Generator of Rainfall and Discharge Extremes (GRADE)

Part F

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Abstract

The project 'GRADE' is carried out for RWS Waterdienst in Lelystad. GRADE (Generator of Rainfall and Discharge Extremes) is a new methodology to provide an alternative method with better scientific basis for the estimation of the design discharge of the main Dutch rivers compared to the present method based on frequency analysis of extreme values. It consists of a Rainfall Generator and a hydrologic/hydraulic river model. The goal of this project is to research the reliability of the GRADE instrument for the determination of the design discharges for the river Rhine (Rijn) at Lobith and the river Meuse (Maas) at Borgharen.' The project consists of 7 parts; in this report the results of part F of the GRADE project are presented.

First the GRADE Maas model is validated against the measurements and the current design discharge line (werklijn TMR2006). It was noted that for the same return period the design discharge line generated with the GRADE instrument gives lower peak discharges than the current design discharge line (werklijn TMR2006). This is due to an underestimation of the peak values in HBV. The difference between both lines can be reduced by changing the parameter settings in the HBV model. Secondly the difference is reduced by taking into account the ratio between the peak discharge values for hourly and daily mean time steps.

In part F of the GRADE project it was concluded that the largest uncertainties in the GRADE instrument are a result of the choice of the basis set for the Rainfall Generator and the parameters in the HBV model. The 95% uncertainty interval of the GRADE is situated between 2950 and 4700 m^3/s (average 3800 m^3/s). The interval of the traditional method (3250 and 4700 m^3/s, average 3950 m^3/s) is comparable to the GRADE interval. However the confidence interval of the traditional method only refers to the statistical uncertainty, the real uncertainty is still unknown. Important advantages of the GRADE model are 1) the availability of both a design peak value and the corresponding shape of the flood wave, and 2) the possibility to arrive at a further reduction of the uncertainty in the future, whereas in the traditional model no major improvements are expected anymore.

References

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Contents

1 Introduction

1.1 Background

In the Netherlands every 5 years the flood protection situation must be evaluated, which includes the evaluation of the design water levels along the Meuse and Rhine branches. At present this evaluation is based on traditional methods of assessing design discharges using frequency analysis of measured extreme discharges.

The current estimation of the design discharges with a return period of 1250 from statistical analyses of the measured peak discharges faces various problems. The estimation of this 1250-year discharge event from statistical information in a discharge record of about 100 years involves a strong extrapolation, and is therefore hampered by a large uncertainty. Several other drawbacks can be mentioned that will be discussed in this report.

In 1996 Rijkswaterstaat RIZA, KNMI and WL│Delft Hydraulics started to work together on a new methodology to provide a better scientific 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 (in this report named ‘Rainfall Generator’), which generates long simultaneous records of daily rainfall and temperature. The second component consists of hydrological and, if necessary, hydraulic models, which transform the generated rainfall and temperature records into synthetic discharge series. The combination of these two components methodology is indicated as GRADE: **G**enerator of **R**ainfall **A**nd **D**ischarge **E**xtremes. Some advantages of the proposed methodology are that:

- long discharge records can be simulated,
- meteorological conditions and basin characteristics can be taken into account,
- the shape and duration of the flood can be analysed,
- it can potentially assess the effects of future development like climate change and upstream interventions such as retention basins and dike relocations.
  (De Wit & Buishand, 2007).

The first five parts (A – E) of the GRADE project were finalized in 2007 and early 2008. In part A and B the configuration of GRADE Rhine and Meuse in Delft-FEWS was carried out. In this report the resulting instruments are referred to by the Dutch names of the two rivers: GRADE Rijn en GRADE Maas. In part C the shape and duration of extreme flood waves were analysed. Part D and E analyse and describe the quantification of the model uncertainties.

In this report part F is discussed, which brings together the present knowledge on the uncertainties. In order to use the new instrument to determine the design discharges on the Rhine and Meuse rivers the overall quantity of the reliability has to be known. For this purpose in this report first the results of the GRADE Maas instrument are validated against the measurements. Secondly the reliability of the GRADE instrument to determine the design discharge for the river Meuse at Borgharen is examined.

1.2 Problem description

The goal of this research consists of two parts:

1 **Validation of the GRADE Maas instrument**

Before the GRADE instrument can be used, sufficient confidence in the system has to be obtained. To find out if GRADE is a reliable system a check was made if the GRADE results are consistent with the measurements and the current design discharge line ('werklijn TMR2006').

2 **Determination of the overall performance of the GRADE Maas instrument.**

To determine the overall performance, the uncertainties in the GRADE instrument are compared with the uncertainties of the traditional method. When GRADE performs better than the traditional method, there is a better basis to take a decision to apply GRADE in projects like WTI. In the WTI project, GRADE can be used to determine the design discharge and the corresponding shape and duration of the flood wave.

1.3 Project approach

In this paragraph first a discussion is presented on the approach that should be followed to validate the GRADE instrument. Secondly the approach is given that was used to determine the overall performance of GRADE.

1 Differences can be found between the current design discharge line ('werklijn' TMR2006) for the river Meuse and the GRADE design discharge line. Two possible reasons for this difference will be studied in Chapter 2:
   a <u>Parameters setting in the HBV model.</u> In part E of the project, it was found that for the river Meuse, the current calibration of the hydrological model (HBV) underestimates the yearly peaks discharges. To solve this problem, an ensemble of new parameter sets was generated. In this study 5 new parameter sets are selected out of this ensemble. These 5 parameter sets are validated using measured historical flood events.
   b <u>Ratio of the hourly and daily mean of the peak discharge.</u> The GRADE instrument uses mean daily time steps. This is in contrast with the traditional method, which is based on measured yearly maxima of hourly discharge series.
2 The goal of the second part of this study is to determine the overall performance of the GRADE model. In part D and E of the GRADE project a study was made of the following uncertainties:
   a sampling uncertainty
   b variations in the basis set of observations
   c errors in the resampling algorithm
   d errors in the parameter choice of the hydrological model

Paragraph 3.1 sums all uncertainties in the GRADE instrument, which are already known. Paragraph 3.2 describes additional research, which has been carries out in part F in order to determine the combined hydrological and meteorological uncertainties.

To make a comparison between GRADE and the traditional method, in chapter 3.3 the uncertainties of the traditional method are discussed.

This study has been carried out for RWS Waterdienst. FEWS-NL Maas will be used by Rijkswaterstaat for flood forecasting along the Dutch part of the Meuse. However, discharge and precipitation data from upstream countries are essential for the forecast. MET-Sethy kindly provided the historical precipitation and discharge data for the Walloon part of the Meuse basin. Meteorological data has also been provided and/or collected by KNMI and the Deutscher Wetter Dienst (DWD).

2 Validation GRADE instrument

In Figure 2.1 the design discharge line ('werklijn') for the river Meuse, generated with the GRADE instrument, is compared with the current design discharge line TMR2006. The figure shows that the current line is situated higher than the GRADE line. Two possible reasons for this difference will be studied in this paragraph.

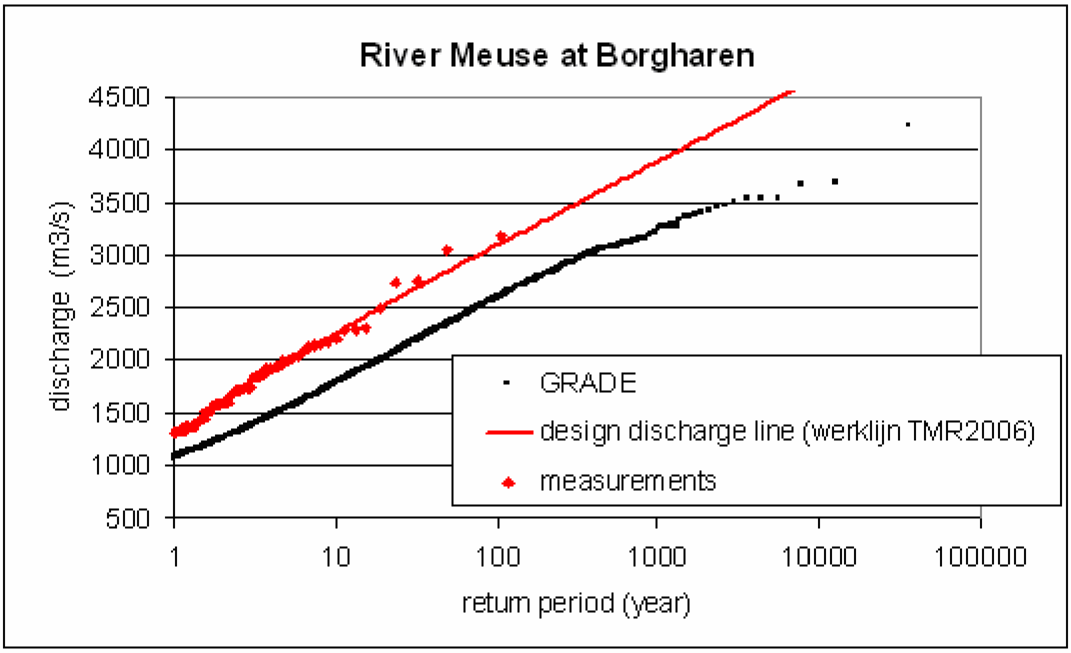

Figure 2.1 Design discharge lines for the river Meuse at Borgharen. The black line is generated with the current GRADE instrument (using Van Deursen parameters). The red line is the design discharge line as used in the TMR2006

One reason is the choice of the parameters in the HBV model in GRADE. In part E, it was found that for the river Meuse, the current calibration of the hydrological model (HBV) underestimates the yearly maximum peak discharge. The current calibration as carried out by Van Deursen (2004) gives a good fit for lower and 'middle-low' discharges, but not for high (peak) values as it was never intended to be used for extreme discharges. In part E of the GRADE project new parameter sets have been selected and in paragraph 2.1 these new parameter sets are validated using historical events.
A second reason is that GRADE uses mean daily time steps, whereas the traditional method uses hourly discharge data. In paragraph 2.2 a correction factor between hourly and mean daily time steps is determined. In the last paragraph the design discharge line for the new parameter sets is compared with the traditional line ('werklijn TMR 2006').

In the paragraph 2.3 the findings of the first two paragraphs are used to make a new comparison between the GRADE discharge line and the current design discharge line TMR2006.

2.1 Selection and validation new parameter sets

Using a GLUE-type (Generalized Likelihood Uncertainty Estimation) analysis a new ensemble of 500 parameter sets has been selected. In part E it was found that all selected parameter sets describe the yearly maximum peaks better than the current parameter set.

2.1.1 Selection limited number of parameter sets

The GLUE analysis in part E selected 500 parameter sets. As validating all these parameter sets is too time consuming, 5 parameter sets out of the total group of 500 sets were selected. For the selection of these parameter sets, the following steps were used:

1 Select five flood frequency curves, describing the mean (50%), the upper (95%), lower (5%) and the quadrants (25% and 75%) percentiles at Borgharen. The percentiles were determined at a return period of 100 years.
2 Select the five corresponding parameter sets.

The 5 parameter sets are given in Appendix A. The corresponding flood frequency lines are plotted in Figure 2.2.

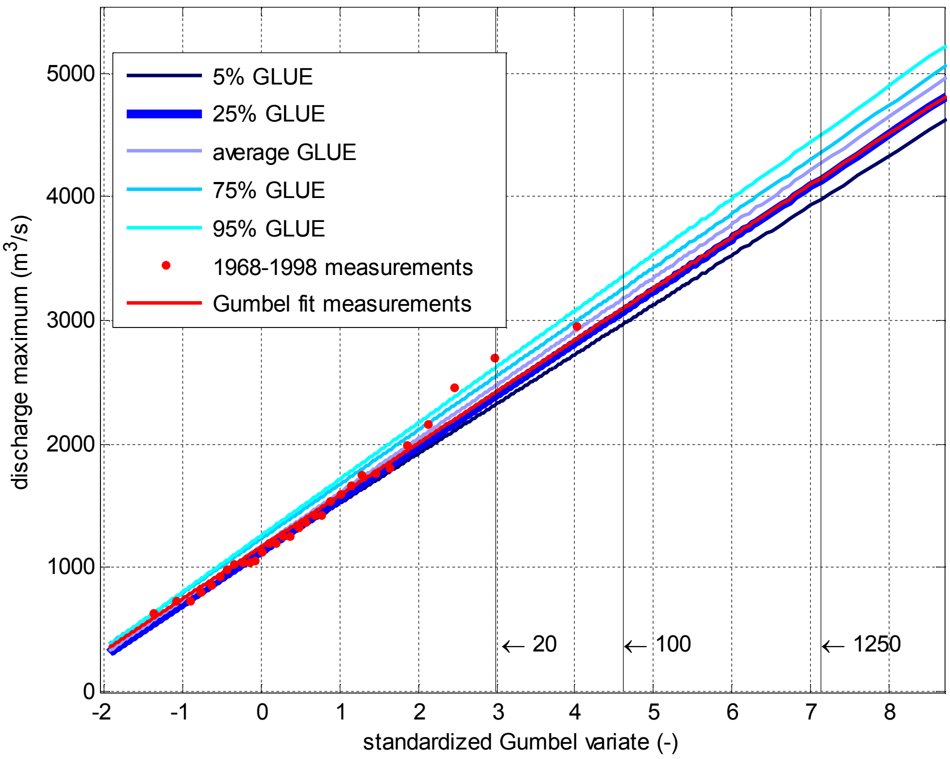

Figure 2.2 Selected flood frequency lines (blue lines). The red dots show the measurements. The red line shows the resulting extreme value distribution using the measurements

2.1.2 Validation historical flood events

The GLUE analysis has been carried out for the period 1968-1998. In order to validate the 5 parameter sets from the GLUE-type analysis eight historical flood events between 1998 and 2008 are investigated:

- December 1993;
- January 1995;
- October-November 1998;
- December 1999;
- January-April 2001;
- February 2002;
- December 2002 / January 2003;
- January 2004.

A hindcast was made of the eight historical flood events mentioned above using the hourly HBV-96 model (as used in the operational system FEWS-NL and based on the parameter set as determined by Van Deursen (2004)). A comparison between the simulated hydrographs and the measurements of the eight historical events gives an impression of the performance of the HBV model in flood situations (paragraph 2.2).

It should be mentioned that the five selected parameter sets were originally derived with a daily model. Weerts (2007) mentions that in case these parameter sets are used in the hourly HBV model the timing of the peaks is incorrect and an adjustment must be made to the MAXBAS parameter in the hourly model to come to better results. The MAXBAS values of the hourly model are given in Table 2.1. Once these changes in the MAXBAS parameter are made, it is possible to use the hourly model with the other parameters equal to those used in the daily model and arrive at satisfactory simulation results.

Table 2.1 HBV-96 calibration values for MAXBAS (day) for the daily and hourly model

model/basin	4	5	8	9	11	12	13	rest
daily MAXBAS	1.2	2.5	2	2.2	1.4	1.1	1.1	1.0
hourly MAXBAS	0.2	1.5	1	1.2	0.4	0.1	0.1	0.0

The Figure 2.3 to Figure 2.10 give the results of the hindcast for the gauging station Borgharen-Dorp for the chosen flood periods. In these figures ‘Measurement’ is the hourly measured discharge at Borgharen, ‘original’ is the value obtained from the original hourly HBV model which was calibrated by van Deursen (2004) and ‘5%’ is the value from the hourly model using the 5% lower parameter set as determined by the GLUE analysis, etc.

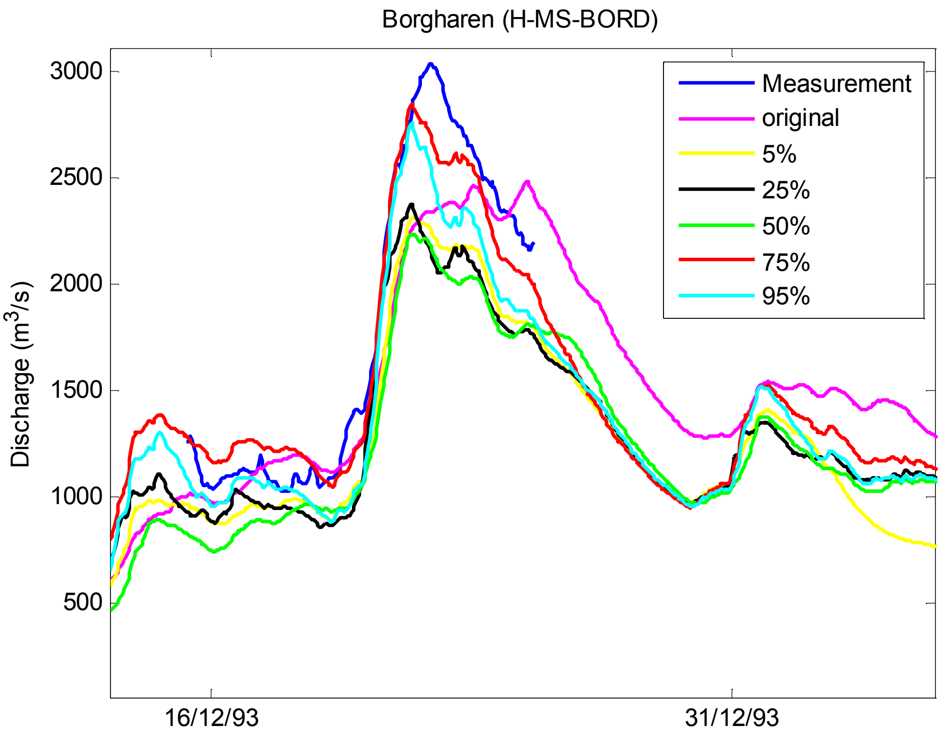

Figure 2.3 Flood peak of December 1993 at Borgharen-Dorp: measured discharge (thick black line) together with HBV simulations for different parameter sets. The original set (as calibrated by van Deursen) is given by the thick pink line

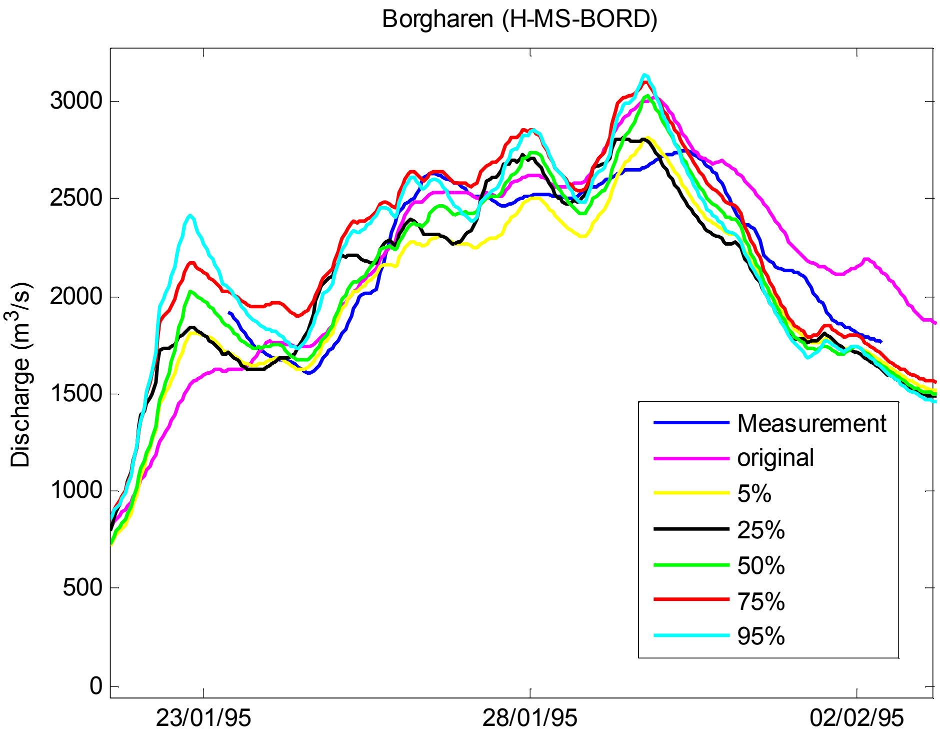

Figure 2.4 Flood peak of January1995 at Borgharen-Dorp: measured discharge (thick black line) together with HBV simulations for different parameter sets. The original set (as calibrated by van Deursen) is given by the thick pink line

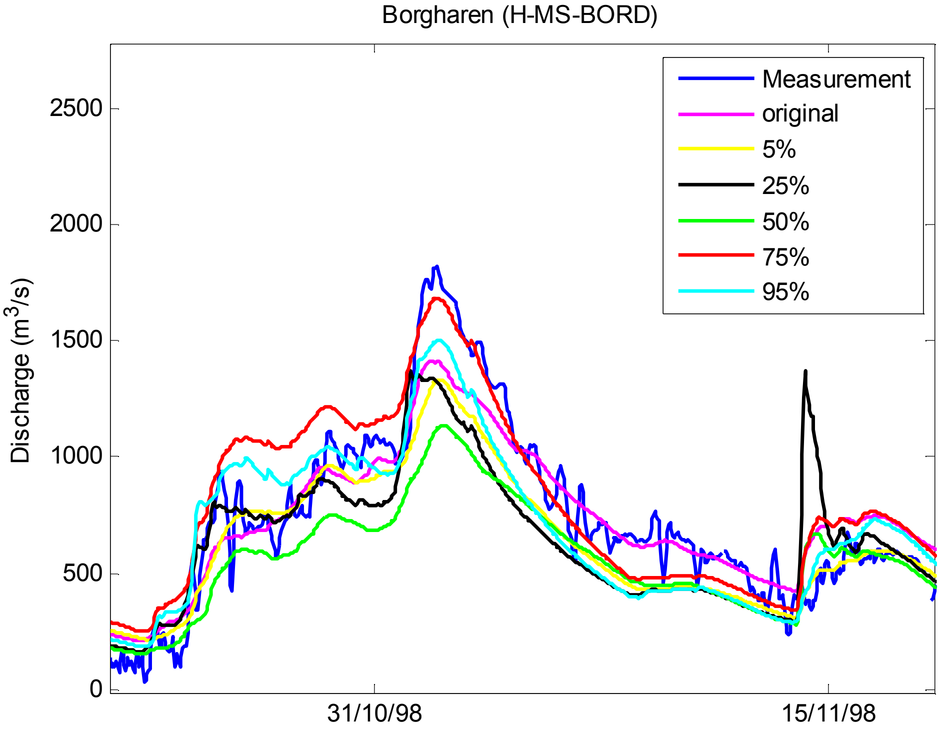

Figure 2.5 *Flood peak of October-November 1998 at Borgharen-Dorp: measured discharge (thick black line) together with HBV simulations for different parameter sets. The original set (as calibrated by van Deursen) is given by the thick pink line*

