Deltares

Enabling Delta Life

Generator of Rainfall and Discharge Extremes

Part D & E

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Report

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Q4424

Client	Rijkswaterstaat Waterdienst
Title	GLUE analyse

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 a better physical basis for the estimation of the design discharge of the main Dutch rivers.

The goal of this project is to research the reliability of the GRADE instrument to determine the design discharges for the river Rhine at Lobith and the river Meuse at Borgharen. The project consists of 7 parts (A – G); in this report part D and E of the GRADE project are discussed.

In part D an assessment was made of the uncertainty caused by the limited length of precipitation data series used for the stochastic rainfall generator. This study concludes that the sampling error of the 1/1250-year discharge from a 20,000 year time series is approximately 100 m^3/s. Secondly, it is concluded that the exclusion of from the values of the extremely wet years 1984 or 1995 and the pre-selection of wet and dry winters have an effect on the normative discharge. The error due to *natural* variation in the basis set is less than 300 m^3/s.

In part E the uncertainty in the parameter choice of the hydrological component (HBV model) was studied, which is an extended research of the study from Weerts and Van der Klis (2006). A GLUE analysis is preformed for all HBV sub basins of the river Meuse. The 1/1250-year mean discharge, determined with the different hydrological models resulting from the GLUE analysis and a 3000 year time series of rainfall and evaporation, is 4300 m^3/s and 2 times the standard deviation is approximately 250 m^3/s. The standard deviation is a measure of the hydrological uncertainty in the 1/1250 year discharge.

References	

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Contents

Appendices

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 using frequency analysis of measured extreme discharges.

In 1996 Rijkswaterstaat RIZA and KNMI started to work together on a new methodology to provide an alternative method for the estimation of the design discharge of the main Dutch rivers, preferably on a (better) physical basis. The first component of this new methodology is a stochastic multivariate weather generator, which generates long simultaneous records of daily rainfall and temperature records into synthetic discharge series. 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. Advantages of the proposed methodology are that:

1. long discharge records can be simulated;
2. meteorological conditions and basin characteristics can be taken into account;
3. the shape and duration of the flood can be analysed; and
4. 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).

Once the overall performance of the Generator of Rainfall and Discharge Extremes (GRADE) instrument is known, it may start to play a role in the determination of the design discharges and corresponding water levels.

The current estimation of the 1250-year design discharges from statistical analyses of the measured peak discharges faces various problems, because it implies a far-reaching extrapolation based on a discharge record of about 100 years and is therefore hampered by a large uncertainty. There are a number of issues regarding this uncertainty that need to be mentioned:

- In the first place, it is unknown how representative the relatively short measured discharge records are for the full population of river discharges.

- Secondly, 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.

- Thirdly, the choice of frequency distributions is also a point of uncertainty.

- Finally, 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.

There is still a lot of indistinctness about the quantity of uncertainty of the GRADE instrument. In order to use the instrument to determine the design discharges the overall quantity of reliability has to be known.

In the parts D and E of the GRADE project the uncertainty analysis of GRADE is applied to the river Meuse upstream of Borgharen. This report gives an overview of the activities that were carried out and the results of this analysis.

1.2 Project description

This report is part of the extensive project where the main goal is to research the reliability of the GRADE instrument to determine the design discharges for the river Rhine at Lobith and the river Meuse at Borgharen.

The project consists of 7 parts.
In parts A and B the configuration of GRADE Rhine and Meuse in Delft-FEWS was carried out. With this instrumentation long generated temperature and rainfall records were transformed into discharge series.
In part C the shape and duration of extreme flood waves were analysed for both the Rhine and Meuse rivers.
In this report Part D and E are described and consist of the quantification of the model uncertainties, based on the application of GRADE to the Meuse river.
In part F an overview of the total uncertainty of GRADE will be given.
The project will finish with a workshop (part G), where the outcomes of the total study will be discussed.

In this report the following uncertainties are determined:

- Part D: Uncertainty caused by the limited length of precipitation data series used for the stochastic rainfall generator.

- Part E: Uncertainty in the parameter choice of the hydrological component (HBV model).

The determination of the uncertainty of the parameter choice is an extended research of the study from Weerts and van der Klis (2006).

1.3 Report layout

In Chapter 2 the uncertainty caused by the limited length of precipitation data series used for the stochastic rainfall generator is discussed. In Chapter 3 the uncertainty in the parameter choice is explained. In Chapter 4 the conclusions of this study are presented. In the last Chapter an indication is given which issues might be included in the research subjects of part F of the GRADE project, which aims at an integration of the uncertainties that were identified in the foregoing steps.

2 Sensitivity analysis GRADE

2.1 Introduction

As part of the development of GRADE (Generator of Rainfall and Discharge Extremes) a number of synthetic time series with a length of 20,000 years each have been produced by KNMI of daily precipitation, potential evapotranspiration (PET) and temperature in the Meuse basin. These time series were employed to calculate extreme discharge statistics of the Meuse river. The time series differ in the way a preselection was made of the historical observations that are used as a basis for the resampling. Also, a small variation was applied in the resampling method. The variation of the resulting discharge statistics gives an impression of the sensitivity to variations in the observation data set and resampling method. Specifically, the differences between the normative 1/1250 year discharges based on each of the time series give insight in the uncertainty of this quantity as a result of the sampling uncertainty.

The next section 2.2 gives a description of the synthetic time series of 20,000 years of precipitation, PET and temperature. In section 2.3 the results of the extreme discharge statistics for the reference time series and the uncertainty are discussed, whereas section 2.4 discusses the results for each of the synthetic time series. In section 2.5 the results are compared to observations and the normative exponential fit for the extreme discharges (werklijn). Conclusions and recommendations are given in sections 5 and 6.

