eds.). IAHS Publ. No. 255. IAHS Press. Wallingford.

Rajagopalan, B., Lall, U. (1999): A k-nearest-neighbor simulator for daily precipitation and other variables. Water Resour. Res., 35: 3089-3101. American Geophysical Union (AGU). Washington.

Wendling, U. (1995): Berechnung der Gras-Referenzverdunstung mit der FAO Penman-Monteith-Beziehung. In: Wasserwirtschaft 85, H. 12. Friedr. Vieweg & Sohn Verlagsges. mbH. Wiesbaden.

White, W. (2001): Spatio-Temporal Structure of Precipitation in the Moselle Basin with Particular Regard to Flood Events. University of Trier. Trier.

Wójcik, R., Beersma, J.J., 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.