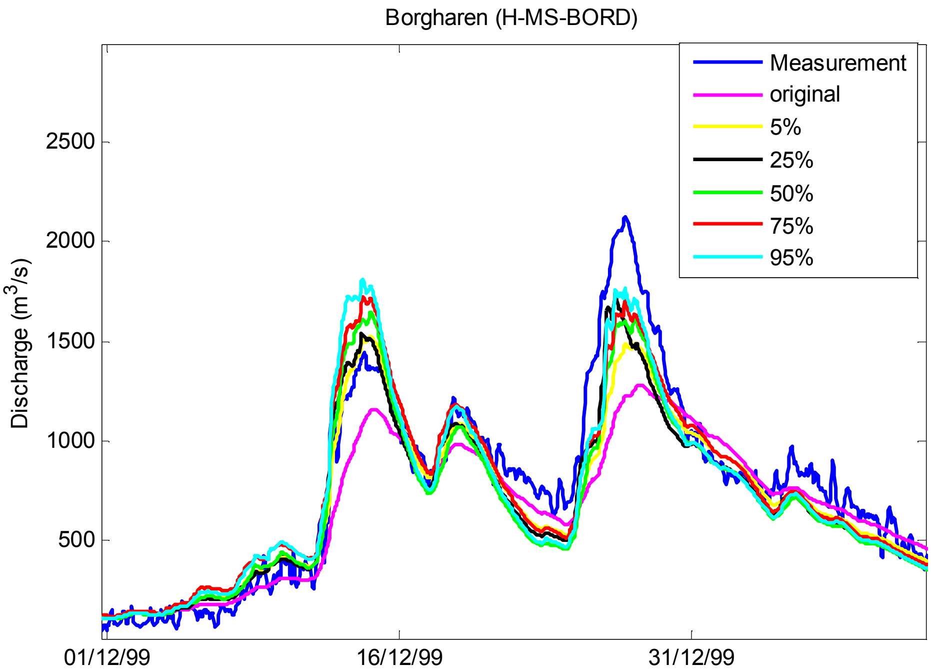

Figure 2.6 *Flood peak of December 1999 at Borgharen-Dorp: measured discharge (thick black line) together with HBV simulations for different parameter sets. The original set (as calibrated by van Deursen) is given by the thick pink line*

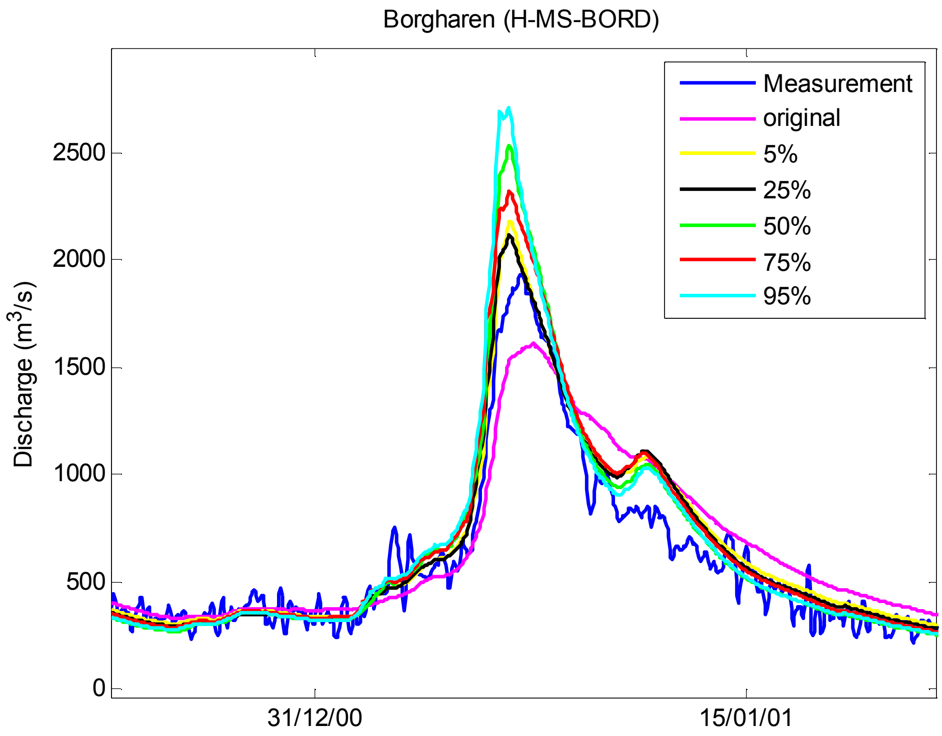

Figure 2.7 Flood peak of January to April 2001 at Borgharen-Dorp: measured discharge (thick black line) together with HBV simulations for different parameter sets. The original set (as calibrated by van Deursen) is given by the thick pink line

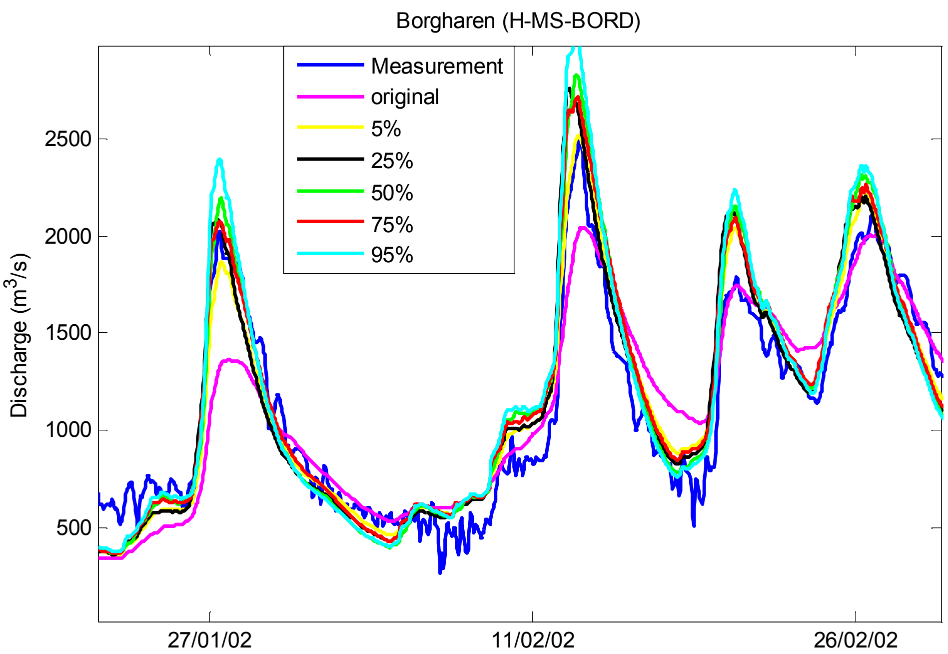

Figure 2.8 Flood peak of February 2002 at Borgharen-Dorp: measured discharge (thick black line) together with HBV simulations for different parameter sets. The original set (as calibrated by van Deursen) is given by the thick pink line

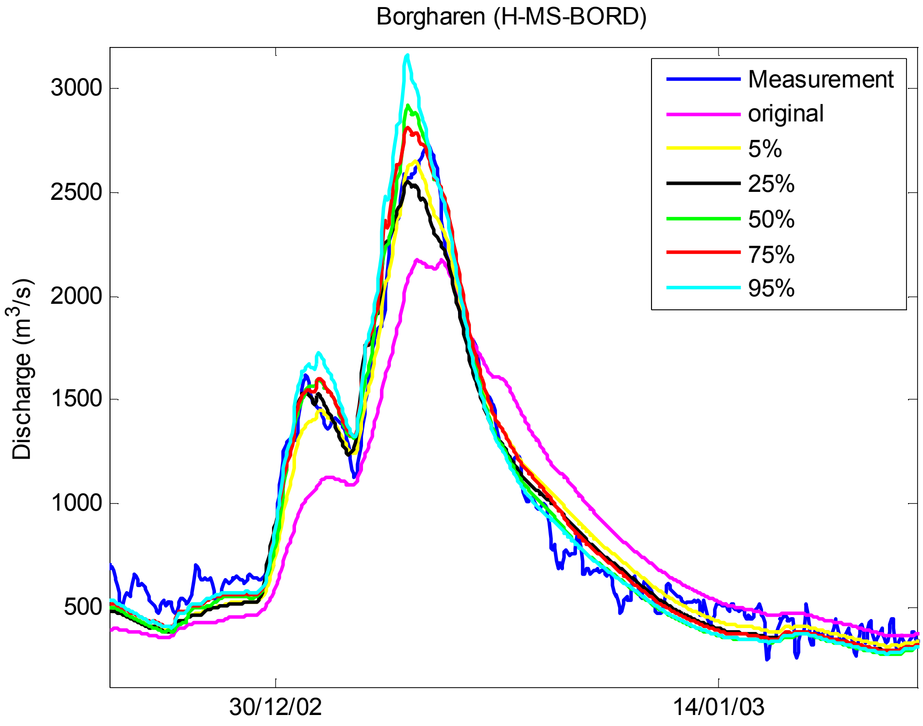

Figure 2.9 *Flood peak of December 2002 at Borgharen-Dorp: measured discharge (thick black line) together with HBV simulations for different parameter sets. The original set (as calibrated by van Deursen) is given by the thick pink line*

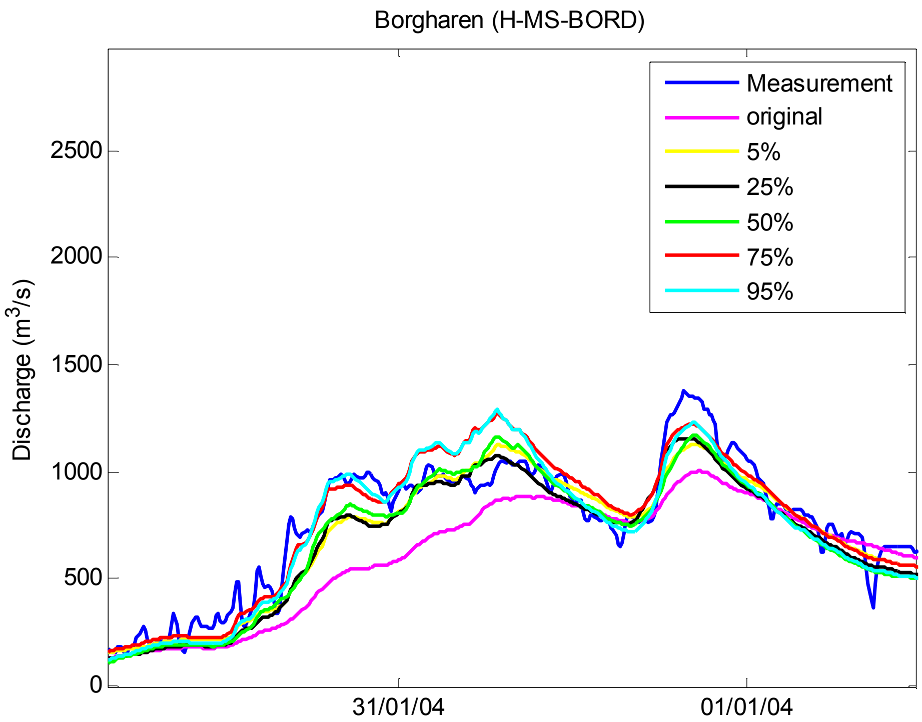

Figure 2.10 *Flood peak of January 2004 at Borgharen-Dorp: measured discharge (thick black line) together with HBV simulations for different parameter sets. The original set (as calibrated by van Deursen) is given by the thick pink line*

Appendix B gives the simulated and measured discharges of the 5 parameter sets for the period October 1998 to June 2005. Appendix C gives the results of the HBV simulation for some upstream locations for a selection of the historical events.

Besides plotting the results, the performance of the model is also quantified by calculating the Nash-Sutcliff efficiency R^2, which is an indication of the overall performance of the model and is given by the following formula:

$$R^2 = \pi(Y \mid \theta) = 1 - \frac{\sum_{i=1}^{n}(Q_m - Q_o)^2}{\sum_{i=1}^{n}(Q_o - \overline{Q_o})^2}$$

where

Q discharge (m^3/s)
i the time step
n the total number of time steps
Q_0 observed discharge (m^3/s)
Q_m modelled discharge (m^3/s)

The Nash-Sutcliffe efficiency coefficient R^2 is situated between minus infinity and 1, the perfect score being 1.

Table 2.2 to Table 2.5 give the Nash-Sutcliffe efficiencies for all tributaries for the some of the peak periods. Note that the period over which the coefficients are determined is rather short.

Table 2.6 gives the Nash-Sutcliff coefficient for different peak periods for Borgharen. In this Table, per peak period, the best score (closest to 1) is marked bold.

Table 2.2 Nash-Sutcliffe coefficient for all tributaries of the Meuse (period 16/12/1993 to 26/12/1993)

	Borg-haren	Chaud-fontaine	Chooz	Gendron	Martinrive	Membre pont	Salzinne	Tabreux	Treignes
original	0.84	0.76	0.85	0.50	0.82	-1.07	-1.32	0.89	-0.37
set 5%	0.71	0.54	0.54	-0.01	0.96	0.02	-3.66	0.93	0.40
set 25%	0.68	0.75	-0.74	0.76	-0.88	-2.54	0.52	0.92	0.40
set 50%	0.58	0.87	0.16	0.83	-0.79	-1.77	-3.33	0.96	0.42
set 75%	0.95	0.86	0.59	0.77	0.96	-0.55	0.68	0.95	0.42
set 95%	0.86	0.87	0.04	0.79	-0.88	0.05	0.59	0.92	0.41

Table 2.3 Nash-Sutcliffe coefficient for all tributaries of the Meuse (period 25/01/1995 to 04/02/1995)

	Borg-haren	Chaud-fontaine	Chooz	Gendron	Martinrive	Membre pont	Salzinne	Tabreux	Treignes
original	0.78	0.49	0.78	0.74	0.78	-2.21	-1.33	0.80	-0.47
set 5%	0.78	0.37	0.57	0.50	0.82	-0.99	-5.12	0.93	0.24
set 25%	0.69	0.49	-0.50	0.89	0.36	-2.87	-2.85	0.92	0.26
set 50%	0.83	0.61	0.44	0.91	0.46	-1.95	-0.39	0.94	0.21
set 75%	0.60	0.49	0.57	0.89	0.81	-1.50	-0.60	0.94	0.19
set 95%	0.64	0.61	0.27	0.90	0.36	-0.90	-2.58	0.92	0.23

Table 2.4 Nash-Sutcliffe coefficient for all tributaries of the Meuse (period 22-01-2001 to 30-03-2001)

	Borg-haren	Chaud-fontaine	Chooz	Gendron	Martinrive	Membre pont	Salzinne	Tabreux	Treignes
original	0.84	0.88	0.70	0.76	0.82	0.14	0.59	0.75	0.65
set 5%	0.91	0.88	0.69	0.33	0.77	0.44	0.76	0.64	0.71
set 25%	0.87	0.89	0.62	0.66	0.48	0.33	0.34	0.64	0.73
set 50%	0.85	0.91	0.55	0.58	0.53	0.44	0.82	0.72	0.64
set 75%	0.88	0.88	0.69	0.63	0.76	0.42	0.80	0.69	0.59
set 95%	0.82	0.91	0.62	0.59	0.48	0.48	0.46	0.64	0.71

Table 2.5 Nash-Sutcliffe coefficient for all tributaries of the Meuse (period 15-12-2002 to 29/01/2003)

	Borg-haren	Chaud-fontaine	Chooz	Gendron	Martinrive	Membre pont	Salzinne	Tabreux	Treignes
original	0.86	0.69	0.44	0.86	-0.03	-0.40	-1.20	0.87	0.00
set 5%	0.97	0.66	0.71	0.79	-0.84	0.53	-0.13	0.62	0.75
set 25%	0.97	0.62	0.48	0.79	-1.29	0.22	0.30	0.45	0.77
set 50%	0.97	0.54	0.87	0.78	-1.19	0.48	0.43	0.64	0.73
set 75%	0.97	0.66	0.87	0.86	-0.82	0.49	0.76	0.57	0.72
set 95%	0.96	0.54	0.83	0.76	-1.29	0.52	0.39	0.45	0.75

Table 2.6 Nash-Sutcliffe coefficient for all tributaries of the Meuse and the Nash-Sutcliffe coefficient for several discharge peaks for Borgharen

start period	16/12/93	25/1/95	20/10/98	1/12/99	15/12/00	22/1/02	31/10/02	15/12/02	5/1/04	mean
end period	26/12/93	4/2/95	16/10/98	15/1/00	15/4/01	30/3/02	30/11/02	29/1/03	31/1/04	
original	0.84	0.78	0.89	0.76	0.83	0.84	0.71	0.86	0.76	0.81
set 5%	0.71	0.78	0.78	0.86	**0.89**	**0.91**	0.81	**0.97**	0.92	**0.85**
set 25%	0.68	0.69	0.70	0.89	0.88	0.87	0.86	**0.97**	0.92	0.83
set 50%	0.58	**0.83**	**0.91**	0.86	0.84	0.85	0.89	**0.97**	0.92	**0.85**
set 75%	**0.95**	0.60	0.75	**0.88**	0.86	0.88	0.79	**0.97**	**0.94**	**0.85**
set 95%	0.86	0.64	0.76	0.87	0.80	0.82	**0.90**	0.96	0.93	0.84

Comparing the results of the hindcast and the Nash-Sutcliff coefficient the following conclusions can be draw:

- Generally, the discharges of the models using the GLUE parameter sets (5%, 25%, 50%, 75% and 95%) give a better approximation of the peaks in Borgharen than the original parameter set as determined by Van Deursen (2004). This is not surprising as the Van Deursen set was calibrated for the ‘low’ and ‘middle low’ value, but was not intended to be used for high (peak) discharges. In high discharge situations the models using the GLUE parameter sets reacts faster than the Van Deursen model. Also the Nash-Sutcliff coefficient is for most sets higher than the original set.

- Generally, the 75% line gives the best approximation of the measured discharges at Borgharen. This further illustrated by the Nash-Sutcliff coefficient (with the exception of the peak in January 1995).

- The hindcast of the different subbasin (Appendix B) show that the selected parameter sets perform better than the original set for the subbasins Treignes, Chaufontaine and Gendron. However the results per period vary substantially for the subbasins Salzinne, Martinrive, Tabreux and Chooz. In this case for some flood events the new parameters sets perform better and for other events worse than the original set. For subbasin Membre Pont the simulation gives a bad approximation as well for the new as the original parameter set, which may well be caused by a too low area precipitation. The same findings can also be seen in the tables with the Nash-Sutcliff coefficients.

- For low water periods and for low peak values all parameters sets (including the Van Deursen set) overestimate the discharge.

As expected for the period 1999 to 2005 the 95% (turquoise) line gives almost everywhere the highest results. However it is noticeable that for historical flood events December 1993 and October-November 1998 the 95% line (turquoise) line is lower than the 75% line. A possible explanation could be the use of different rainfall series. The 75% and 95% lines were derived from the GLUE analysis. For this analysis daily rainfall series were used. This is in contrast to FEWS-NL, where hourly TTRR, MSW and KNMI-SYNOP data were used.

In general this hindcast shows a good performance of the new selected parameter sets and therefore it is advisable to use one of the new parameter sets in the HBV model of the GRADE instrument. In the remaining part of this study use is made of the new parameter sets.

2.2 Ratio of hourly and daily mean of the peak discharges

2.2.1 Comparing daily and hourly discharge.

The GRADE method makes use of simulated discharge series on a daily time basis. However the current design discharge line ('werklijn TMR2006') is calculated from the hourly means of the peak discharges[1]. As discharge peaks are relatively short on the Meuse at Borgharen daily mean discharges will give a significantly lower peak discharge then calculated from hourly mean values (Figure 2.11). Therefore a relation must be found between the daily and the hourly mean of peak discharges.
Earlier studies (WL | Delft Hydraulics, 2004a) show that the difference can be corrected by adding 70 m^3/s to the daily mean discharge. This was calculated using discharge data from 1973 to 1993. Such a correction by addition only implicates that the shape of the discharge peak does not change with increasing discharge. This is not physically likely and a recalculation was done using recent data.

1. The base set consists of measured maxima discharge series for the years 1911 to 2003 at Borgharen. The data from 1911 to 1973 is based on the 8 hour measurement values (i.e. daily discharges measured at 8:00). The data after 1973 is based on hourly discharge values. All discharge maxima are transformed into hourly discharges.