2.2 Description of the 20,000 year time series

In an earlier study (Aalders *et al*, 2004), meteorological series were produced for the Meuse basin for a period of 3.000 years. For this study, 20,000 year time series were used. 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 and Buishand (2007).

The sensitivity of the extreme discharge statistics of the Meuse river to changes in the underlying 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, excluding both 1984 and 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.

For each case, two subsets (each of 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. This results in a total of 8 series.

Four additional series labelled '**c**' were generated, starting off from four subsets '**b**', using a slightly modified resampling algorithm in which the sampling of the same historical day on two consecutive days in the generated time series was not allowed (Leander, KNMI, pers.comm. 2007). All time series were created using a large moving calendar-day window of 121 days.

A reference time series (marked "00") was produced, based on all the available data (both 1984 and 1995). Altogether there are 13 time series. The settings used to create each of the 13 time series are listed in Table 2.1.

2.3 Reference time series

The time series discussed in the previous section were used to generate discharge time series of the Meuse river, using the HBV rainfall runoff model. From the discharge time series of 20,000 years extreme discharge statistics were calculated, using the annual maxima (ANN_MAX) and peaks over threshold (POT) methods. For the POT method a threshold of 1000 m^3/s and a time window of 30 days were used. The results for the reference time series ("00") are displayed in Figure 2.1. The resulting lines for the two methods differ only slightly at the lower return periods, but merge at higher values (T > 20 years).

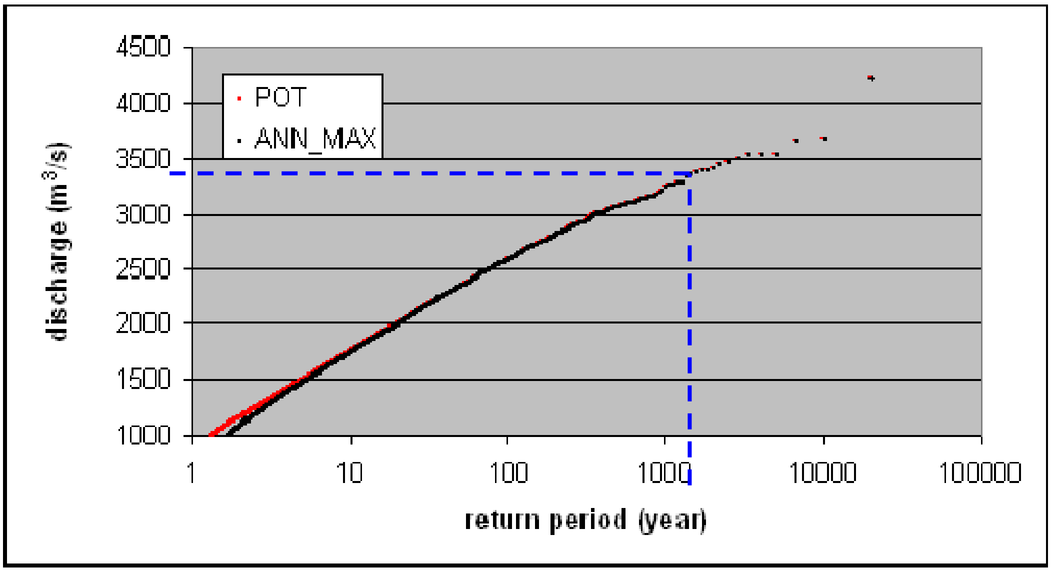

Figure 2.1: Extreme discharges of the Meuse river based on the reference time series ("00").

Theoretically, the difference between the return period T of a given discharge from the ANN_MAX method and the POT method is given by:

$$T_{ANN\_MAX} = \frac{1}{1 - \exp\left(-\frac{1}{T_{POT}}\right)} \qquad (1)$$

From Figure 2.1 we conclude that for return periods of 20 years or longer the two methods give the same result indeed.

The normative discharge for the dikes along the Meuse river has a return period of 1250 years. This discharge can be found from the list of extreme discharges as the 16th largest annual discharge in the 20,000-year time series (20,000/16=1250). From the reference time series (Figure 2.1) this discharge was found to be 3300 m^3.

The uncertainty of this discharge as a result of the limited length of the time series, defined as the root mean square error (RMSE), can be calculated from:

$$\mathrm{RMSE(Q)}=\frac{\partial \mathrm{Q}}{\partial \mathrm{T}}\mathrm{RMSE(T)} \qquad (2)$$

where the RMSE of the return period is given by:

$$\mathrm{RMSE(T)}=\sqrt{\frac{(1\text{-}\mathrm{P})}{\mathrm{NP}^3}} \qquad (3)$$

In equation 3, N is the number of samples (20,000) and P is the probability of sampling an ‘event’. For the normative discharge we take P=1/1250[1]. Combining equations 2 and 3 and estimating the slope ∂Q/∂T from Figure 2.1, we calculate the sampling uncertainty (RMSE) of the normative discharge to be about 100 m^3, or 3%. The discharges for this and other return periods and the associated uncertainties are plotted in Figure 2.2. Note that this uncertainty does not include possible errors in the HBV model or its input.

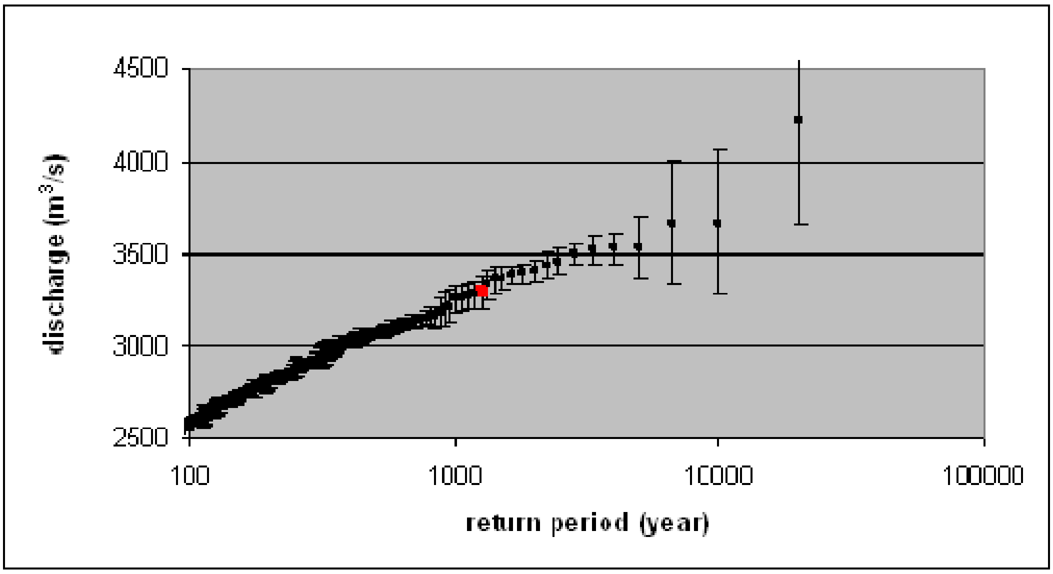

Figure 2.2: Discharge exceedance probabilities for the reference time series. The normative discharge (16th largest annual discharge) is indicated in red. Error bars represent the sampling uncertainty (RMSE). Note that any uncertainty in the HBV model or input is not included in this RMSE.

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[1] *Formally, it is incorrect to use P=1/1250, because we do not know whether the simulated number of events reflects their ‘true’ probability of occurrence. In practice, however, this method gives a fair estimate of the uncertainty.*

2.4 Alternative time series

The normative discharges (with a 1250 year return period) for all the 13 series are listed in Table 2.1. The extreme discharges are displayed in Figure 2.3.

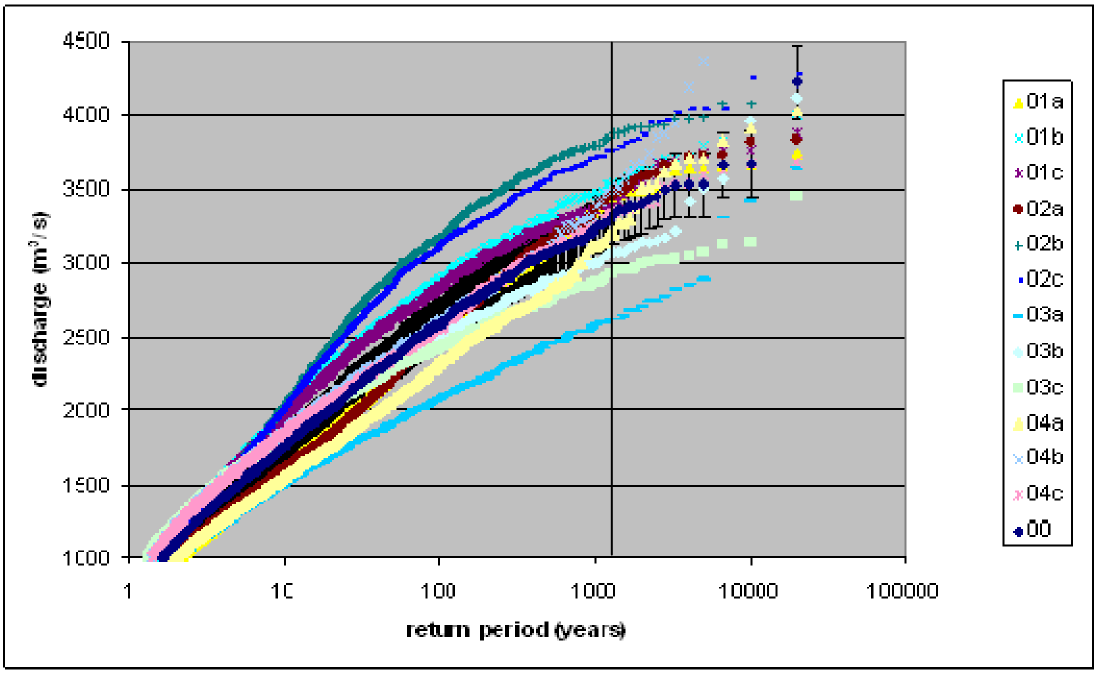

Figure 2.3: Discharge exceedance probabilities for each of the time series. The reference is "00".

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	Average discharge	Discharge (T=1250 years)
1a	x			x				210	3400
1b		x		x				239	3500
1c			x	x				240	3400
2a	x				x			213	3400
2b		x			x			**257**	**3800**
2c			x		x			**257**	**3800**
3a	x					x		**207**	**2600**
3b		x				x		266	3100
3c			x			x		**268**	**2900**
4a	x						x	228	3200
4b		x					x	262	3500
4c			x				x	262	3300
00				x				232	3300

Table 2.1: 1250-year discharges for the 13 time series.