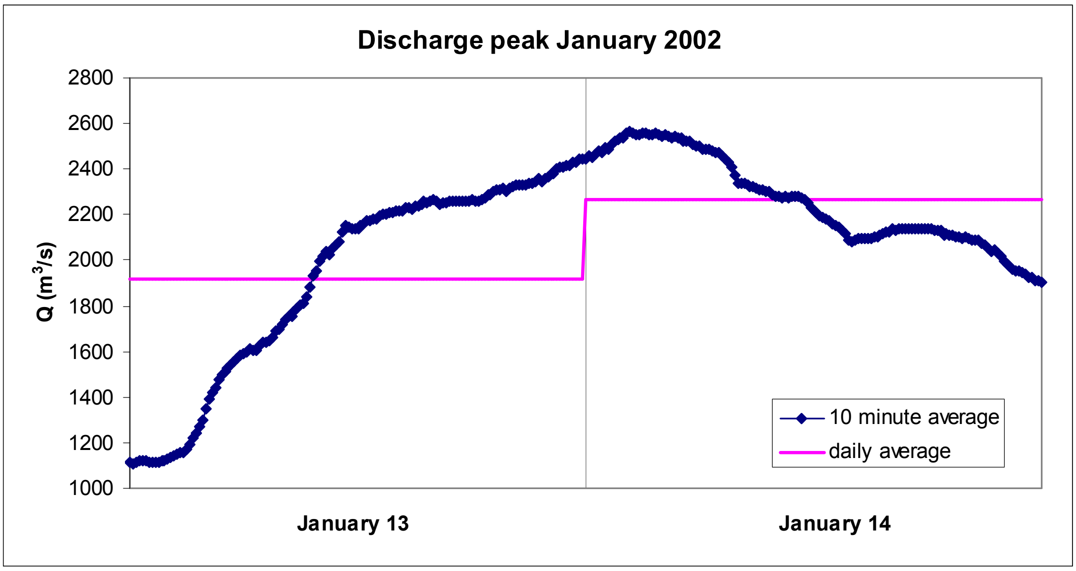

Figure 2.11 10 minute and daily average discharge at Sint Pieter over two days in January 2002

2.2.2 Recalculation using data from 1993 to 2008

Discharge data from Borgharen is available as ten minute averaged data from 24-10-1996 onwards. This data was supplemented with discharge data of the two major discharge events in 1993 and 1995. From these data hourly and daily mean discharges were calculated[2]. Over this period 21 isolated peaks (local maxima separated by at least 8 days) above 1200 m^3/s where identified (See Figure 2.12).

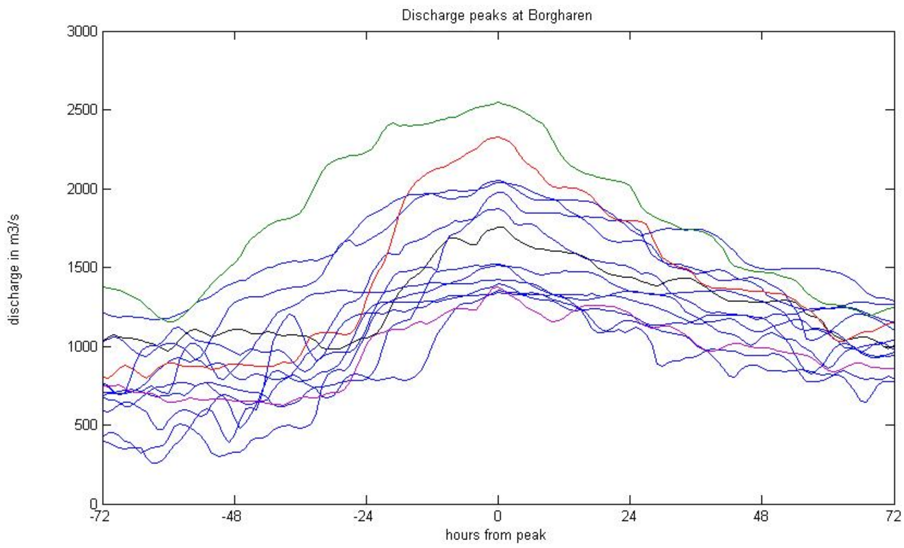

Figure 2.12 A number of discharge peaks at Borgharen displayed from 3 days before until 3 days after the peak

The maximum hourly discharge (Q_{hour}) is always higher then the daily averaged maximum (Q_{day}), but an exact relation could not be found. Three linear relations were

2. *Recalculation of stage discharge (Qh) relationships over the years was not applied. These would have to be applied to both mean values and would therefore not change the ratio of these peak values and would have limited effect on any offset between the values*

tested based between the Q_{hour} and Q_{day} set. This resulted in the following alternative equations and corresponding coefficients:

$Q_{hour} = a \cdot Q_{day} + b$	a = 1.01 ± 0,04,	b= 80 ± 65
$Q_{hour} = Q_{day} + b$	b = 92 ± 14	
$Q_{hour} = a \cdot Q_{day}$	a = 1,05 ± 0,01	

Using these three equations a daily averaged peak discharge of 4000 m^3/s would correspond with a corrected value of respectively 4120, 4092 and 4200 m^3/s.
The first of these relations has the best fit to the data, although the difference is small. However it is physically more plausible that the discharge peak will gradually change shape as discharge increases. This is best accomplished by the first relation (fit is shown in *Figure 2.13*) and therefore this relation was adopted for the conversion.

Older discharge peaks from 1973 to 1993 could also have been taken into account using data from individual measurement campaigns. However it is unlikely that data over more years would give a different insight, but it could strengthen the present analysis and result in a more reliable probability distribution.

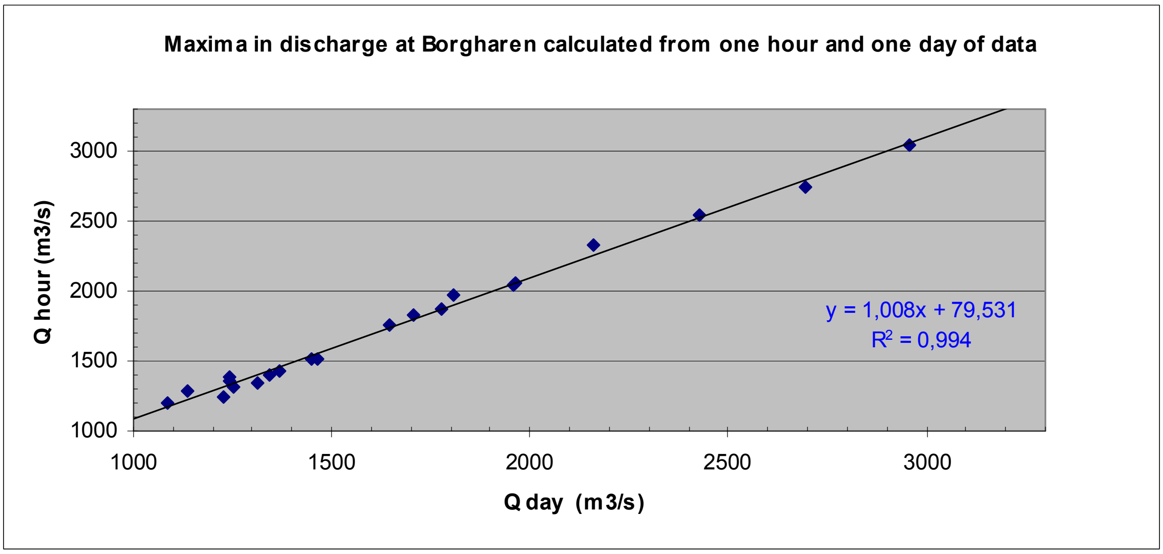

Figure 2.13 Comparison of hourly mean discharge and daily mean discharge at Borgharen

2.2.3 Conclusion

The most reliable way to calculate hourly peak discharges from a daily averaged discharge peak at Borgharen is to multiply by 1.01 and add 80 m^3/s. This transformation is nearly identical to the correction by 70 m^3/s in the “Boertien II” reports. The ‘old’ 70 m^3/s is within the 95% probability interval of the newly calculated correction for discharge value of the order of 4000 m^3/s.

2.3 Comparison design discharge line

In this paragraph the findings of the first two paragraphs are used to make a new comparison between the GRADE discharge line and the current design discharge line

TMR2006. This is done by applying new parameter sets in the HBV model and making a correction for the hourly and daily mean discharge.

GRADE produces a yearly peak discharge series of 3000 years for the Meuse river at Borgharen. These yearly discharge series is corrected, using the daily-hourly ratio (as described in paragraph 2.2). Subsequently the discharge is plotted against the accompanying return period. using the following plotting position formula:

$$P = \frac{r - c}{N + 1 - 2c}$$

with:

P = exceedance probability,
c = plotting constant (here c = 0.44),
N = number of time units (years),
1 = ranking number (1 for highest value, 2 for highest but one, etc)

Figure 2.14 gives the GRADE results (blue dots), using the HBV model with the five new parameter sets and the daily-hourly correction. The GRADE results are compared with the current design discharge line as used in TMR2006 (red line).
The figure shows that in general, the results of all the five GRADE models are close to the current design discharge line. The two adjustments to the GRADE model have improved the results.

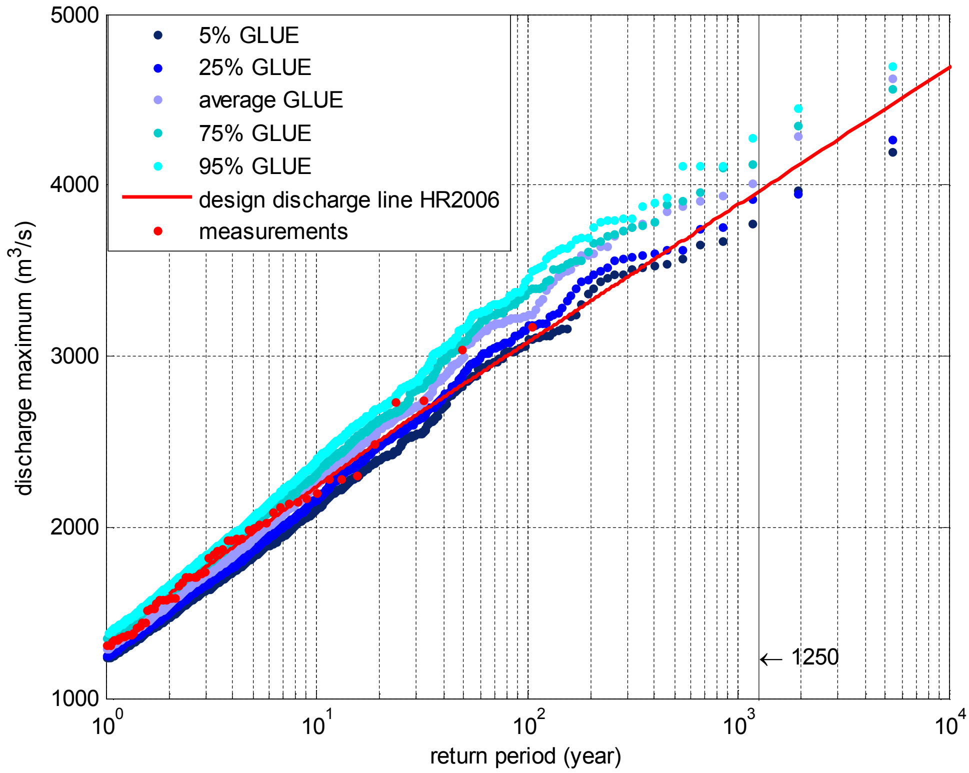

Figure 2.14 Design discharge lines determined with the GRADE instrument (dots in five different hues), using the five selected parameter sets. The measurements are shown as red dots. The red line gives the current design discharge line TMR2006

3 Uncertainties

In order to use the GRADE instrument to determine the design discharges the overall quantity of reliability has to be known. In Part D and E an effort was made to quantify the model uncertainties. In Paragraph 3.1 uncertainties in the GRADE instrument are described. Paragraph 3.2 describes additional research in order to determine the combined hydrological and meteorological uncertainties. In order to make a comparison between GRADE and the traditional method, in paragraph 3.3 the uncertainties of the traditional method are discussed. In the last paragraph of this chapter the uncertainties of the GRADE model are compared with the uncertainties of the traditional method.

3.1 Uncertainties in the GRADE instrument

The GRADE instrument of the Meuse involves a Rainfall Generator and the hydrological HBV model. In both parts there are uncertainties:

- The Rainfall Generator generates long synthetic rainfall series (20.000 years) based on a relatively short historical series (basis set). Uncertainties can be found in the following parts:
  - The resample algorithm to generate synthetic time series
  - The basis set of the rainfall observations, and whether this set is representative for the current climate
  - Length of the synthetic time series (sampling uncertainty).

- The hydrological model translates the synthetic rainfall to a daily mean discharge. Uncertainties can be found in the following parts:
  - Model concept (simplification of the reality)
  - The behaviour of the hydrological model in extreme situations
  - Parameter choices.

In part D, E and F of the GRADE project uncertainty in the model instrument is quantified for the river Meuse at Borgharen. The results are as follows:

- Variation, caused by an adapted resample algorithm has no significant effect.
- A limited length of the time series increases the uncertainty (sampling uncertainty). The sampling uncertainty (RMSE) of the 1/1250 discharge and a 20.000 year time series is approximately 3%
- The largest uncertainties are found in the basis set and the parameter choices. In paragraph 3.2 the combined uncertainty of these two elements is determined.

3.2 Combined hydrological and meteorological uncertainty

In order to give an indication of the uncertainty of the GRADE model, in this chapter the combined hydrological and meteorological uncertainty is determined. For this purpose 20.000 years discharges were simulated, using the hydrological model (HBV) with different parameter sets and meteorological input sets.

In the current analysis a total 40 model simulations were made: 5 different parameters sets and 8 meteorological input sets. Paragraph 2.1.1 describes the selection of the 5 parameters sets. The 8 meteorological input sets are equal to the sets as used in part D. However in part D, 13 metrological input time series sets were investigated. These input sets were derived using different base sets and different sample algorithms. In part D, it was concluded that the variation, as a result of the modified resampling algorithm has no significant effect. So, in the current analysis only the 8 time series sets based on different base sets were calculated. Information about the generation of the input sets is explained in paragraph 3.2.1

3.2.1 Background meteorological uncertainty

In order to generate the 20,000 year synthetic time series of precipitation, temperature and PET for the Meuse river basin, the measurements in the period of 1930-1998 were used for resampling. Details on the resampling method can be found in various publications on this subject by KNMI. A full description of the simulations is given in Leander & Buishand (2007).
The sensitivity of the extreme discharge statistics of the Meuse river to changes in the set of historical observations was investigated. Specifically, the effect of exclusion of two particularly wet years was analysed. Four cases can be distinguished:

- Case 1, including both the years 1984 and 1995;
- Case 2, including year 1995, but without 1984;
- Case 3, including year 1984, but without 1995;
- Case 4, including neither 1984 nor 1995.

A further selection was made, based on two characteristics of the subsets:

‘P’ value = mean daily winter amount of precipitation
‘f’ value = mean fraction of winter days with 10 mm of precipitation or more.

From each case, two subsets (of each 35 years) were selected: one with low values of P and f (denoted as ’**a**’) and one with high values of P and f (denoted as ’**b**’). For each subset a time series of 20,000 years of precipitation, temperature and PET was generated.

Altogether 8 time series out of an original set of 13 time series from part D of the GRADE project have been used in the uncertainty analysis. The settings used to create each of the 8 time series are listed in Table 3.1. The names of the timeseries (1a,1b, etc.) are identical to the names used in part D.

Table 3.1 Characteristics of the 8 time series used in the uncertainty analysis

Time series	Low f & P	High f & P	High f & P, no repeat	Both 1984 & 1995	including only 1995	including only 1984	Neither 1984 nor 1995
1a	x			x			
1b		x		x			
2a	x				x		
2b		x			x		
3a	x					x	
3b		x				x	
4a	x						x
4b		x					x

3.2.2 Results of the 40 HBV simulations of each 20.000 years

Figure 3.1 gives the yearly maxima of the 40 HBV simulations (5 parameters sets and 8 meteorological input sets) of each 20.000 year. Table 3.2 shows the discharge with a return period of 1250 year.

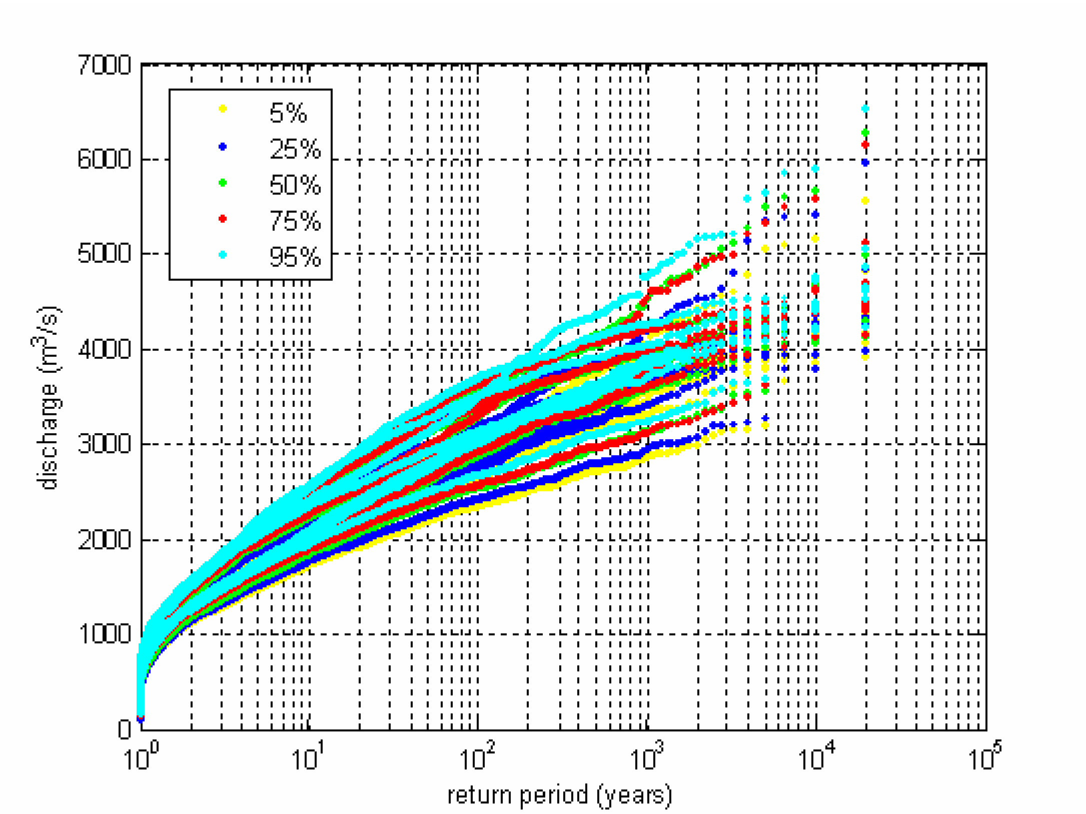

Figure 3.1 Discharge exceedance probabilities for each of the 40 combinations of time series and parameter sets

Table 3.2 Design discharge (T=1250 years)

Series	set 5%	set 25%	set 50%	set 75%	set 95%
1a	3578	3671	3780	3827	3848
1b	3710	3750	3988	4024	4059
2a	3598	3684	3840	3891	3922
2b	3965	4025	4224	4220	4268
3a	2888	2991	3143	3182	3281
3b	3368	3467	3611	3659	3738
4a	3560	3650	3833	3869	3925
4b	4195	4294	4637	4618	4888

3.2.3 Determination standard deviation of the input sets and the parameter values

For the determination of the combined standard deviation of the input sets and the parameter sets the values of Table 3.2 (design discharges) were used. The standard deviation is a measure of the hydrological uncertainty in the 1/1250 discharge. The combined uncertainty of the input sets and the parameter sets can be expressed as:

$$\sigma^2_{combined} = \sigma^2_{input} + \sigma^2_{parameters} \tag{1}$$

Per parameter set, 8 simulations are made using different input sets. The standard deviation of the input (σ_{input}) was determined using of the design discharge of the 8 accompanying input sets. The standard deviation was calculated for the 5 parameter sets. The average value of σ_{input} is 417 m^3/s.

The determination of the standard deviation of the parameters ($\sigma_{parameters}$) set is more difficult. Because the parameters sets are not randomly drawn, it is not allowed to derive the standard deviation directly (as was done for the σ_{input}). In the indirect method, first the design discharges were plotted against their percentages (Figure 3.2). Secondly, a normal distribution was fitted through these dots. For the 8 input sets the standard deviation was derived using the fitted function. The average value of $\sigma_{parameters}$ is 152 m^3/s.

The combined standard deviation ($\sigma_{combined}$) of the input set (σ_{input}) and the parameter sets ($\sigma_{parameters}$) can be calculated using formula (1). Applying the formula results in a combined standard deviation of 444 m^3/s. The average 1/1250 discharge of all combinations is 3817 m^3/s. As the 95% confidence interval equals 1.96 * $\sigma_{combined}$ (1.96 * 444 m^3/s = 870 m^3/s), time series with normative discharges between 2947 and 4687 m^3/s fall within this confidence interval (rounded to resp. 2950 and 4700 m^3/s).