Many of the time series in Table 2.1 yield a discharge curve that is within the sampling uncertainty of the reference time series “00”.
The calculated RMSE of the 1/1250-year discharge of 3300 m^3/s is 100 m^3/s. This corresponds to a 95% confidence interval of plus or minus 200 m^3/s. Time series with normative discharges between 3100 and 3500 m^3/s fall within this confidence interval. Series with a normaltive discharge outside these limits are shown in bold red in Table 2.1.

Time series 2b and 2c yield discharges that are larger than those from time series 1b and 1c. This can be the result of the exclusion of the wet year 1984 from the sampling data set. On the other hand, the difference between time series 2a and 1a is almost zero, which is not consistent with this hypothesis. Still, we conclude that there is some indication that the exclusion of 1984 from the basis data set enhances the 1/1250-year discharge in the Meuse river by an estimated 100-300 m^3/s.

Time series 3a and –to a lesser extent– 3b and 3c produce discharges that are significantly smaller than the corresponding time series that include the 1995 data (resp. 1a, 1b and 1c). The year 1995 saw rather extreme discharges and near-flooding of the Meuse river. Excluding the year 1995 from the sampling basis set reduces the 1/1250-year discharge by 400 to 800 m^3/s.

Finally, the average difference between the “low f&P” and the “high f&P” time series is 300 m^3/s. This suggests that the selection of low precipitation (P) and fraction of winter days (f) has an effect on the 1/1250-year discharge of approximately 10%.

2.5 Comparison to observations and exponential fit

The extreme value statistics of calculated discharges (for the reference series “00”) are compared to observations and the exponential fit that was used for HR2001 (‘werklijn’) in Figure 2.4. A clear deviation of approximately 400-500 m^3/s is observed.

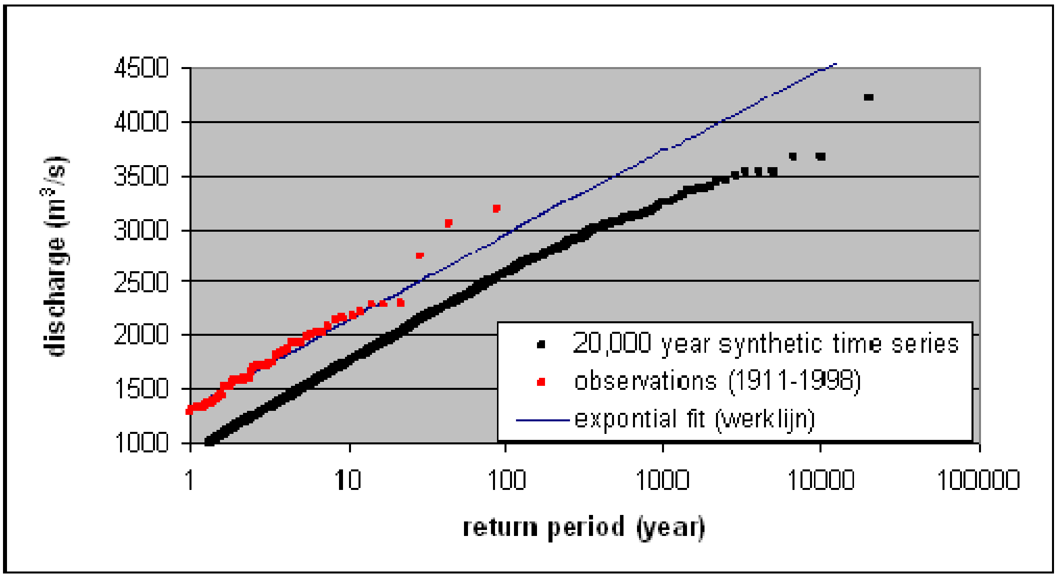

Figure 2.4: Extreme value statistics from the synthetic time series compared to 32 year observations and the expontential fit (“werklijn”).

There are (at least) three possible causes for this deviation:

- At least part of the difference can be attributed to the fact that the 'werklijn' is based on instantaneous peak discharges, whereas the resampling time series represent maximum daily averages. However, this effect should be no larger than 5 to 10% (M. de Wit, personal communication) and cannot be the only explanation for the observed difference in Figure 2.4.

- The average daily precipitation of the 20,000 year synthetic time series is found to be 3.4% lower than that of the basis set (1930-1998). According to KNMI (A. Buishand) it is a known that the nearest-neighbour resampling method does not reproduce the mean exactly due to a 'selection effect'. This 'selection effect' has been studied for the Rhine in (Buishand & Brandsma, *Water Resour. Res.*, **37** (2001), 2761 – 2776, Section 3.4 en Beersma & Buishand, *Clim. Res.*, **25** (2003), 121-133, Section 3.2.2). However, the average discharges in Table 2.1 show that there is little correlation between the average and the extreme (1/1250) discharges. Also, the average discharge for the reference time series "00" is close to the observed average discharge of 230 m^3/s at Borgharen[2].

- The third and most plausible cause for the difference between the 'werklijn' and the probability of exceedance from the resampled data set, is that the HBV model systematically underestimates the high discharge peaks. This was also found in a previous study in 2006[3]. The reason for this is that HBV is calibrated on the full time series, instead of on the discharge peaks. Figure 2.5 suggests that there is a correlation between the bias of the HBV model and the discharge. For less extreme discharge peaks around 1000 m^3/s the bias is small. For discharges around 4000 m^3/s the underestimation of the HBV model is much larger: between 400 and 600 m^3/s. This magnitude corresponds to the difference between the synthetic time series and the standard exponential fit (Figure 2.4).