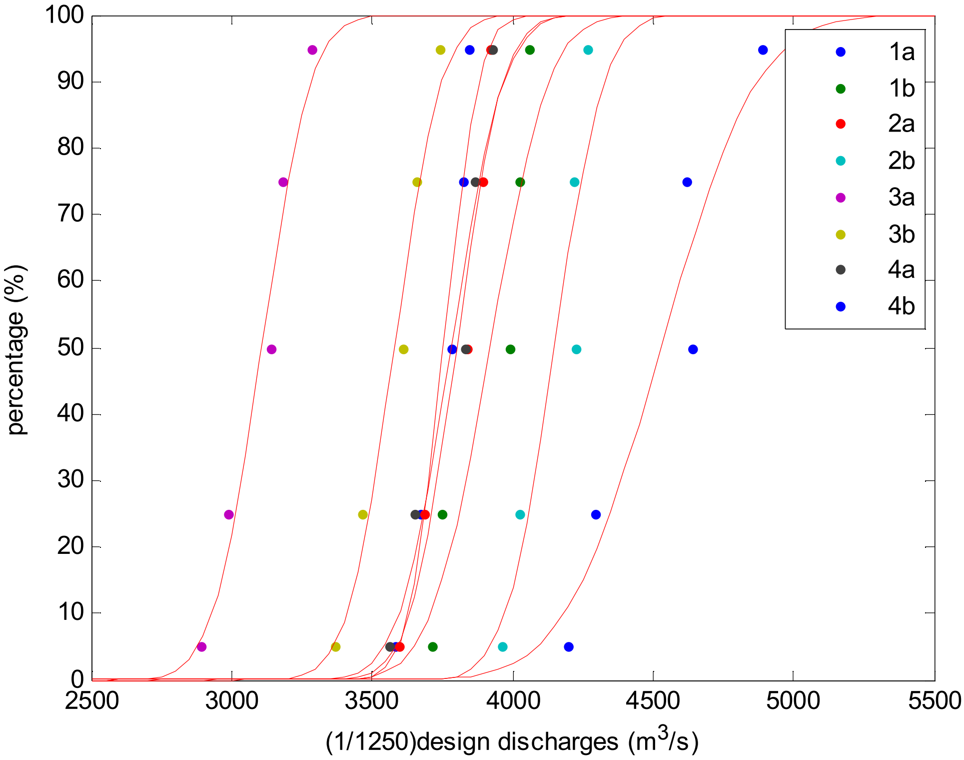

Figure 3.2 Design discharges plotted against normal plot through the design discharges

3.3 Uncertainties in traditional estimations of the design discharge

The traditional method is based on the statistical extrapolation of measured discharges. Below, the larges sources of uncertainty in this method are summarised:

- It is unknown how representative the relatively short measured discharge records (100 years) are for the full population of river discharges.
- The discharge record is often non-homogeneous because of changes in the upstream basin, the river geometry and climate. In theory the estimation would improve with increasing length of the measurement series, but a longer series will also imply a larger chance of non-homogeneity.
- The choice of frequency distributions is also a point of uncertainty.
- The extrapolation does not take into account the physical properties of the river basin, such as the start of inundation above a certain water level.

WL | Delft Hydraulics (2004) determined the 1/1250 year design discharge for the Meuse at Borgharen in the framework of the Hydraulic Boundary conditions 2006 (Hydraulische Randvoorwaarden 2006). For this purpose use was made of measured discharges of the hydraulic years 1911 t/m 2003. The design discharge was calculated at 3965 m^3/s. The 95% confidence interval was located between 3250 en 4705 m^3/s. This bandwidth does only take into account statistical uncertainty and not e.g. certain limitations of the physical properties of the river on the extrapolated values.

In the conclusions and abstract of this report, the design discharge and 95% confidence interval values for the traditional method are rounded to resp. 3950, 3250 and 4700 m^3/s.

3.4 Comparison

Both methods have to deal with large uncertainties. Below a comparison is given of the uncertainties in both methods.

Both methods use a basis set of data. The traditional method is based on discharge data, where GRADE uses precipitation data. The advantage of the use of precipitation data is that the precipitation measurements are more homogeneous than discharges. Precipitation data is not subjected to changes of the river geometry and changes in the upstream part of the river. However for both data sets it is important to known how representative the set is for the ‘current’ climate. Statistically it is best to use an as-long-as possible basis set. However, the longer the series the larger the possible effect of climate change and so possibly the inhomogeneity.

An uncertainty in the traditional method is caused by the fact that extrapolation does not take into account the physical properties of the river. It is unknown if the use of extrapolation is really permitted. The extrapolated value for a certain return period might never be reached due to e.g. inundation of the upstream floodplains.

4 Conclusions

4.1 Validation of the GRADE instrument

For the same return period the design discharge line generated with the GRADE instrument gives lower peak discharges than the current design discharge line (werklijn TMR2006). The difference between both lines can be reduced by changing the parameter settings in the HBV model. Secondly the difference can be reduced by taking into account the ratio between the hourly and daily mean time steps.

The current calibration, as determined by Van Deursen of Carthago gives only a good fit for ‘low’ and ‘middle low’ discharges, but fails to produce a good fit for the high (peak) discharges, because this calibration did not focus on extreme values. In the GLUE method of part D an ensemble of 500 new parameter sets was determined. A selection of five parameter sets out of this ensemble of parameter sets is validated in this study using eight historical flood events. On the basis of this validation it can be concluded that the selected parameter sets give good results for the high (peak) discharges. For most historical events all selected parameters sets approximate the peak flows at Borgharen better than the original (Van Deursen) parameter set and therefore it is advisable to implement one of the new parameter sets in the new GRADE instrument. However, it is yet to be determined which set should have preference.

Research was done to the effect of the use of daily time steps in the GRADE model, where the traditional method uses hourly data. Because of the use of daily time steps in GRADE the design discharge will be lower than when using hourly data. In this study it was found that the most reliable way to calculate hourly peak discharges from a daily averaged discharge peak at Borgharen is to multiply the value by 1.01 and add 80 m^3/s. This conversion was used during this study.

4.2 Determination of the overall performance of the GRADE instrument

In this study the uncertainties in the GRADE instrument were compared with the traditional method to determine the design discharge at Borgharen. Both methods have to deal with large uncertainties.
In this study it was concluded that the largest uncertainties in the GRADE instrument are found in the basis set for the Rainfall Generator and the parameter choices for the HBV Model. Several simulations of 20.000 year were made, using 5 different parameter sets and 8 basis sets for rainfall and temperature. The average daily design discharge of the resulting 40 simulations was about 3800 m^3/s. The 95% uncertainty interval of the GRADE is situated between about 2950 and 4700 m^3/s (interval 1750 m^3/s)
Using the traditional method the design discharge was calculated at about 3950 m^3/s. The 95% confidence interval was located between about 3250 en 4700 m^3/s (interval 1450 m^3/s).

The interval of the traditional method is comparable to the GRADE interval. However in the confidence interval of the traditional method only the statistical uncertainty is taken into account, so that the real uncertainty is unknown. Another advantage of the GRADE model is that improvement in model will reduce the uncertainty, where in the traditional model no large improvements can be expected.

5 Recommendations

- An improvement of the GRADE instrument can be made by changing the parameter sets of the HBV model.

- In this study a method was analysed to recalculate daily average discharge peaks at Borgharen to hourly discharges. It is advisable to research how this can be integrated in the GRADE model.

- It is unclear how the HBV model performs in extreme situations. This can be tested by validating the behaviour of the model per subbasin at historical extreme situations.

6 References

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Van Deursen, W., 2004. Afregelen HBV model Maasstroomgebied. Rapportage aan RIZA. Carthoga Consultancy. Rotterdam, The Netherlands.

Weerts, A. & van der Klis, H, 2006. Reliability of the Generator of Rainfall and Discharge Extremes (GRADE), Client: RWS-RIZA. WL-report Q4268. December 2006

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WL Delft Hydraulics 2004: HR2006-Herberekening werklijn Maas. WL Delft Hydraulics, Q3623

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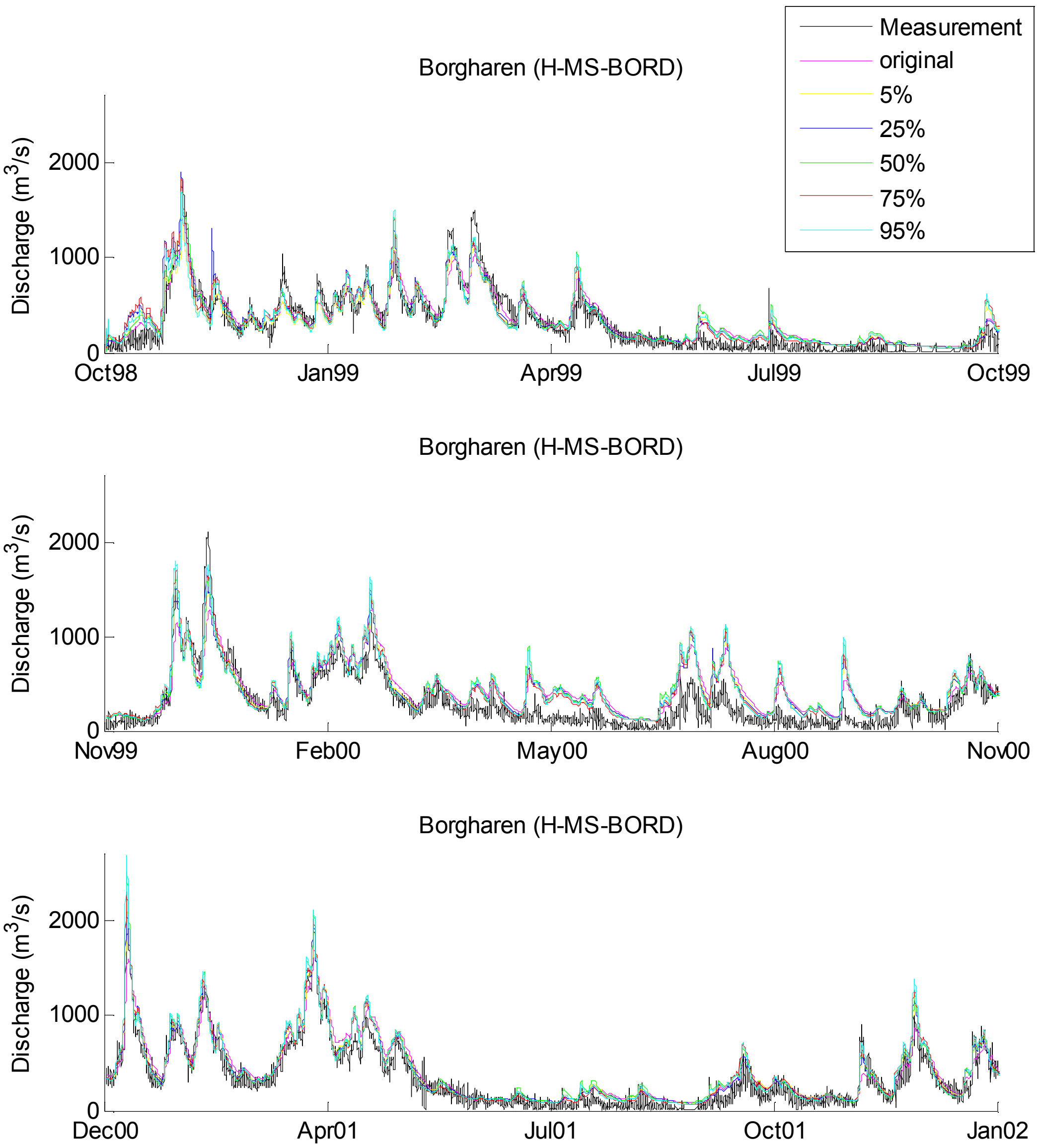
A Values selected 5 parameter sets HBV model

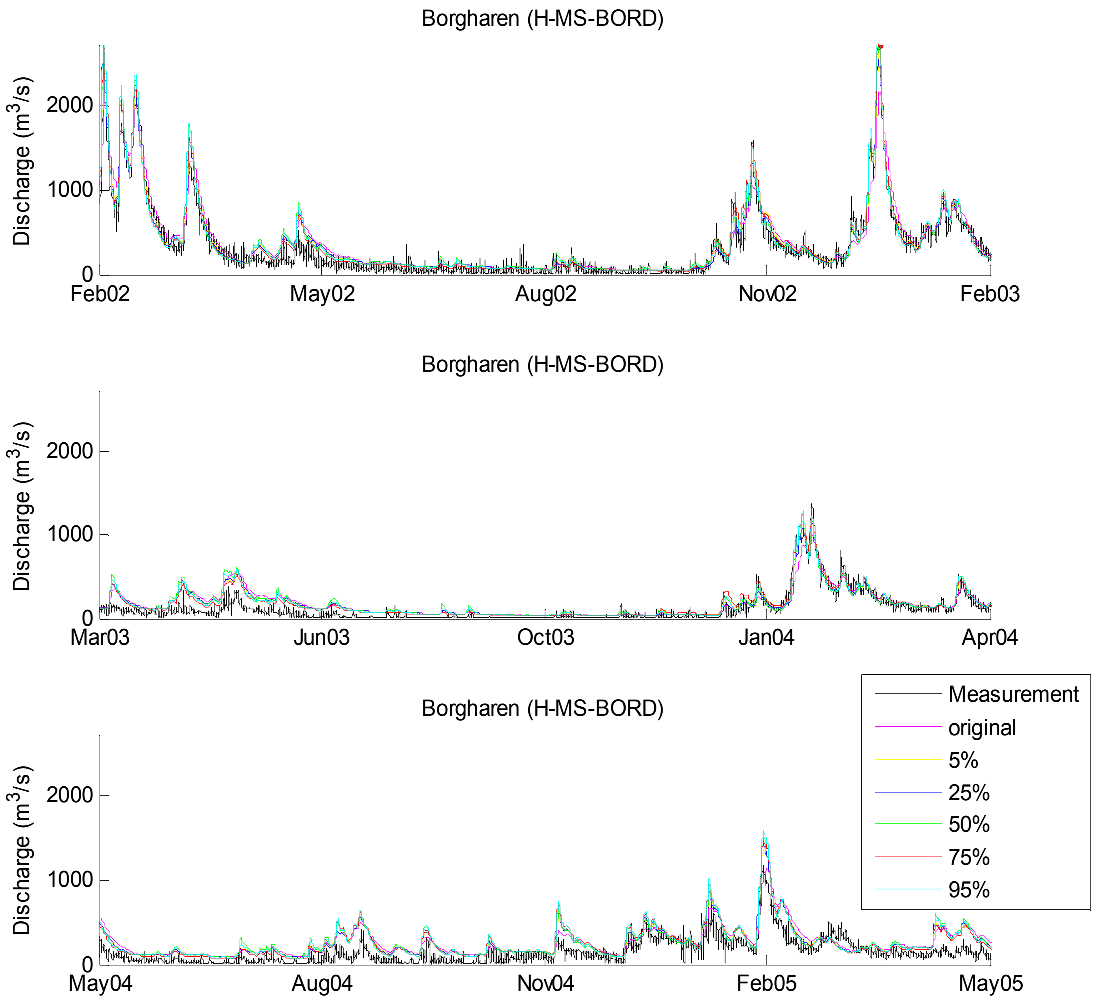
Selected parameter values for every sub basin.

	set	fc	beta	lp	alfa	hq	khq	maxbas
sub basin1	5%	428.06	2.74	0.62	1.09	1.49	0.08	3.93
	25%	368.19	2.54	0.56	1.26	2.06	0.09	3.88
	50%	204.00	2.73	0.21	1.00	2.39	0.09	3.52
	75%	436.08	3.34	0.69	1.45	1.38	0.06	3.32
	95%	321.98	3.27	0.57	1.16	1.46	0.06	3.98
sub basin2	5%	367.46	1.07	0.41	0.38	3.69	0.04	
	25%	417.35	0.98	0.41	0.33	2.66	0.03	
	50%	497.78	1.04	0.49	0.45	3.03	0.04	
	75%	497.78	1.04	0.49	0.45	3.03	0.04	
	95%	490.41	1.93	0.63	0.33	1.56	0.03	
sub basin3	5%	225.18	3.11	0.99	1.21	2.85	0.08	
	25%	255.38	2.27	0.85	1.31	2.22	0.07	
	50%	450.43	2.17	0.85	1.21	1.75	0.09	
	75%	189.05	2.19	0.75	1.55	2.87	0.07	
	95%	468.72	2.13	0.85	1.54	1.86	0.07	
sub basin 4	5%	206.07	1.08	0.69	0.55	3.91	0.10	
	25%	475.78	1.43	0.94	0.49	4.87	0.12	
	50%	381.58	1.97	1.00	0.31	3.68	0.37	
	75%	54.24	1.72	0.54	0.55	2.73	0.12	
	95%	309.67	0.78	0.88	1.11	2.08	0.13	
sub basin 5	5%	117.30	2.80	0.36	1.12	1.28	0.05	
	25%	464.14	2.52	0.72	1.07	1.29	0.06	
	50%	419.11	2.79	0.64	1.21	2.48	0.10	
	75%	364.49	1.57	0.41	1.28	1.59	0.09	
	95%	265.04	3.00	0.34	1.11	2.60	0.09	
sub basin 6	5%	263.16	2.85	0.28	1.54	1.32	0.08	
	25%	237.74	3.36	0.24	1.63	1.40	0.08	
	50%	272.91	2.66	0.22	1.60	1.65	0.10	
	75%	226.22	2.23	0.28	1.35	1.00	0.09	
	95%	279.13	3.25	0.49	1.61	1.38	0.08	
sub basin 7	5%	112.22	1.57	0.62	0.49	4.09	0.30	
	25%	416.40	1.48	0.26	0.36	3.71	0.16	
	50%	340.97	2.59	0.75	0.46	2.85	0.15	
	75%	361.00	2.12	0.87	1.05	2.12	0.26	
	95%	157.06	1.46	0.30	0.77	2.20	0.22	
sub basin 8	5%	364.96	2.84	0.66	1.05	1.53	0.13	
	25%	189.05	2.87	0.30	0.97	2.74	0.12	
	50%	196.87	2.44	0.32	1.05	1.53	0.09	
	75%	230.18	2.42	0.21	1.06	2.35	0.11	
	95%	213.22	2.81	0.50	0.74	1.76	0.13	
sub basin 9	5%	497.36	2.30	0.80	0.43	1.96	0.09	
	25%	215.17	2.58	0.50	1.54	2.31	0.11	
	50%	471.54	2.50	0.38	1.24	4.32	0.15	
	75%	121.18	2.35	0.45	0.41	2.31	0.16	
	95%	180.04	2.35	0.31	0.90	3.06	0.18	
sub basin 10	5%	189.32	1.75	0.23	0.93	2.63	0.13	
	25%	139.01	2.70	0.21	1.10	2.37	0.11	
	50%	140.42	2.16	0.34	0.96	4.13	0.14	
	75%	161.22	2.49	0.42	1.00	3.32	0.13	
	95%	139.01	2.70	0.21	1.10	2.37	0.11	
sub basin 11	5%	187.46	2.65	0.62	1.04	4.10	0.12	
	25%	364.53	2.86	0.81	1.03	2.59	0.14	
	50%	355.74	2.97	0.78	0.97	1.82	0.12	
	75%	137.34	1.58	0.45	0.94	2.74	0.11	
	95%	364.53	2.86	0.81	1.03	2.59	0.14	
sub basin 12	5%	249.17	1.23	0.46	1.44	3.85	0.20	
	25%	228.59	1.18	0.45	1.34	2.99	0.18	
	50%	159.30	1.13	0.40	1.41	2.34	0.12	
	75%	249.17	1.23	0.46	1.44	3.85	0.20	
	95%	159.30	1.13	0.40	1.41	2.34	0.12	
sub basin 13	5%	488.07	1.90	0.24	0.60	4.11	0.14	
	25%	416.48	2.80	0.23	0.21	4.39	0.13	
	50%	475.03	2.15	0.25	0.68	2.36	0.10	
	75%	440.08	2.18	0.28	0.12	2.19	0.14	
	95%	460.82	2.37	0.25	0.49	1.75	0.10	
sub basin 14	5%	467.93	2.37	0.29	0.82	3.02	0.19	
	25%	261.02	1.74	0.39	1.46	1.94	0.23	
	50%	338.41	1.62	0.82	0.63	2.15	0.25	
	75%	330.31	1.33	0.45	0.61	4.73	0.28	
	95%	424.37	1.12	0.68	0.11	1.18	0.21	

B Hindcast Borgharen

As described in this report five parameter sets have been selected that were given in Annex A above. For all selected parameters a HBV run has been carried out for the period 1998-2005. The hydrographs of the measured and simulated discharges of the total period are given below.