Although it is not possible to simply add up these three causes to account for the deviations, together they can easily explain the differences between the normative discharge and the values found in this study.

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[2] *From: www.waternormalen.nl, based on observations between 1911 and 1990.*

[3] *Reliability of the Generator of Rainfall and Discharge Extremes (GRADE), WL | Delft Hydraulics report Q4268, December 2006.*

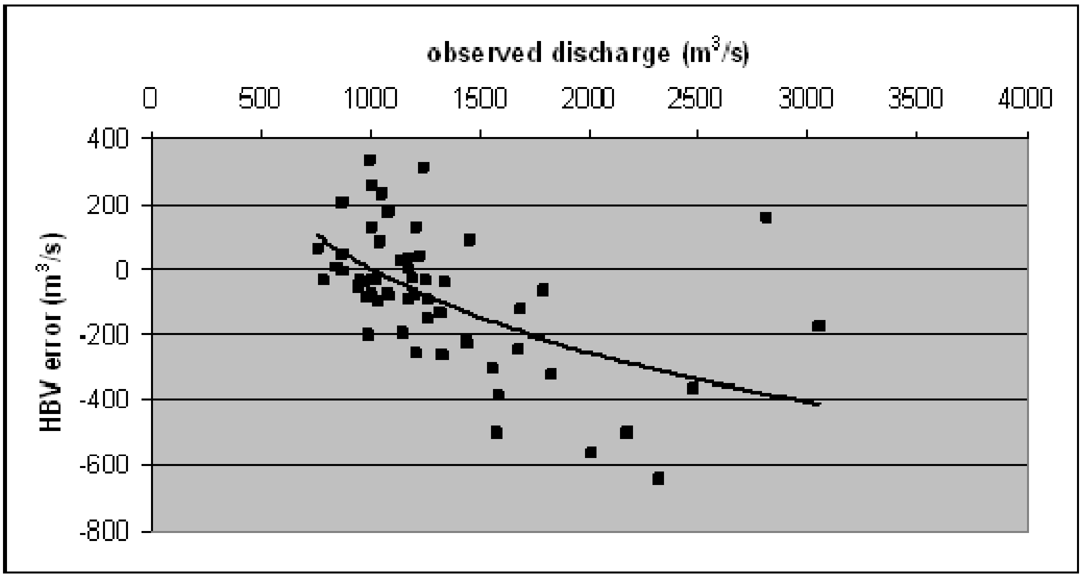

Figure 2.5: Bias of the HBV model as a function of observed discharge (POT observations between 1967-1998). The trend line indicates a possible increase of the systematic error for larger discharges.

3 GLUE analysis

3.1 Introduction

3.1.1 Background

The so-called GLUE (Generalized Likelihood Uncertainty Estimation) method is used to assess the effect of this uncertainty in the model parameters on the design discharges of the river Meuse at Borgharen. The GLUE method rejects the calibration concept of a single global optimum parameter set and instead accepts the existence of multiple acceptable parameter sets (Beven and Binley, 1992). In Weerts and Van der Klis (2006) a GLUE analysis was applied to the HBV-96 model for the river Meuse. Their study was a first step towards a quantitative analysis of the uncertainties in the design discharges derived with GRADE, in particular concerning the parameters of the hydrological model HBV. The uncertainty in these parameters have previously been mentioned as a potentially important source of uncertainty with respect to the extreme discharge peaks and the shape of the synthetic hydrographs (Passchier et al., 2004; Van der Klis, 2005; Ogink, 2006).

3.1.2 Study Weerts and Van der Klis (2006)

The purpose of Weerts and Van der Klis analysis was to determine an optimal model parameter set. Three criteria, R^2, RVE, and REVE (discussed later in this paper) were used to define the likelihood of each of the parameter sets. An ensemble of parameter sets was then formed by selecting those parameter sets which resulted in a model performance above a pre-defined threshold. The choice of the criteria and thresholds applied in the GLUE analysis was a subjective choice based on expert judgement (Weerts / Booij / De Wit).

The GLUE analysis resulted in a flood frequency curve at Borgharen, see Figure 3.1. The figure shows the mean flood frequency curve and the 95% confidence interval, derived from 1000 samples, together with the frequency curve obtained with the traditionally-calibrated HBV model by Van Deursen (2004) and the curve based on the discharge measurements at Borgharen.