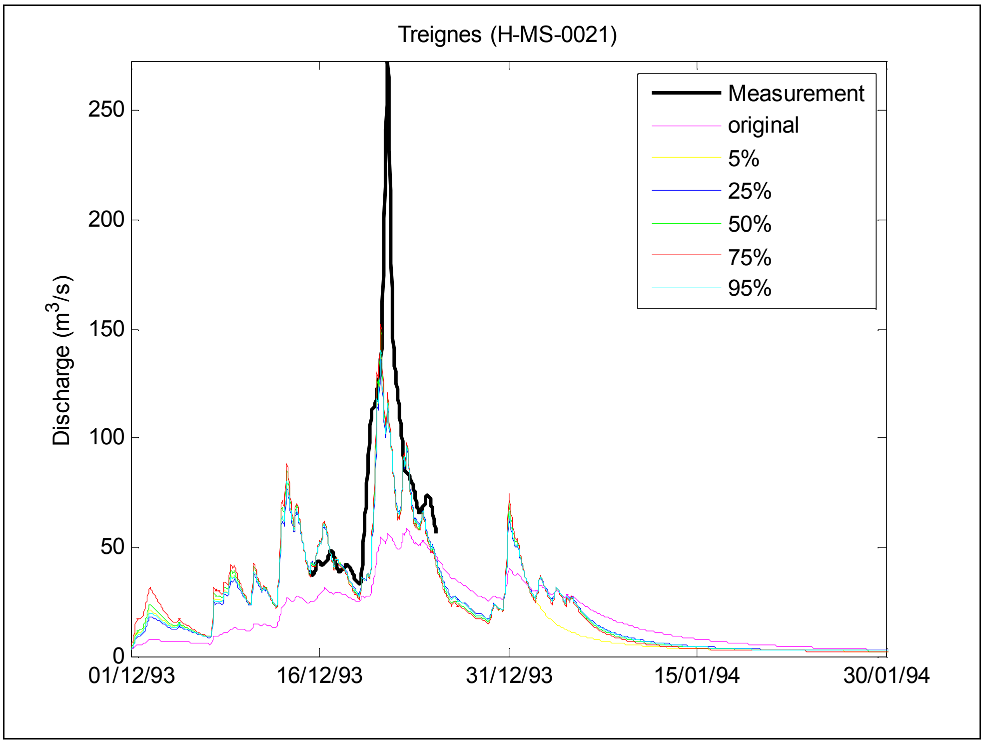




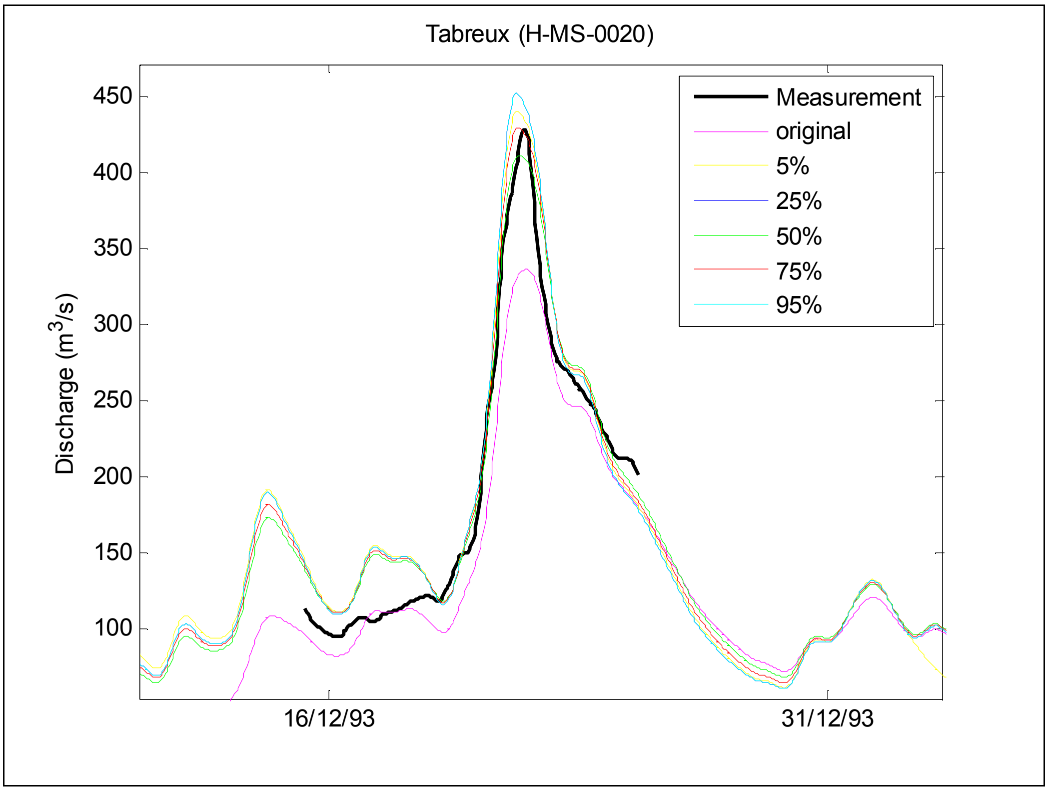
Measured and simulated discharges at Borgharen for 1998 to 2005. The measured discharge is given by the black line. The original set (van Deursen parameters) is given by the pink line. The remaining lines are the HBV simulations for different new parameter sets (5% - 95%).

C Hindcast downstream catchments

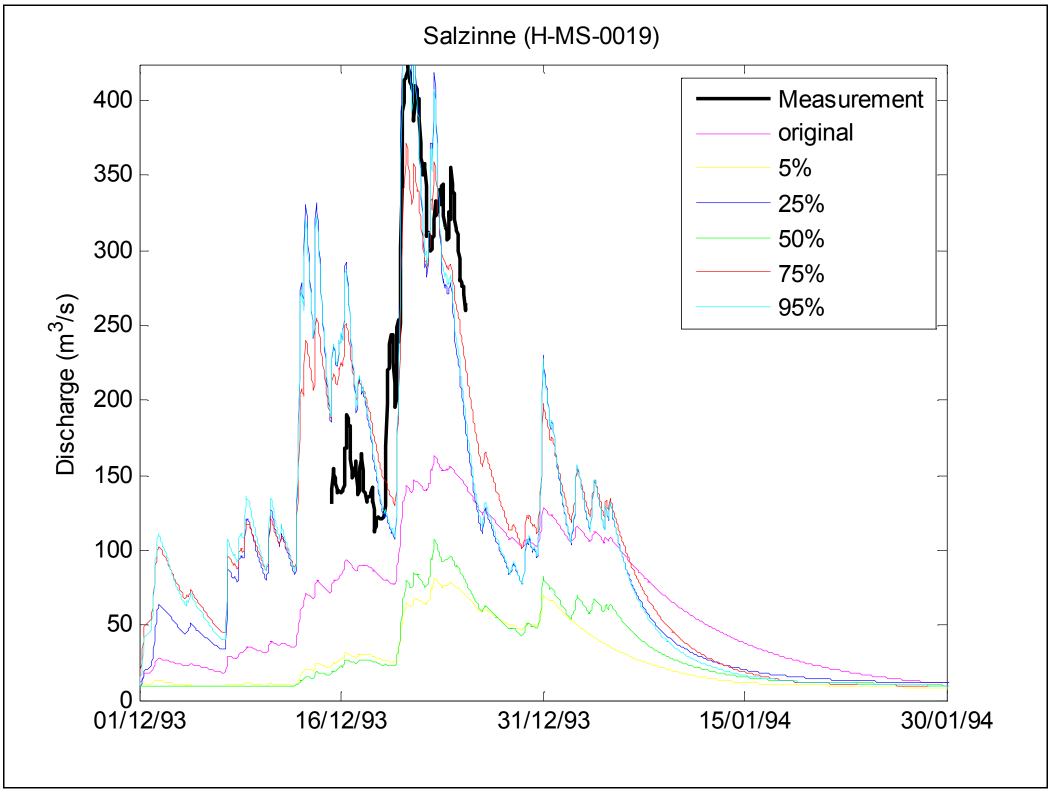
As described in this report five parameter sets have been selected. For all selected parameters a hindcast has been carried out using the HBV model. In the figures below for different subbasins the calculated discharges are plotted against the measured discharges (black). The figures give results for the high water periods December 1993, January 1995 and December 2002/January 2003. In these figures the measured discharge is given by the black line. The original set (van Deursen parameters) is given by the pink line. The remaining lines are the HBV simulations for different parameter sets (5% - 95%).



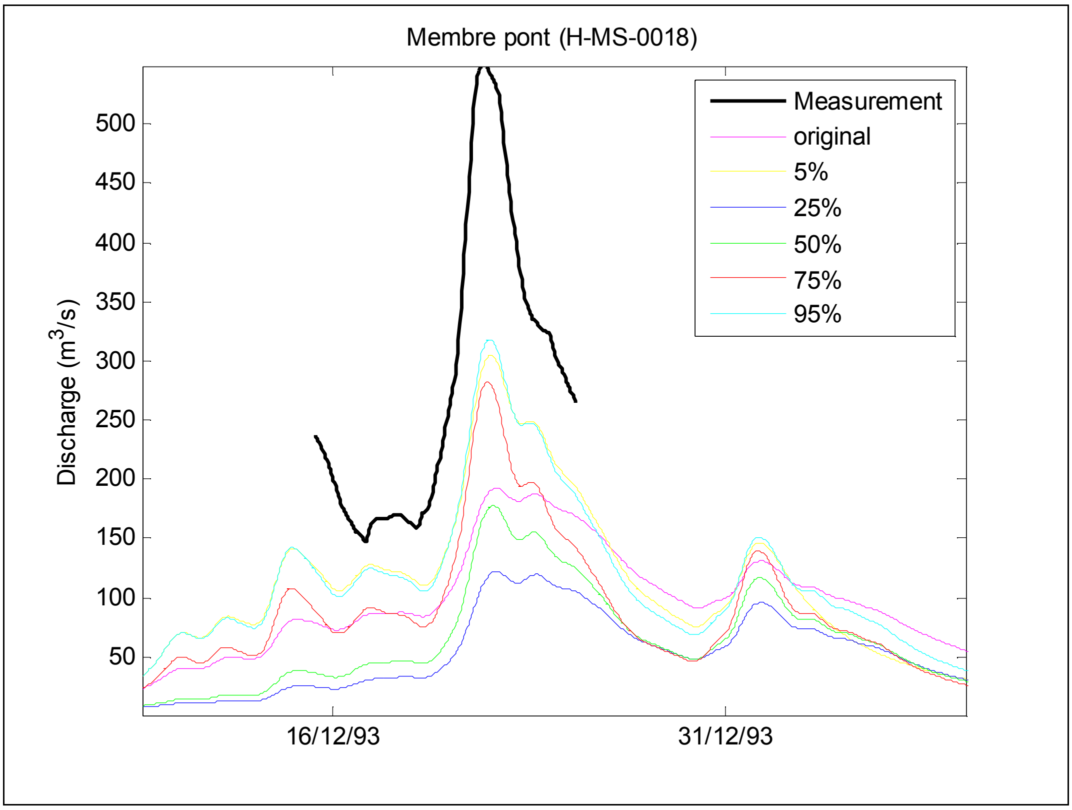
Measured and simulated discharges at Treignes for December 1993



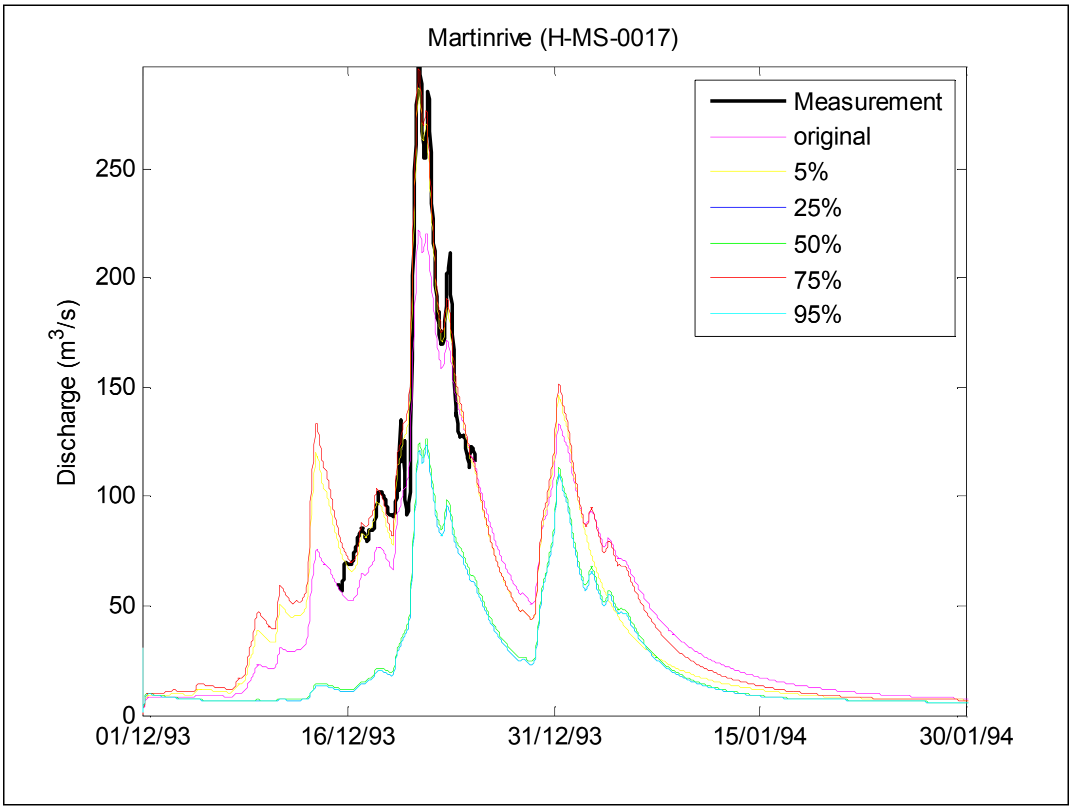
Measured and simulated discharges at Tabreux for December 1993



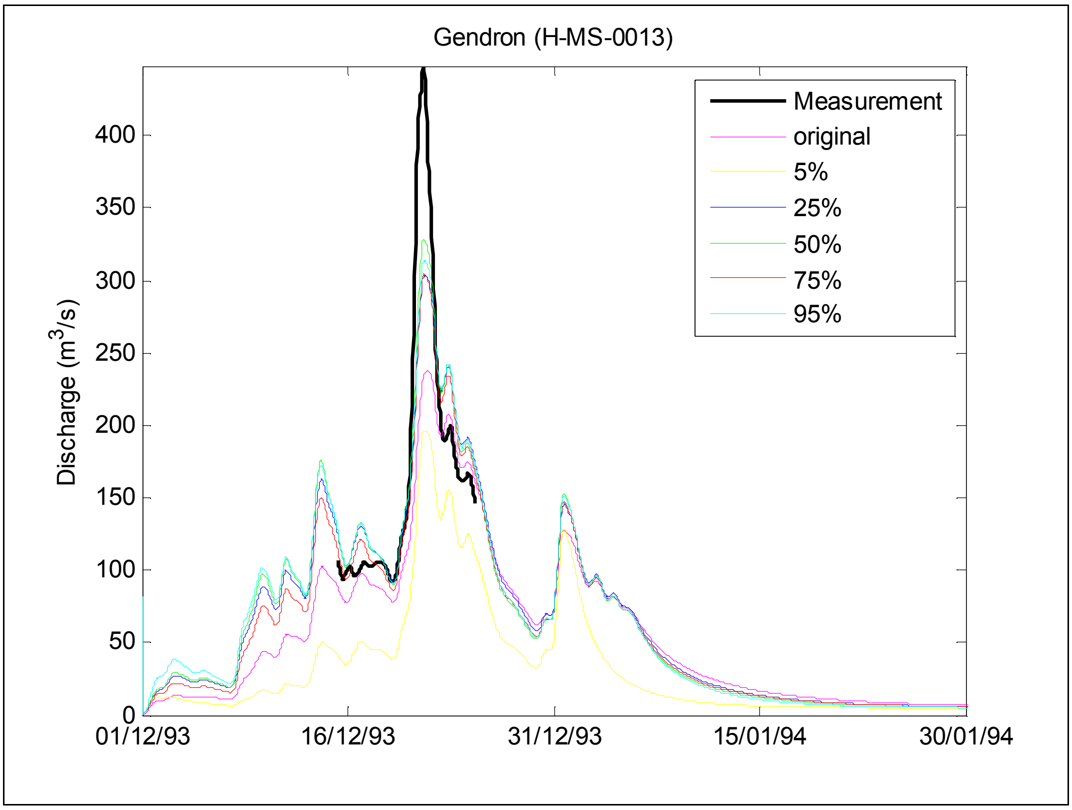
Measured and simulated discharges at Salzinne for December 1993



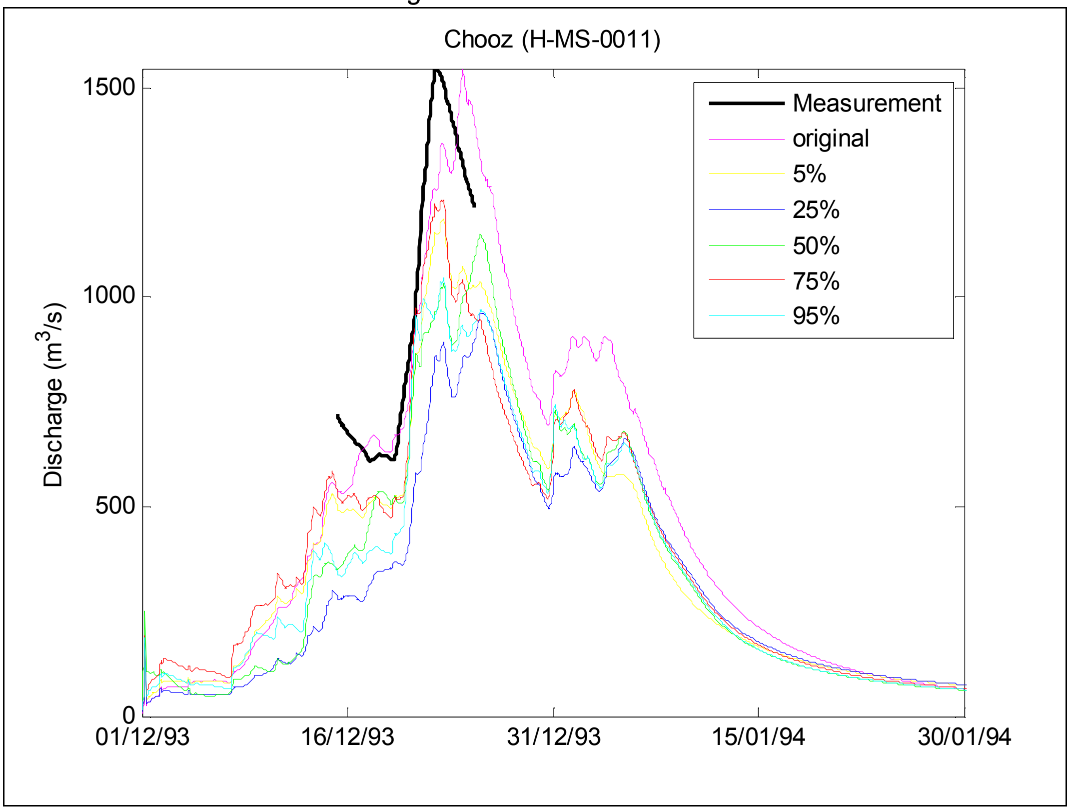
Measured and simulated discharges at Membre Pont for December 1993



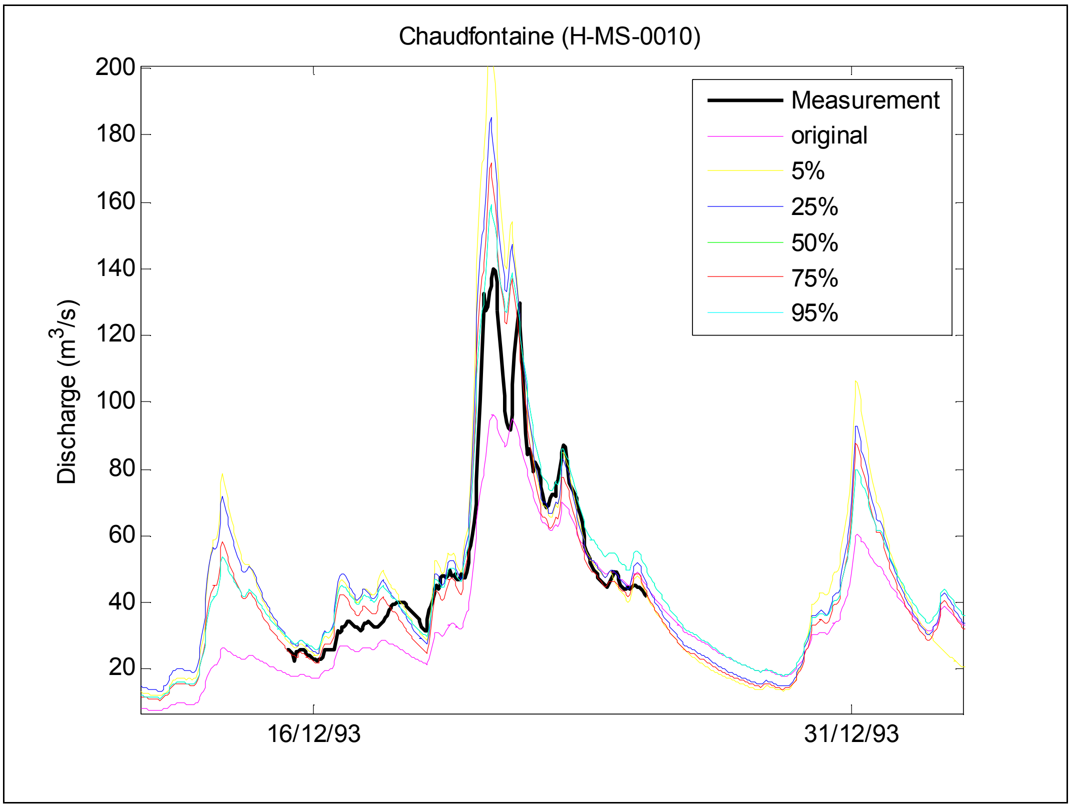
Measured and simulated discharges at Martinrive for December 1993



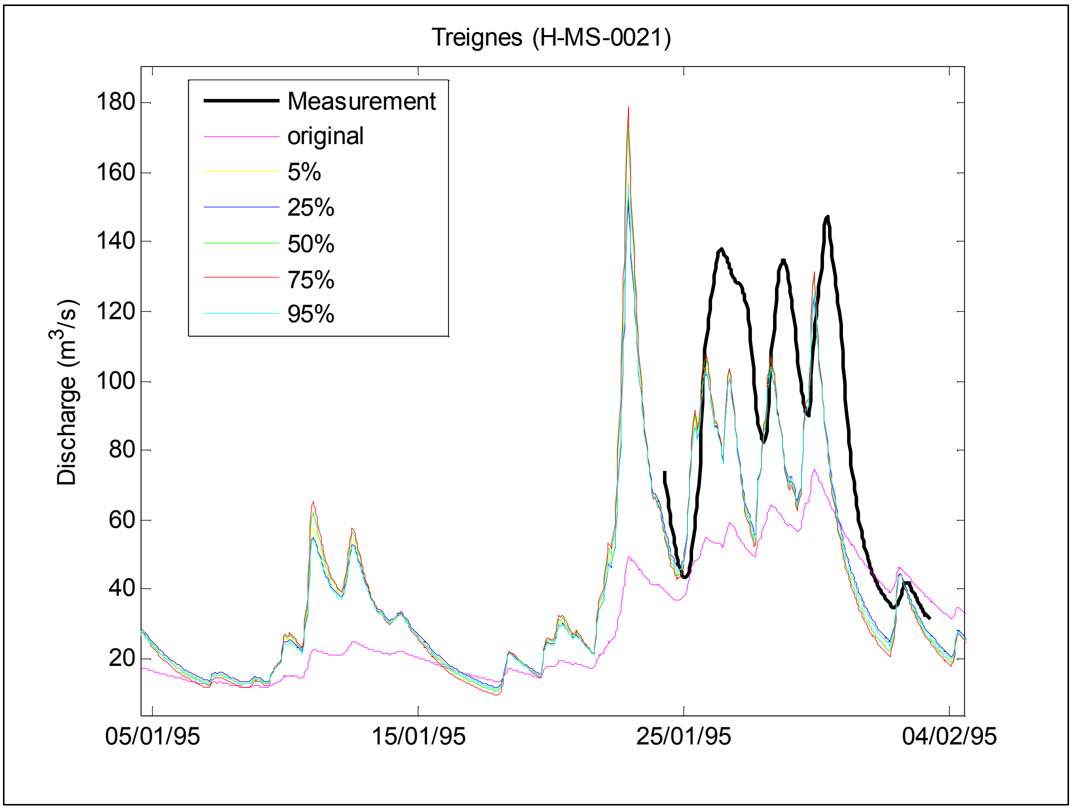
Measured and simulated discharges at Gendron for December 1993



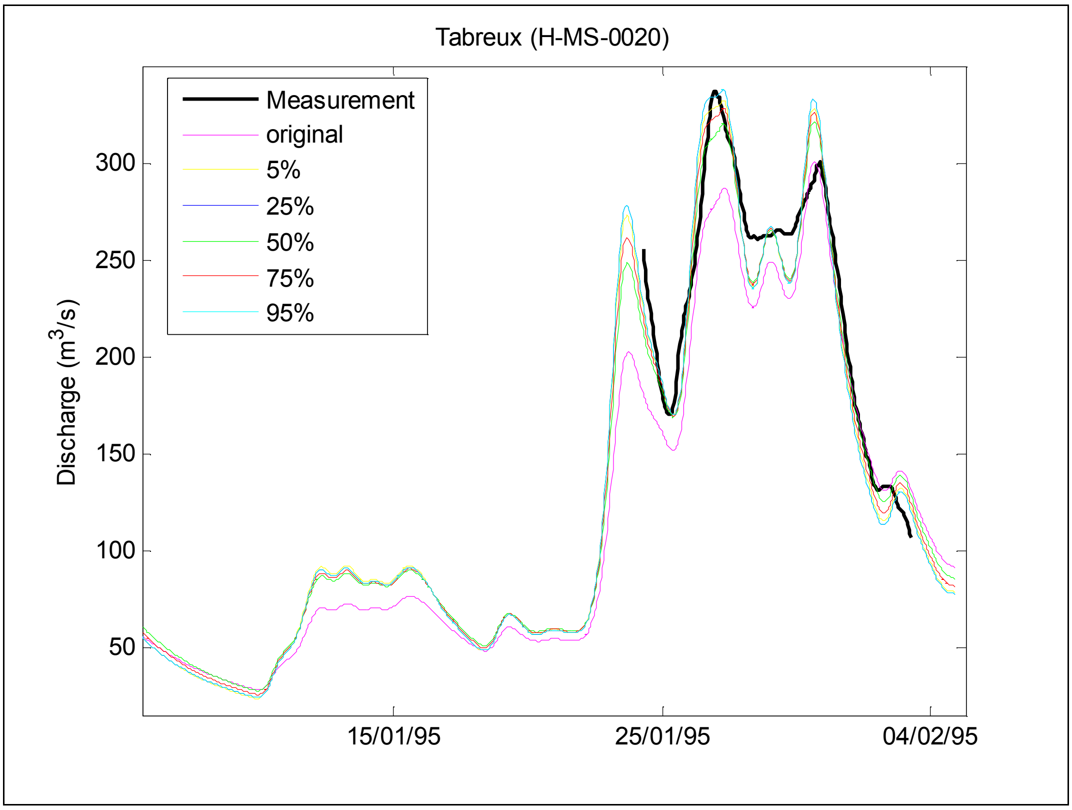
Measured and simulated discharges at Chooz for December 1993



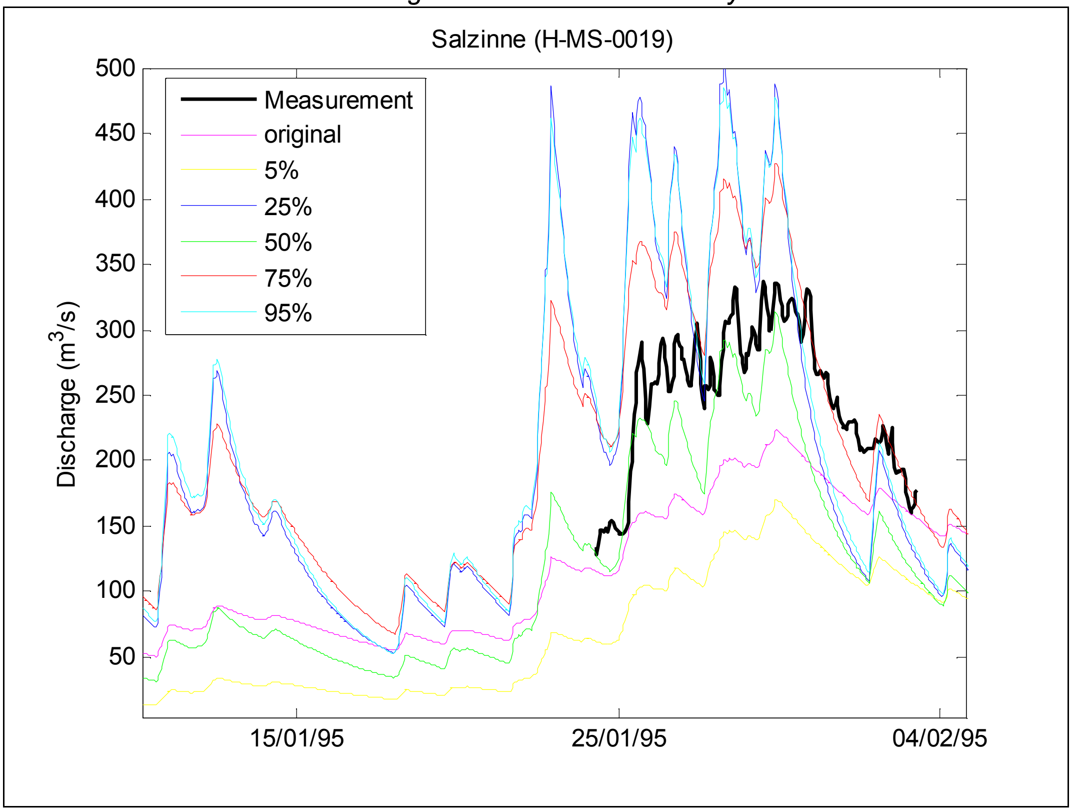
Measured and simulated discharges at Chaudfontaine for December 1993



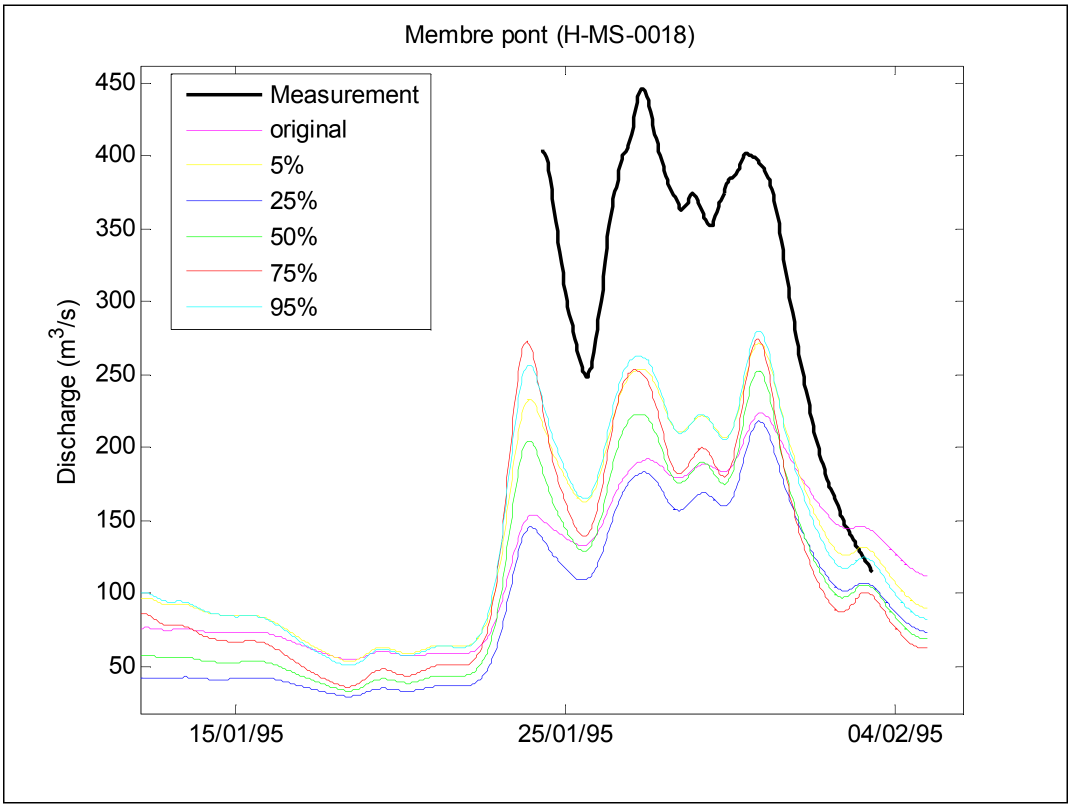
Measured and simulated discharges at Treignes for January 1995



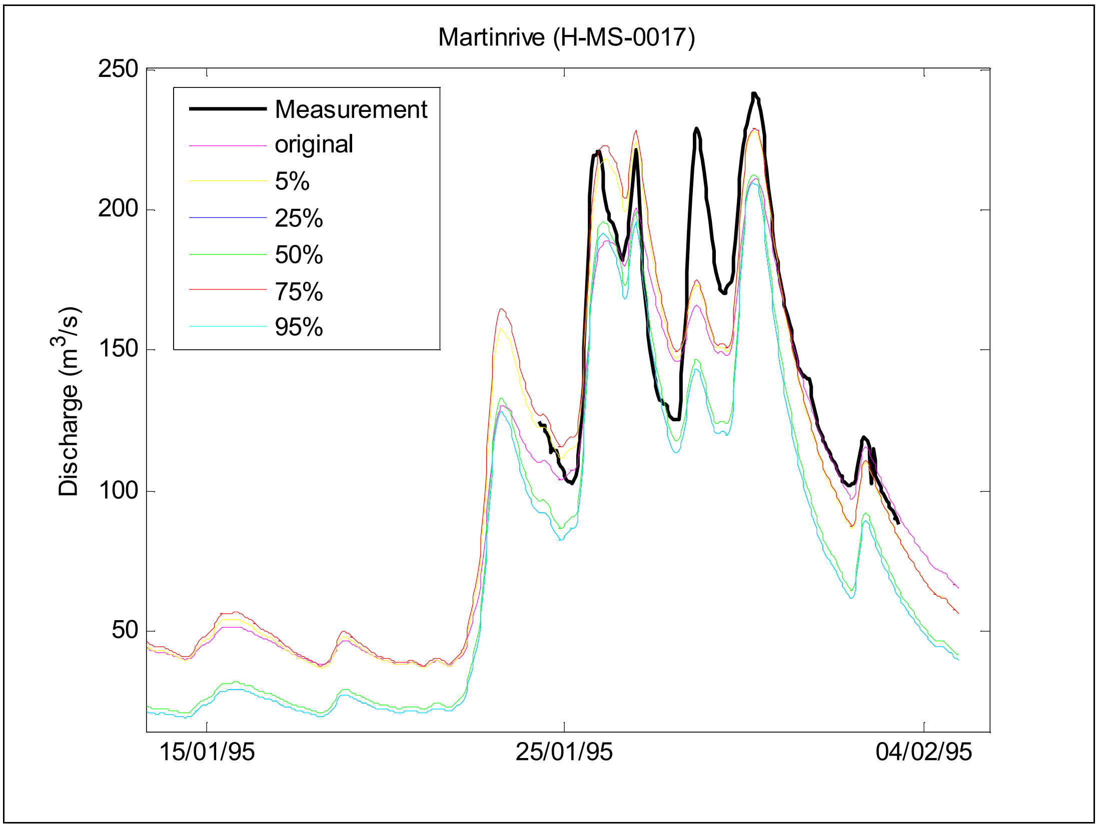
Measured and simulated discharges at Tabreux for January 1995



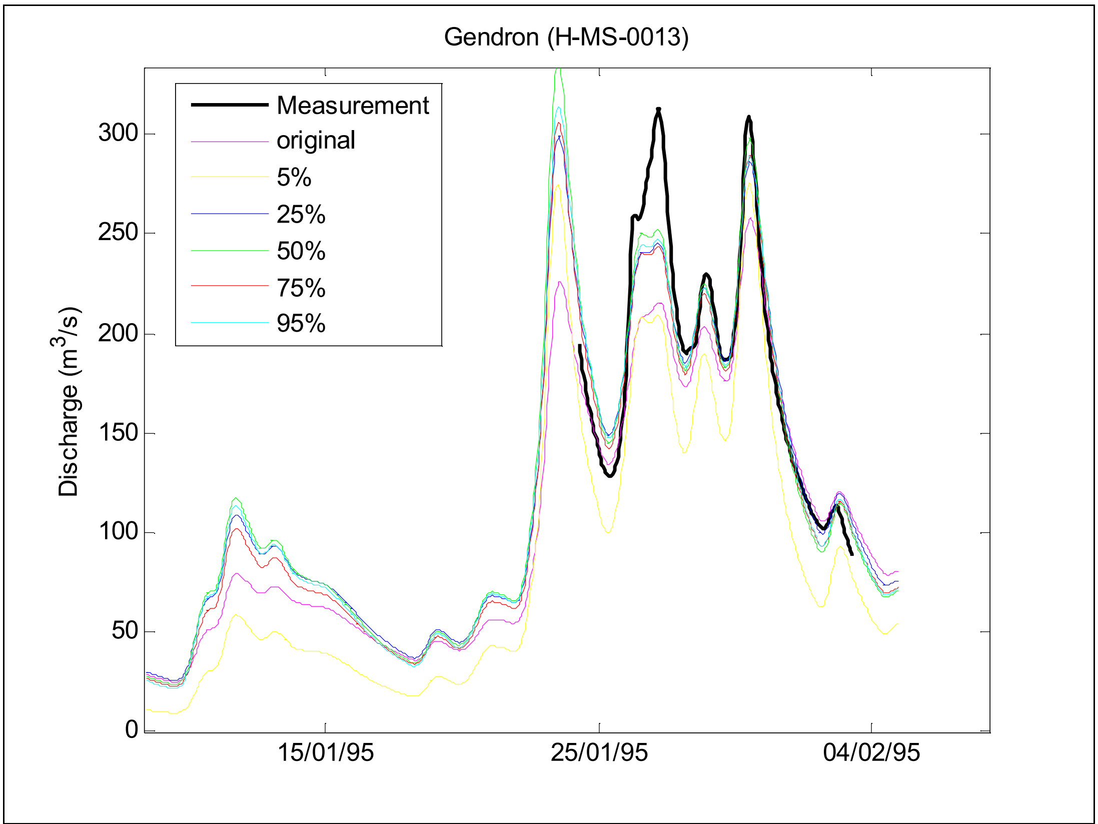
Measured and simulated discharges at Salzinne for January 1995



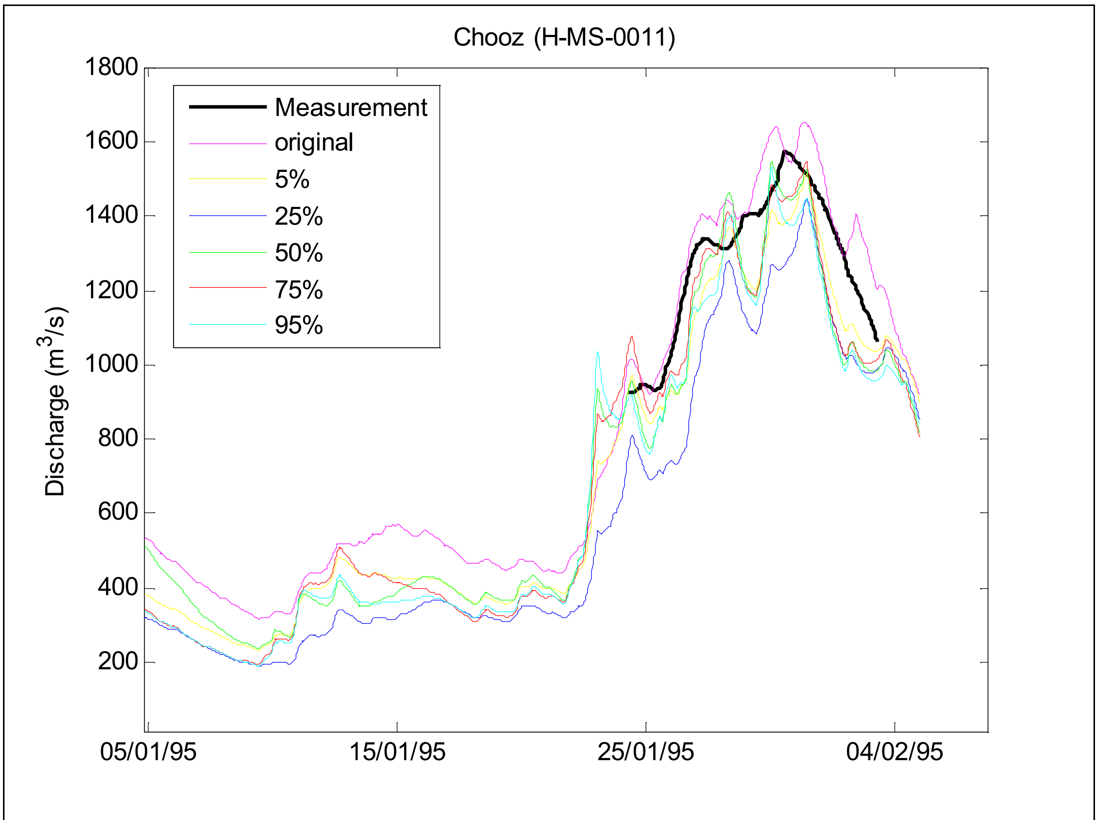
Measured and simulated discharges at Membre Pont for January 1995



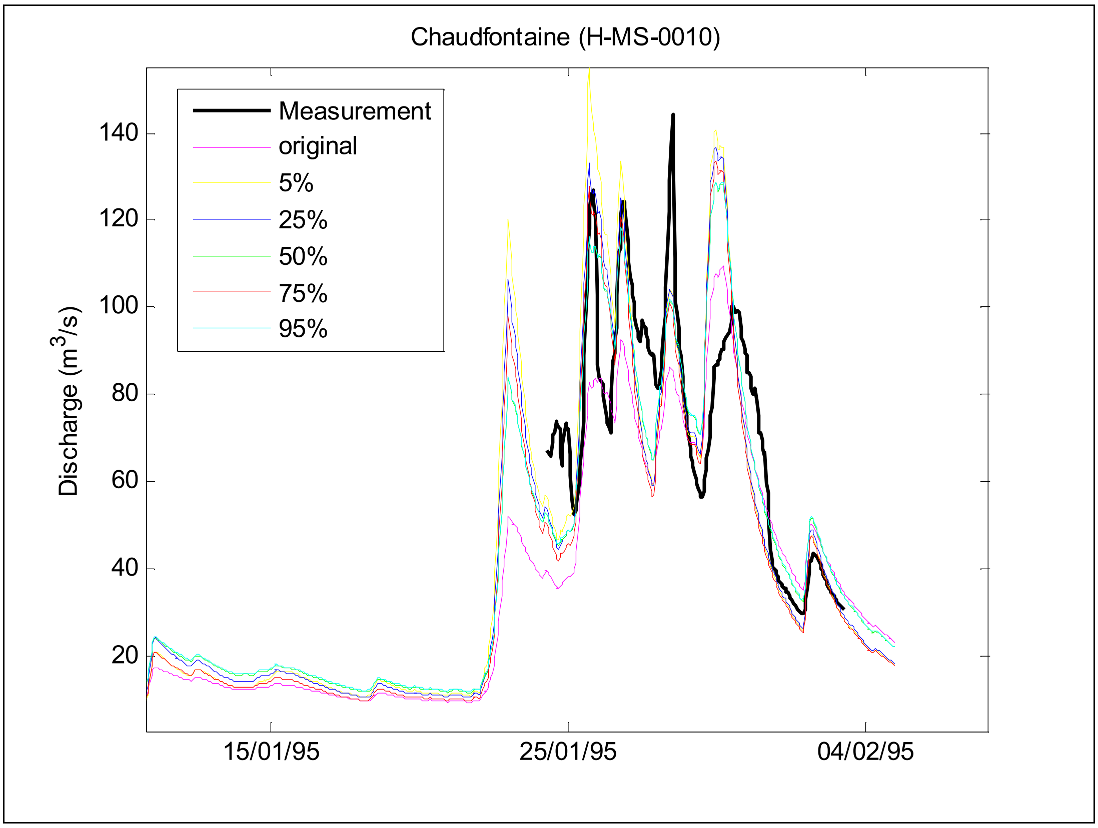
Measured and simulated discharges at Martinrive for January 1995