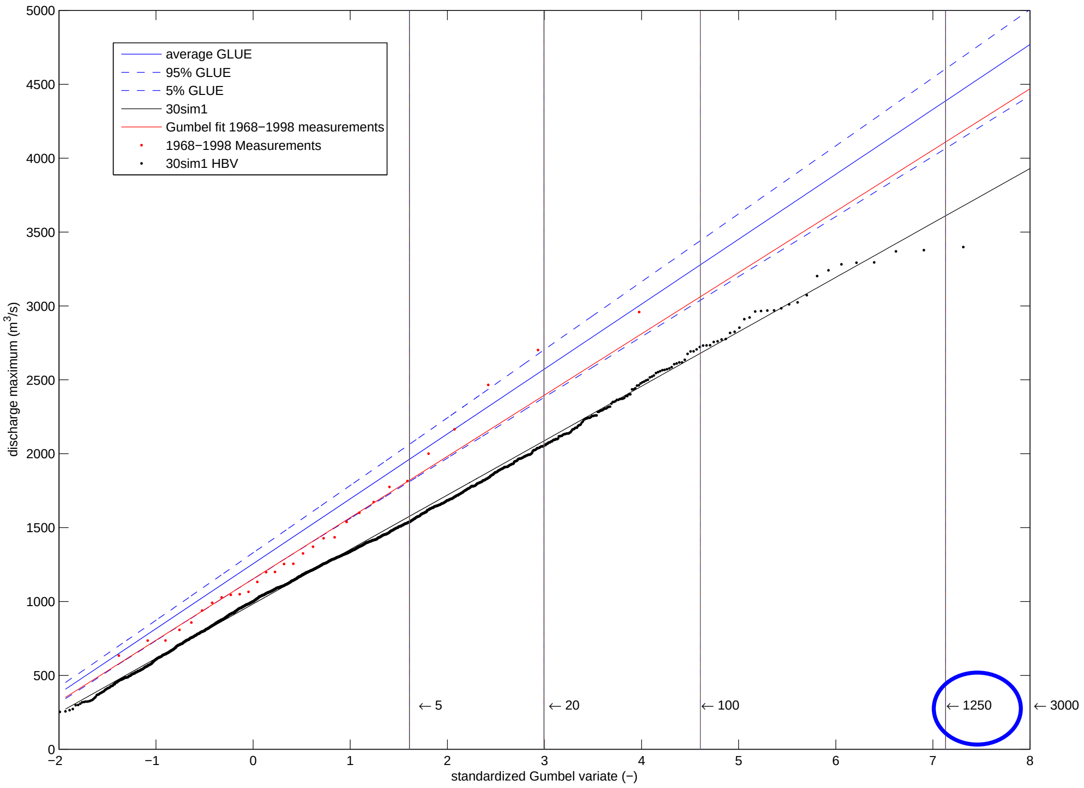

Figure 3.1 *Obtained mean (1000 realizations) flood frequency curve (blue line) with uncertainty (standard deviation, red lines). The line obtained with the original parameter set is also shown (black line). (Weerts and Van der Klis (2006))*

The results of this GLUE analysis were discussed at a workshop in December 2006 with specialists of RIZA KNMI, WL, HKV and Twente University. The discussion at the workshop indicated that there was insufficient confidence in the results, and resulted in some new questions:

1 What is the sensitivity of parameter sets to the chosen threshold values?

2 Why do the lower measured discharges (T < 5 years) fall outside the confidence interval?

3.1.3 Goal

The goal of the work described in this chapter is to provide an answer to the two questions in the previous paragraph raised during the workshop in December 2006, reformulated as:

1 Investigate the sensitivity of the outcomes to the choices which were made for return period and confidence interval.

2 Investigate why the lowest discharge lies outside the confidence interval.

3 Determine uncertainty in the 1/1250 year discharge at Borgharen.

During the project discharge data for the tributaries Viroin, Lorraine Sud and Nord and Semois in France became available. This data was not available during the earlier study.

3.1.4 Content

In paragraph 3.2 a description is given of the GLUE method and the HBV model of the river Meuse and the data used. Subsequently a sensitivity analysis is preformed on the return period and confidence interval, followed by a validation of the selected parameters for two downstream subbasins. Paragraph 3.5 describes the results of the GLUE analysis per sub basin. The effect on the river Meuse discharge at Borgharen is discussed in paragraph 3.6.

3.2 Data and methods

3.2.1 GLUE analysis

The GLUE method is a calibration method. In this method, an ensemble of parameter sets is selected from a large number of randomly sampled sets using prior probability distributions. For each of these randomly-sampled sets the model performance is measured using a likelihood function (or objective function). The ensemble is then formed by selecting those parameter sets that show a model performance above a chosen threshold.

The method used in a GLUE analysis is explained in Weerts and Van der Klis (2006). In this chapter some basic elements and values are clarified.

3.2.2 Fit-criteria

The choice of the likelihood function is critical, since it defines the likelihood of the parameter sets. Similar to Weerts and Van der Klis (2006), three functions (or fit-criteria) to define the likelihood of each of the parameter sets were used in the this study (part E). The functions used are the Nash-Sutcliffe efficiency coefficient R^2, the relative volume error RVE and the relative extreme value error REVE:

$$R^2 = \pi(Y \mid \theta) = 1 - \frac{\sum_{i=1}^{n} (Q_m - Q_o)^2}{\sum_{i=1}^{n} (Q_o - \overline{Q_o})^2} \tag{3.1}$$

$$RVE = \pi(Y \mid \theta) = \frac{\sum_{i=1}^{n} (Q_m - Q_o)}{\sum_{i=1}^{n} Q_o} \tag{3.2}$$

$$REVE = \pi(Y \mid \theta) = \frac{RV_m(T) - RV_o(T)}{RV_o(T)} \tag{3.3}$$

where

i	the time step,
n	the total number of time steps,
o	Observed value,
m	Modelled value, and
RV(T)	the T-year return value determined by fitting the Gumbel distribution to annual maxima (here, T=20 years).

The Nash-Sutcliffe efficiency coefficient is an indication of the overall performance of the model, RVE indicates if the cumulative discharge generated by the model does not deviate too much from the cumulative measured discharge and REVE indicates if the extreme value distribution matches the extreme value distribution obtained from the measured yearly maxima.

3.2.3 HBV-Model

The rainfall-runoff processes in the Meuse river basin are modelled by the HBV model gives a schematic overview of a HBV model in general (Figure 3.2).