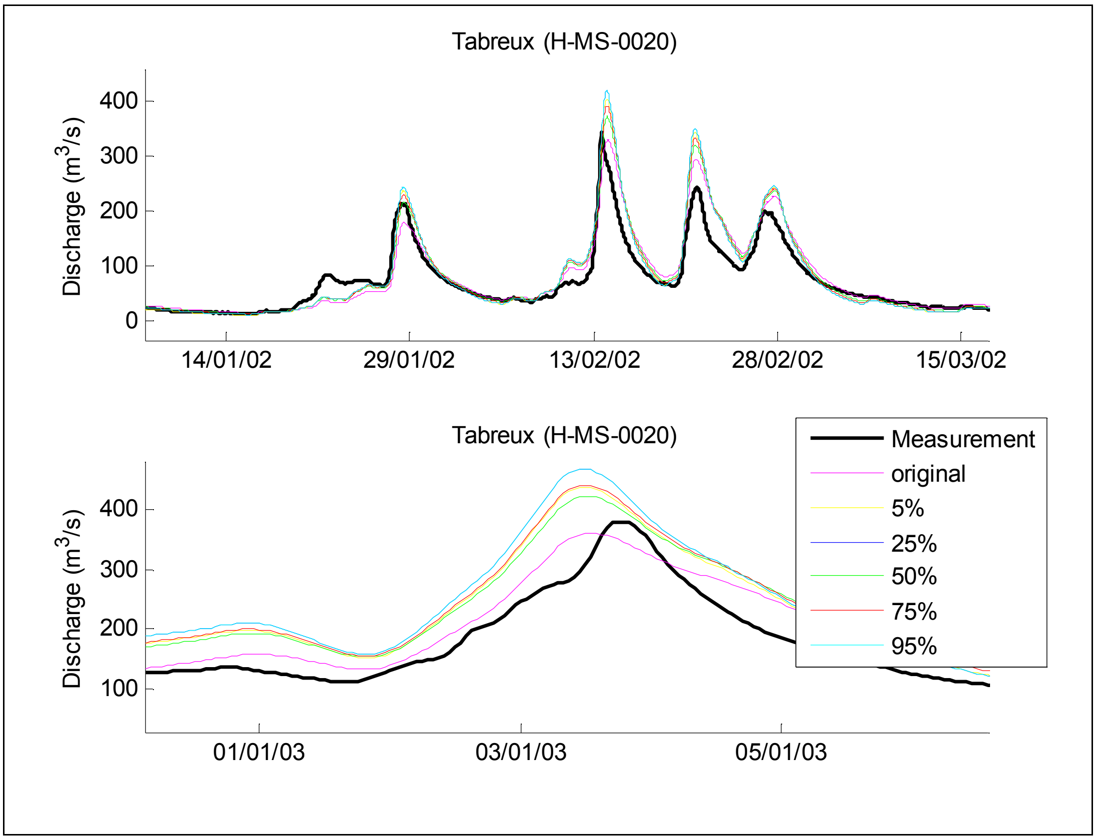
Measured and simulated discharges at Gendron for January 1995



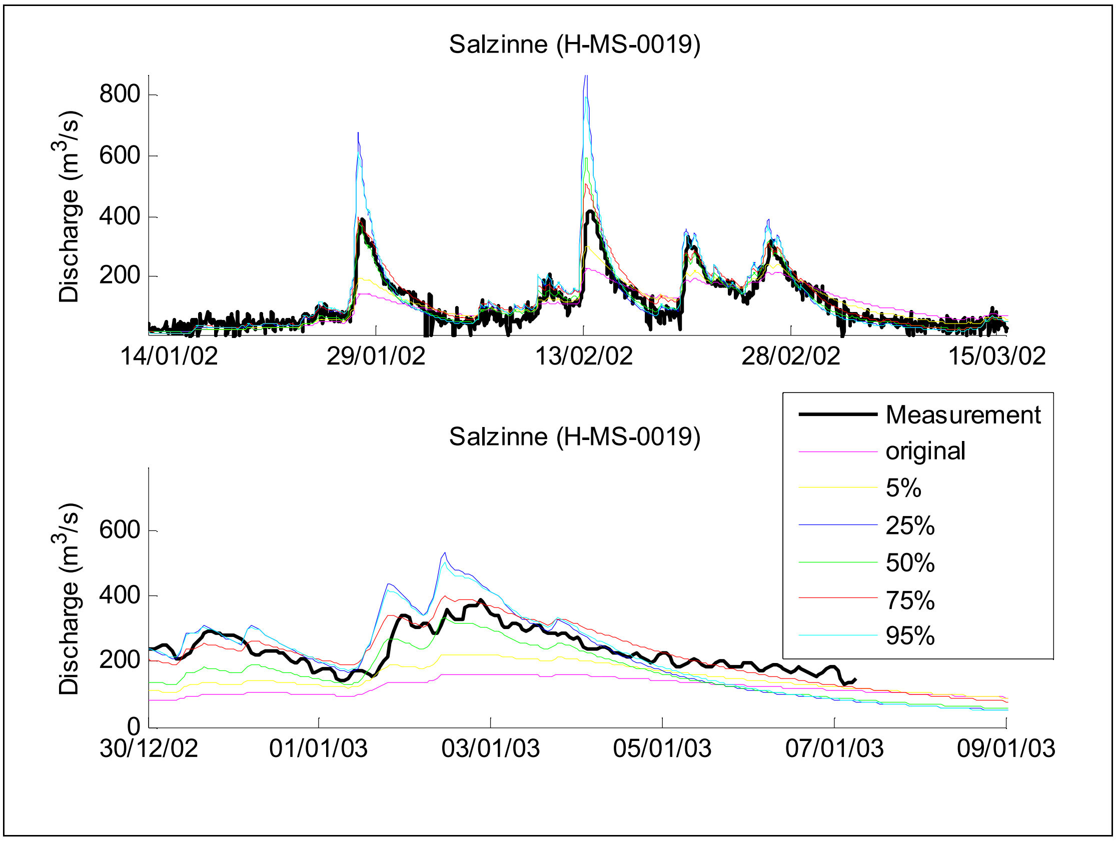
Measured and simulated discharges at Chooz for January 1995



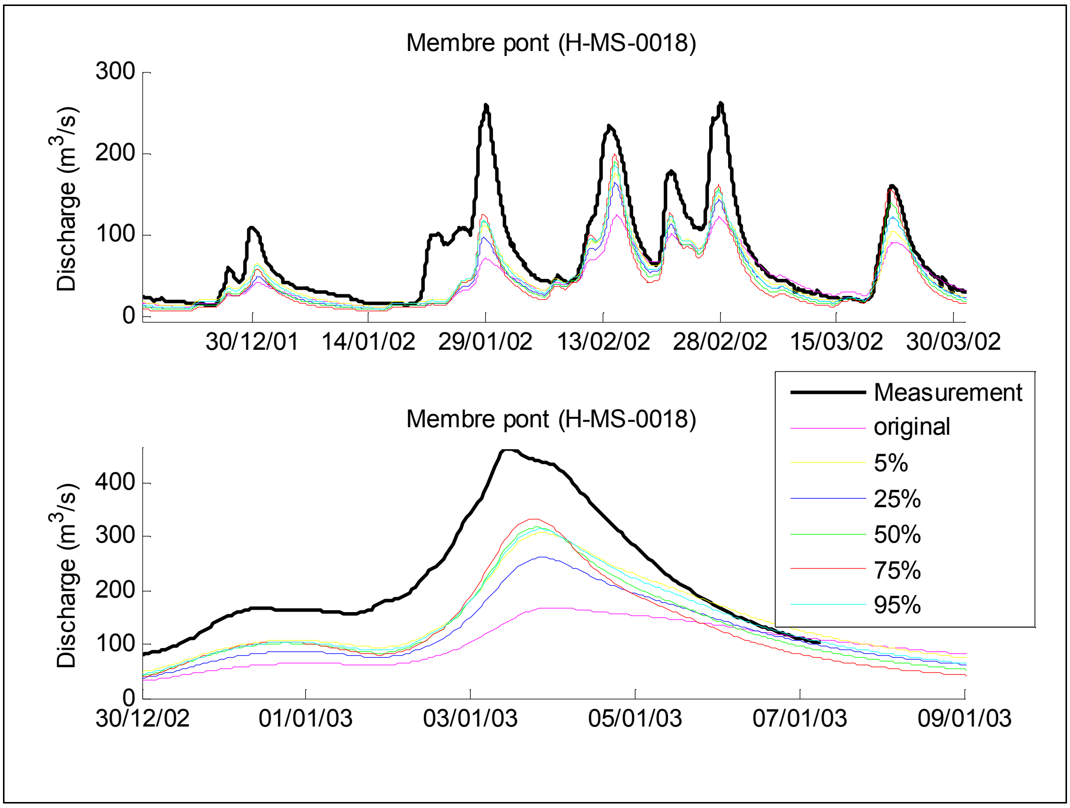
Measured and simulated discharges at Chaudfontaine for January 1995



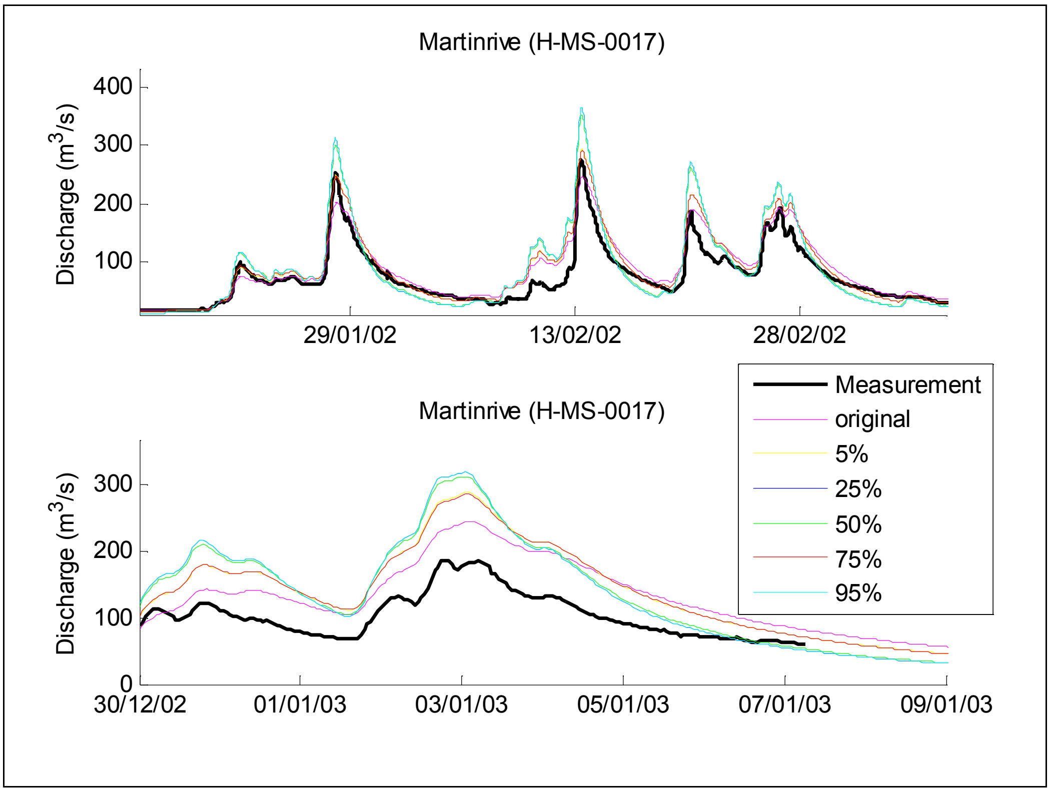
Measured and simulated discharges at Tabreux for February 2002 and January 2003



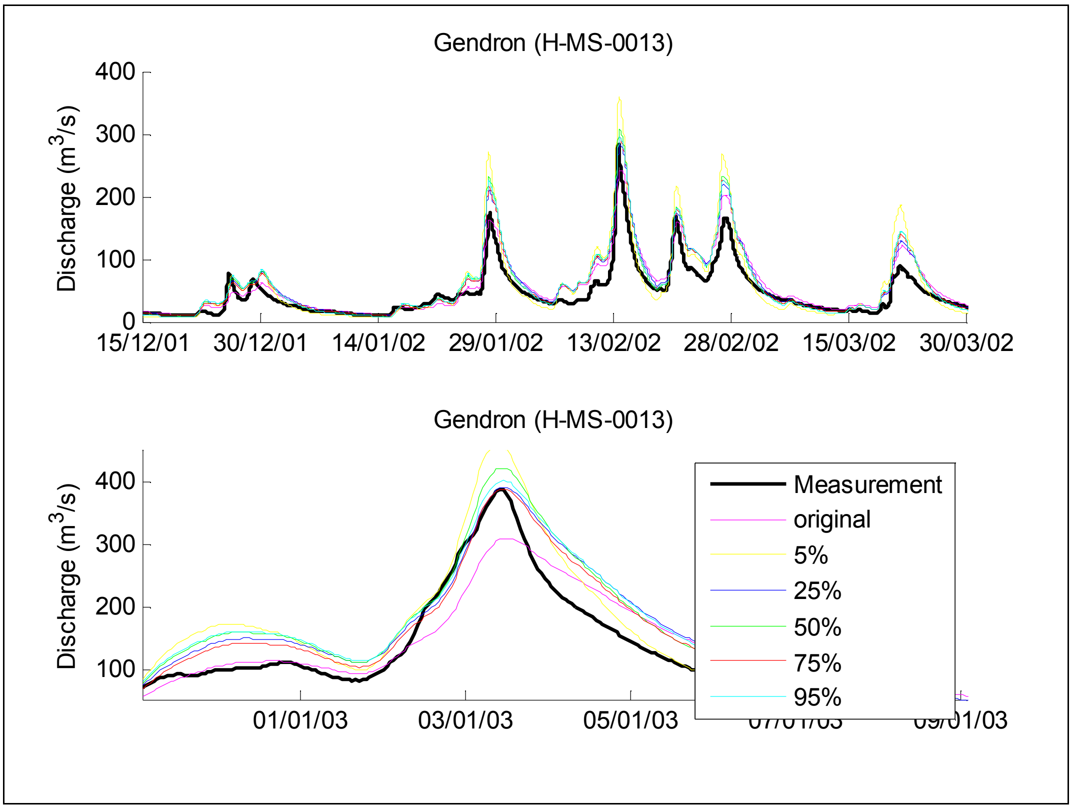
Measured and simulated discharges at Salzinne for February 2002 and January 2003



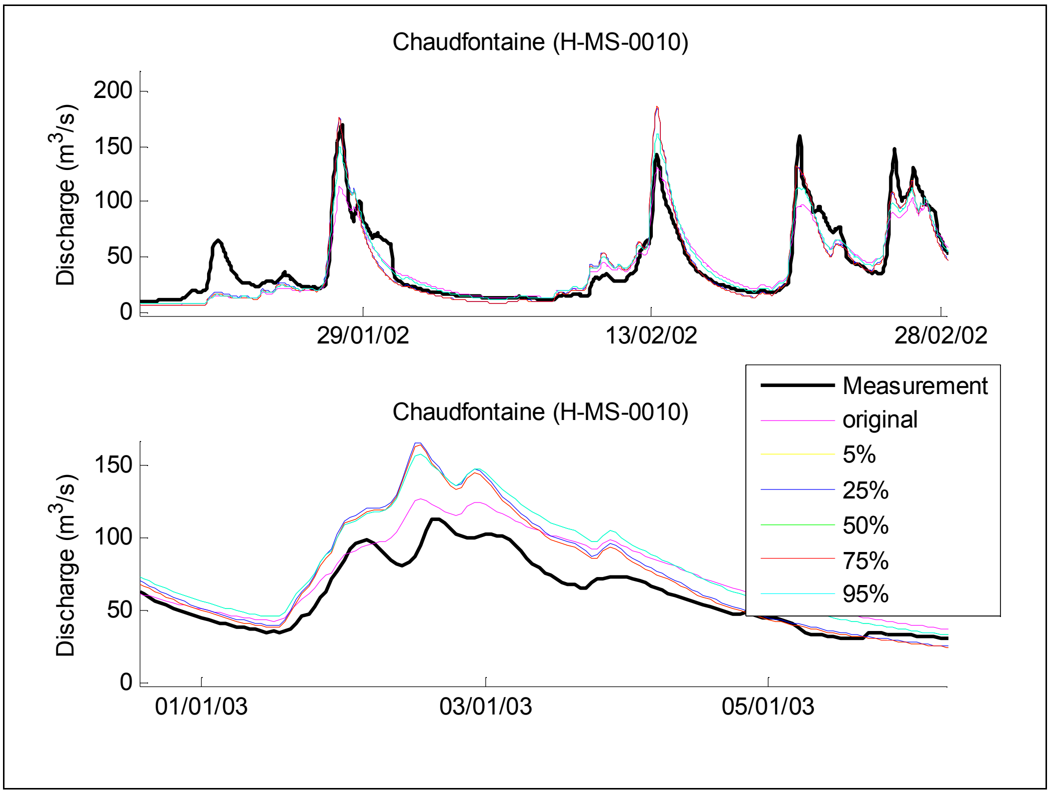
Measured and simulated discharges at Membre Pont for February 2002 and January 2003



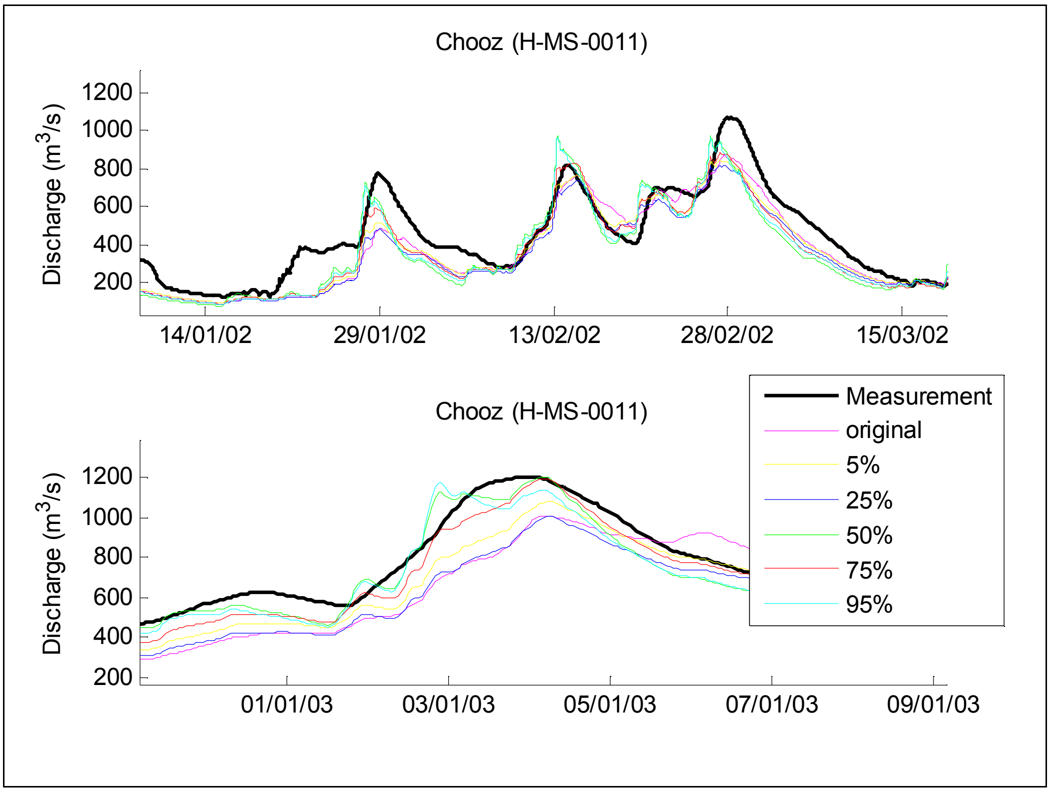
Measured and simulated discharges at Martinrive for February 2002 and January 2003



Measured and simulated discharges at Gendron for February 2002 and January 2003.