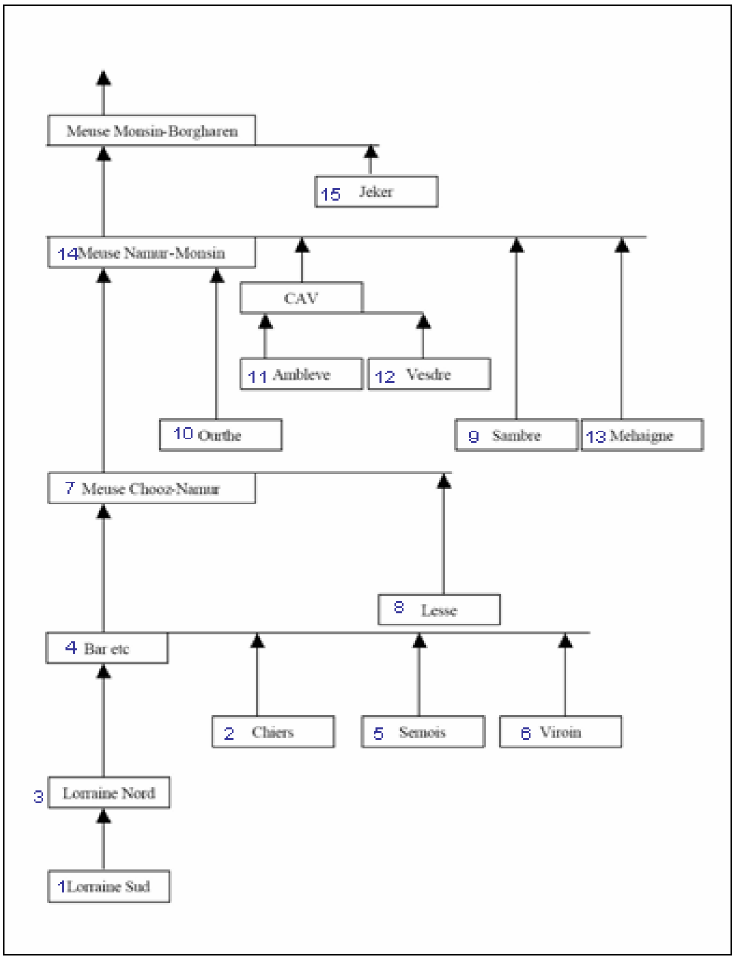

Figure 3.2 Overview of the HBV model of the river Meuse and the links between the subbasins. (CAV is a convolution of the subbasins Ambleve(11) and Vesdre (12)).

3.2.4 Parameters

In the HBV model the most important and uncertain parameters occur in the soil routine and in the fast flow routine (Booij, 2002).
The main parameters in the soil routine are *fc* (maximum soil moisture storage in millimetres), *lp* (fraction of *fc* above which evaporation will be reduced), and β (describing the relative contribution to runoff from a millimetre precipitation at a given soil moisture deficit).
The main parameters in the fast flow routine are α (measure of non-linearity), *hq* (geometric mean of the mean discharge and mean annual maximum discharge), and *khq* (recession coefficient at *hq*).

The current HBV model has been calibrated by Van Deursen (2004), of which the parameter values are listed in Table 3.1. For the calibration Van Deursen used the fit criteria; Nash-Sutcliffe efficiency coefficient (R^2) and the accumulated difference.

Table 3.1 Parameter values of the HBV model as calibrated by Van Deursen (2004).

subbasin	*fc*	*lp*	β	α	*hq*	*khq*
1 Lorraine Sud	293	0.39	1.39	0.73	2.54	0.079
2 Chiers	321	0.36	1.48	0.61	1.69	0.082
3 Lorraine Nord	318	0.35	1.73	0.68	2.54	0.079
4 Bar etc	160	0.95	1.2	0.7	3.5	0.076
5 Semois	300	0.45	1.62	0.62	4.3	0.086
6 Viroin	384	0.28	1.92	0.8	3.66	0.089
7 Chooz-Namur	365	0.31	1.58	0.57	3.23	0.078
8 Lesse	260	0.5	1.6	1.1	3.02	0.095
9 Sambre	365	0.28	1.42	0.27	2.56	0.08
10 Ourthe	260	0.53	1.8	1.1	3.27	0.0988
11 Ambleve	210	0.68	1.9	1	4.3	0.1
12 Vesdre	270	0.68	1.8	1.1	3.5	0.145
13 Mehaigne	266	0.41	2.07	0.24	2.56	0.078
14 Namur-Monsin	180	0.66	1.8	0.7	3.4	0.12
15 Jeker	273	0.4	1.97	0.15	2.56	0.078

Similar to the analysis by Weerts and Van der Klis (2006) an ensemble of parameter sets is selected from 5000 randomly sampled sets using prior probability distributions. The ranges from which the 5000 sets were sampled (Table 3.2) were based on literature (see Booij (2002) and references therein).

Table 3.2 Parameter values and ranges used in this study (based on Booij (2002)).

ter	Description	Min	Max
fc	maximum soil moisture storage [mm]	100	500
lp	fraction of *fc* above which evaporation is reduced	0.2	1
β	determines the relative contribution to runoff from a millimetre precipitation at a given soil moisture deficit	1	3
α	measure of non linearity in quick runoff	0.2	1.1*
hq	geometric mean of the mean discharge and mean annual maximum discharge	1.5	4.5
khq	recession coefficient at *hq*	0.05	0.15
maxbas	Routing, length of weighting function	3	4

* For some catchments this 1.1 was adjusted to 1.6 (Vesdre, Mehaigne)

For extra information about the applied method is referred to Weerts and van der Klis (2006).