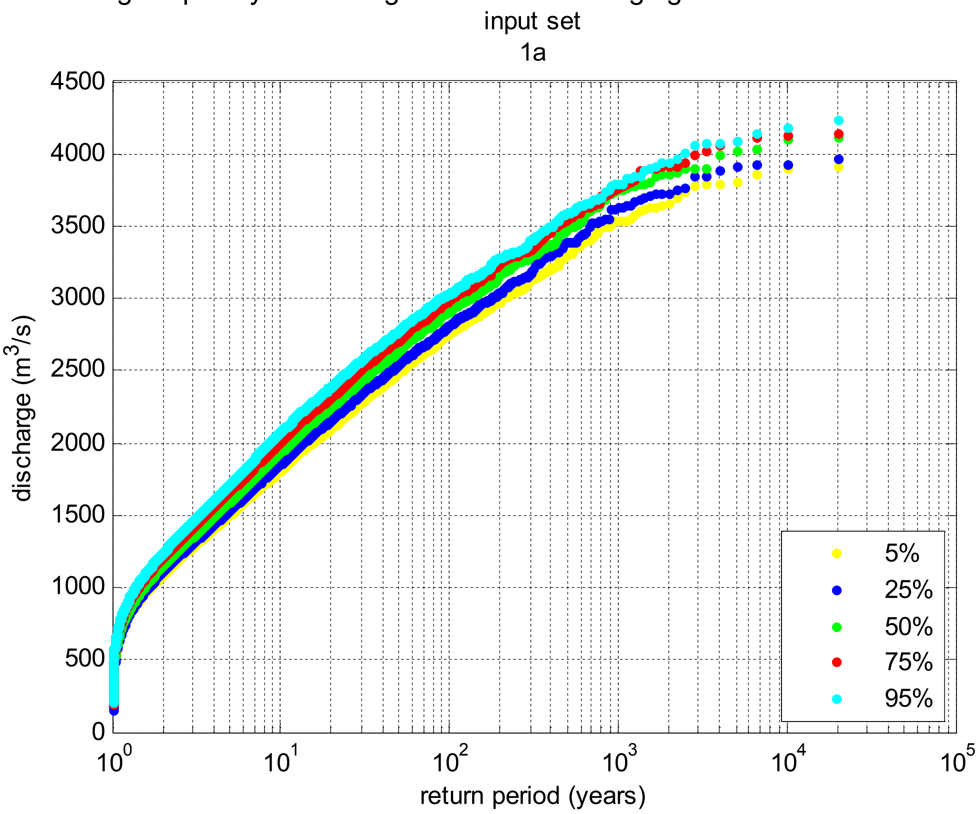
Measured and simulated discharges at Chaudfontaine for February 2002 and January 2003.

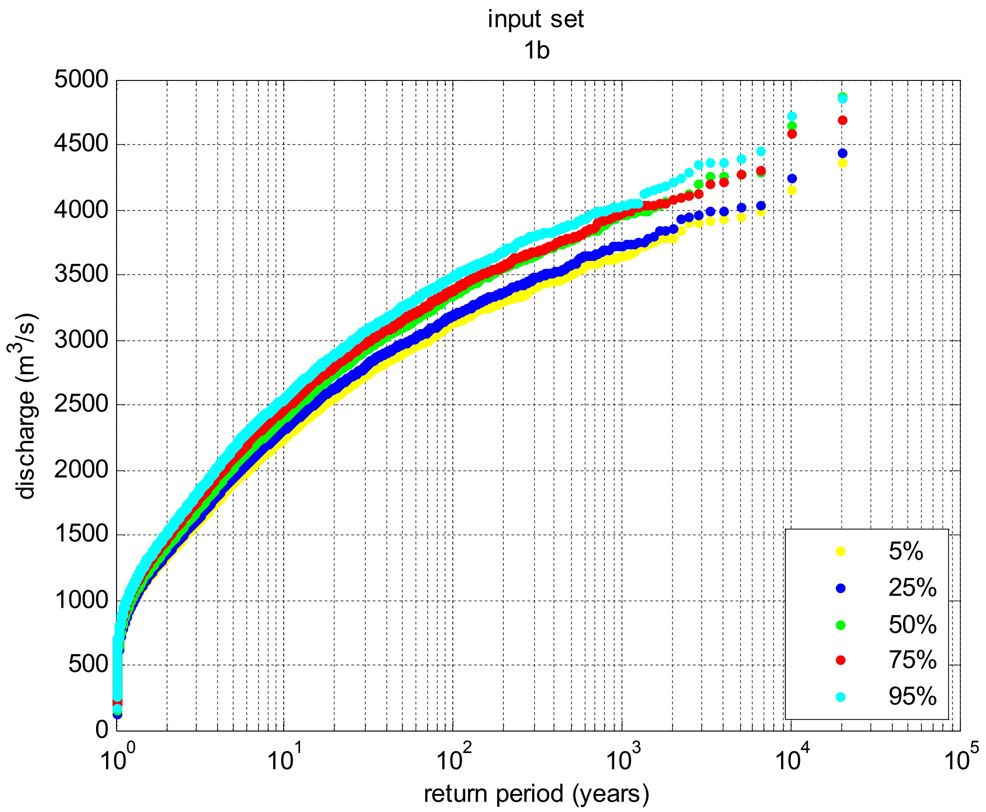


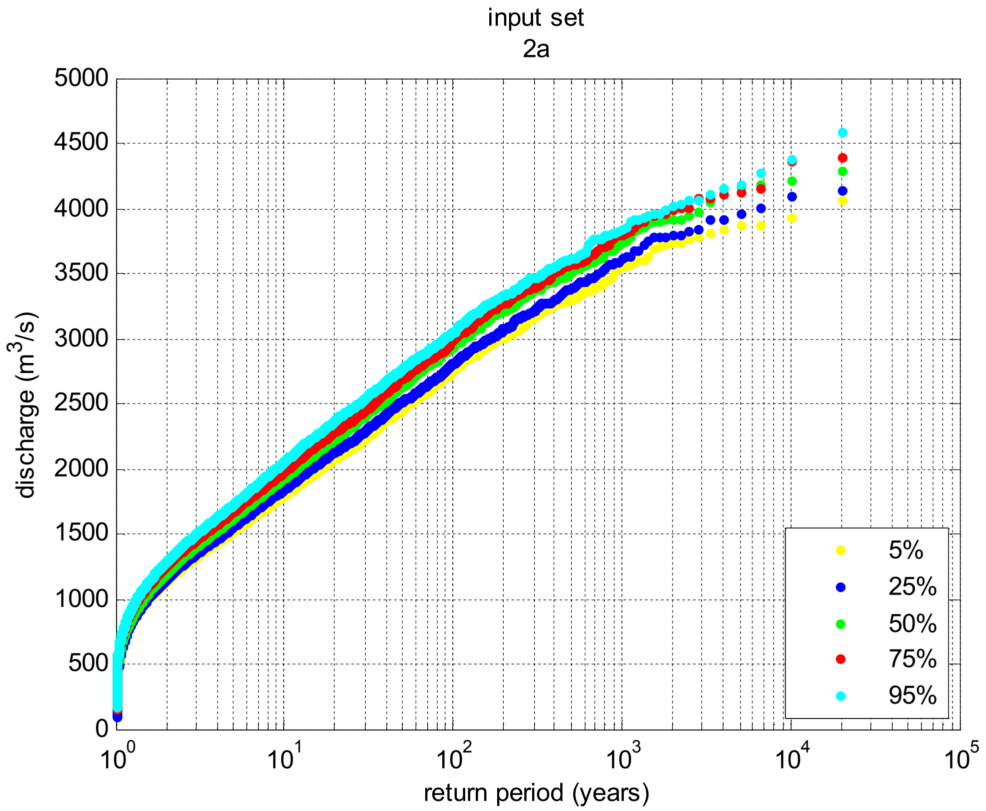
Measured and simulated discharges at Chooz for February 2002 and January 2003.

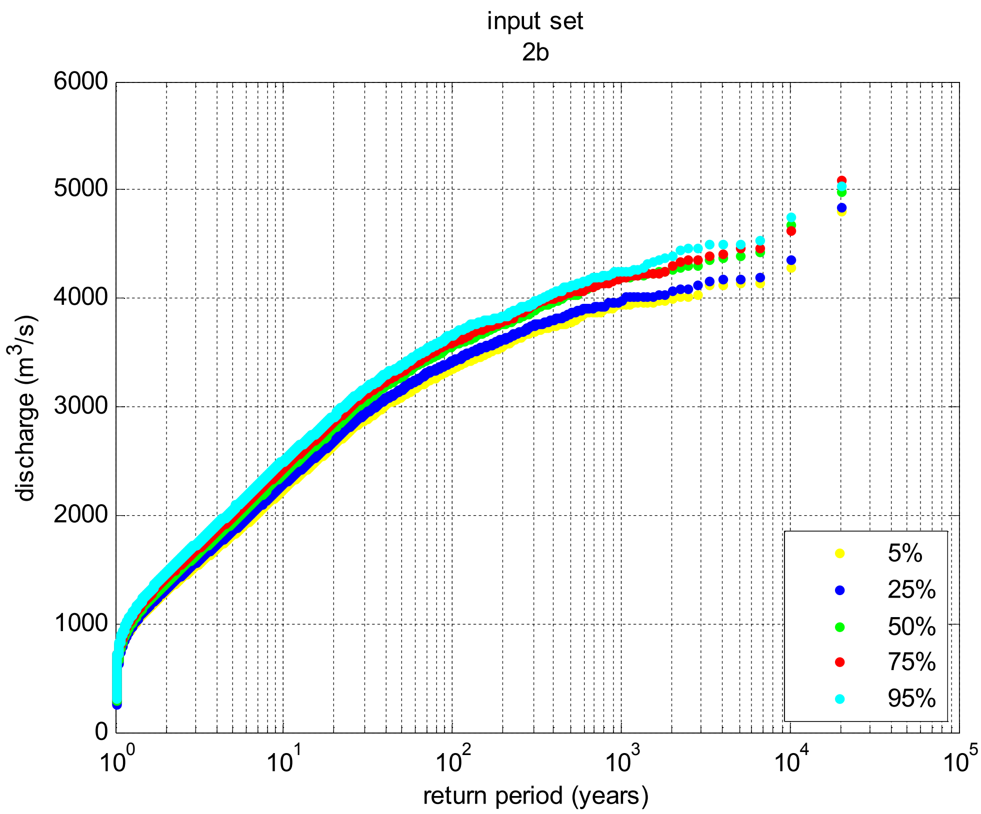
D Discharge exceedance probabilities

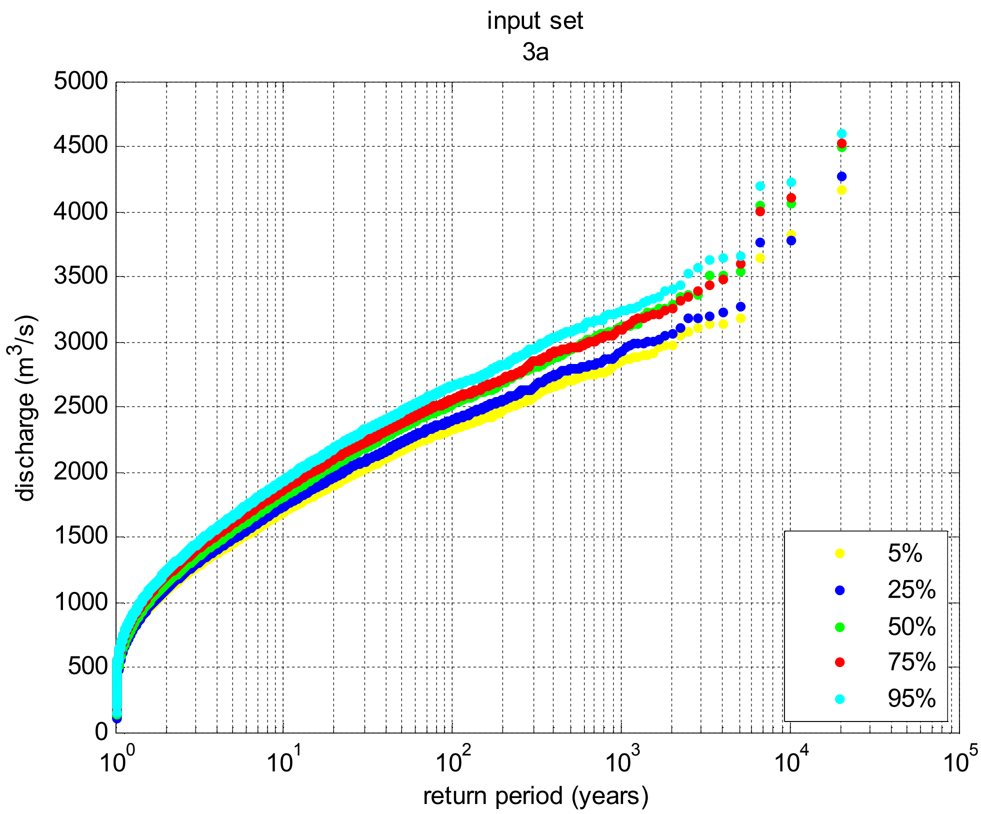
In this study five parameter sets were selected, describing the mean (50%), the upper (95%), lower (5%) and the quadrants (25% and 75%) percentiles of the flood frequency lines (as generated in the GLUE analysis) for Borgharen. These 5 parameter sets were combined with 8 times series input sets. This resulted in 40 combinations. For all combinations a simulation was made, using the GRADE instrument over 20.000 years. The resulting frequency lines are given in the following figures.

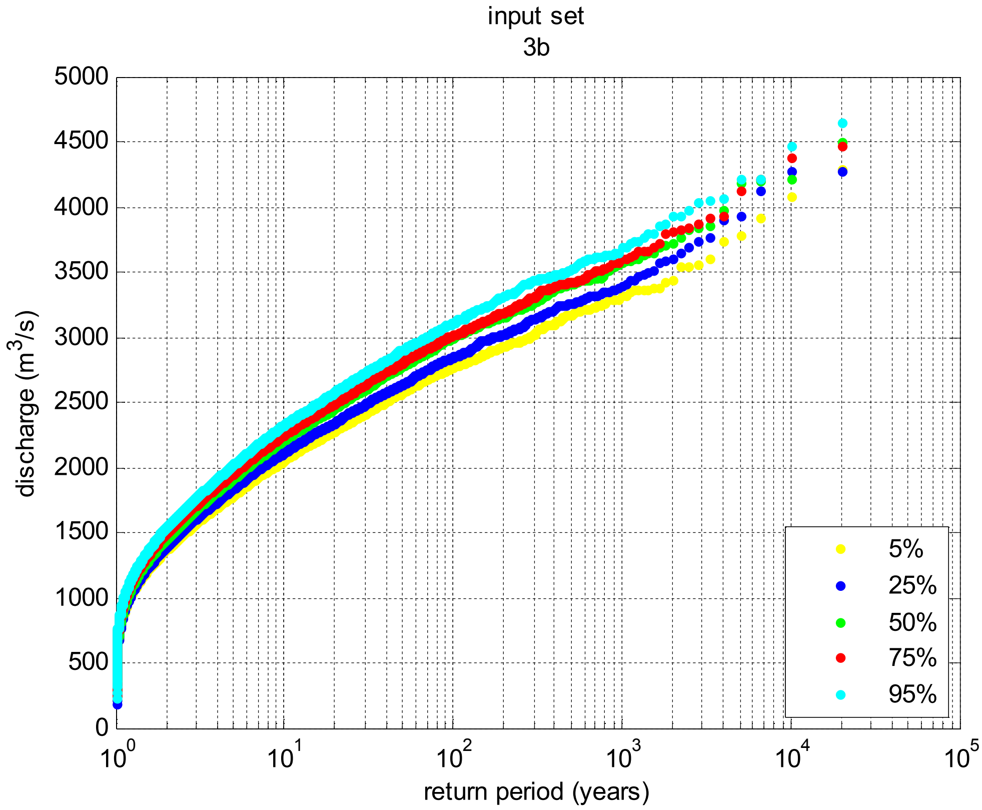


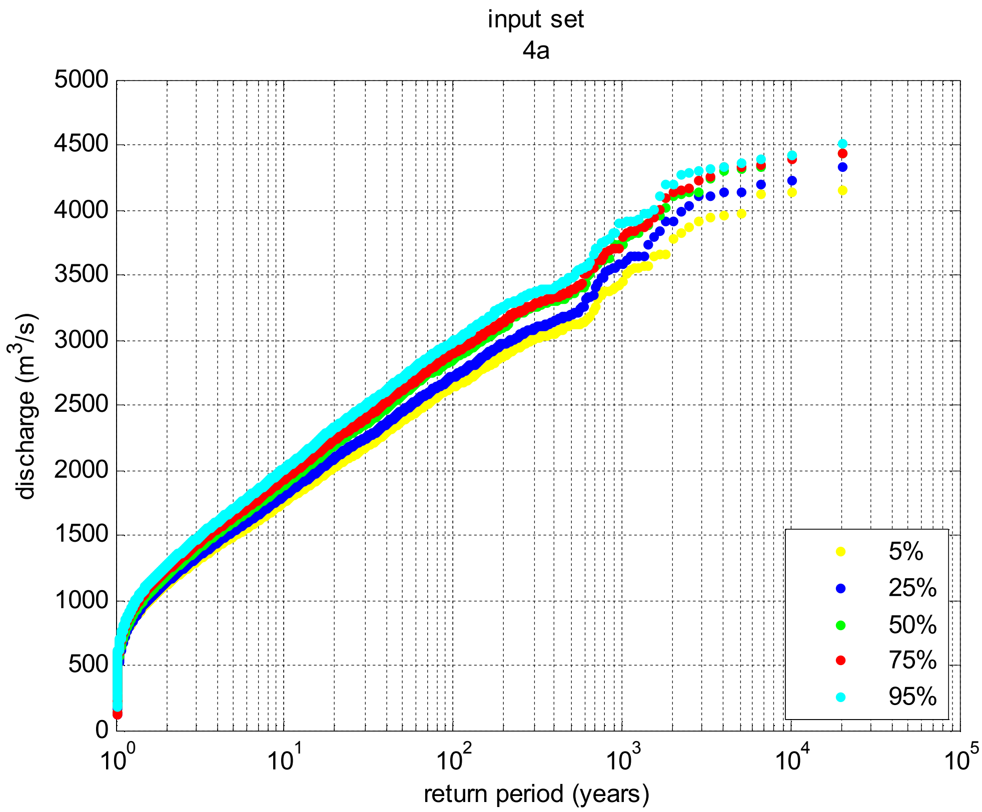

input set
1b
discharge (m3/s)
return period (years)
5%
25%
50%
75%
95%

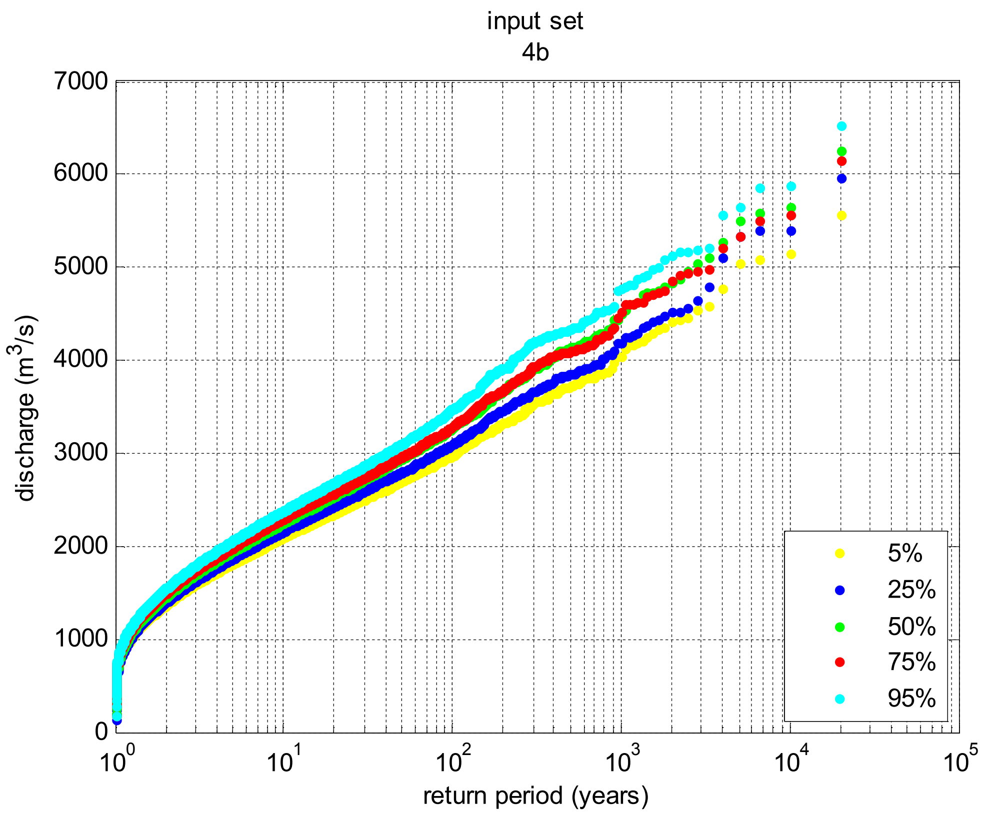

input set
2a
discharge (m3/s)
return period (years)
5%
25%
50%
75%
95%


input set
2b
discharge (m^3/s)
return period (years)
6000
5000
4000
3000
2000
1000
0
10^0
10^1
10^2
10^3
10^4
10^5
5%
25%
50%
75%
95%


input set
3a
discharge (m^3/s)
return period (years)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
10^0
10^1
10^2
10^3
10^4
10^5
5%
25%
50%
75%
95%


input set
3b
discharge (m3/s)
return period (years)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
10^0
10^1
10^2
10^3
10^4
10^5
5%
25%
50%
75%
95%


input set
4a
discharge (m3/s)
return period (years)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
10^0
10^1
10^2
10^3
10^4
10^5
5%
25%
50%
75%
95%


input set
4b
7000
6000
5000
4000
3000
2000
1000
0
discharge (m3/s)
10^0
10^1
10^2
10^3
10^4
10^5
return period (years)
5%
25%
50%
75%
95%