3.2.5 Selection measured discharge data

For the GLUE analysis three datasets were available: the datasets already used in the study by Weerts and Van der Klis (2006) and datasets from the websites of Banque Hydro and Regional Wallonne (see references).
In Appendix A a discussion is given on whether to uses the origin data set (as used in Weerts and Van der Klis) or the new datasets. Table 3.3 gives an overview of the origin of the chosen sets.

Table 3.3 Overview of origin of measured discharge series per sub basin.

sub-basin	river	measurement location	source data	source data	period
1	Meuse	St-Mihiel	Banque Hydro	website	1968-2008
2	Chiers	Carignan	Banque Hydro	website	1968-2008
3	Meuse	Stenay	Banque Hydro	website	1968-2008
4	Meuse	Chooz	Région Wallonne	Weerts e.a.	1953-2008
5	Semois	Membre	Région Wallonne	website	1968-1982
6	Viroin	Treignes	Région Wallonne	website	1974-2006
8	Lesse	Gendron	Région Wallonne	website	1968-1998
9	Flor./Salz.	Sambre			-
10	Ourthe	Tabreux	Région Wallonne	Weerts e.a.	1968-1998
11	Ambleve	Martinrive	Région Wallonne	Weerts e.a.	1968-1998
12	Vesdre	Chaudfontaine	Région Wallonne	Weerts e.a.	1968-1998
13	Mehaigne	Moha	Région Wallonne	Weerts e.a. + website	1969-1996
14	Meuse	Monsin	Région Wallonne	Weerts e.a.	1968-1998
15	Jeker	Maastricht	Région Wallonne	Weerts e.a.	1980-1993 (missing values)
	Meuse	Borgharen	Région Wallonne	Weerts e.a.	1968-1998

3.3 Sensitivity analysis of the chosen threshold values

As described in the previous sections Weerts en van der Klis (2006) have chosen the return period and acceptance interval of the criteria based on expert judgement. The following criteria for acceptance were applied:

- The Nash-Sutcliffe efficiency coefficient R2 is situated between 0 and 1, the perfect score is 1. Using a threshold of 10 % the set is accepted for R2 score of >0.9 * maximum value of R2.
- The relative volume error RVE is situated between -1 and 1, the perfect score is 0. Using a threshold of 10 % the set is accepted for scores between -0.1 and 0.1.
- The relative extreme value error REVE is situated between -1 and 1, the perfect score is 0. Using a threshold of 10 % the set is accepted for scores between -0.1 and 0.1.
- T = 20

The following step is to determine the sensitivity of these choices. For two HBV sub-basins the results are compared using different threshold values and return periods.

The threshold values for the acceptance interval were adjusted by 5%, 10% and 20%. Return periods of 5, 10, 20 and 100 years were considered.

3.3.1 Results

The sensitivity analysis was preformed on 2 HBV catchments; Ambleve en Vesdre. Table 3.4 and Table 3.5 show the result of the sensitivity analysis. The first three columns give the acceptance interval (threshold) of the fit criteria. The fourth column gives the applied return period (which is used in the REVE fit criteria). Collum 5 to 8 give the number of accepted sets per threshold and return period. Collum 9 to 11 give the mean absolute error and the mean parameter value of all accepted sets. And the last column indicates whether the Van Deursen (2004) parameter sets is accepted for the applied fit criteria threshold values. The bold line values are the thresholds and return periods as used in Weerts and Van der Klis (2006).

Table 3.4 Results sensitivity analysis of sub basin Ambleve (Martinrive)

threshold			return period (year)	number of accepted parameter sets				mean value			Van Deursen parameter set accepted?
R2 (%)	RVE (%)	REVE (%)		R2 criteria	RVE criteria	REVE criteria	all criteria	R2 (-)	|RVE| (-)	|REVE| (-)	
Van Deursen parameterset				-	-	-	-	*0.88*	*0.004*	0.20	-
5	5	10	5	1220	1394	491	12	0.85	0.02	0.09	no
5	5	20	5	1220	1394	1132	137	0.86	0.03	0.16	no
10	5	10	5	2943	1394	491	85	0.82	0.03	*0.06*	no
10	5	20	5	2943	1394	1132	277	0.84	0.03	0.13	no
10	10	10	5	2943	2800	491	155	0.82	0.05	0.07	no
10	10	20	5	2943	2800	1132	527	0.84	0.05	0.13	no
20	20	20	5	4537	4966	1132	1033	0.81	0.08	0.11	no
Van Deursen parameterset				-	-	-	-	*0.88*	*0.004*	0.22	-
5	5	10	10	1220	1394	409	3	0.85	0.02	0.09	no
5	5	20	10	1220	1394	1015	104	0.86	0.03	0.16	no
10	5	10	10	2943	1394	409	55	0.82	0.03	0.07	no
10	5	20	10	2943	1394	1015	235	0.84	0.03	0.14	no
10	10	10	10	2943	2800	409	98	0.82	0.05	*0.07*	no
10	10	20	10	2943	2800	1015	445	0.84	0.05	0.14	no
20	20	20	10	4537	4966	1015	914	0.81	0.08	0.12	no
Van Deursen parameterset				-	-	-	-	*0.88*	*0.004*	0.23	-
5	5	10	20	1220	1394	373	2	0.85	0.03	0.10	no
5	5	20	20	1220	1394	910	73	0.85	0.02	0.16	no
10	5	10	20	2943	1394	373	40	0.82	0.03	*0.08*	no
10	5	20	20	2943	1394	910	194	0.83	0.03	0.14	no
10	**10**	**10**	**20**	**2943**	**2800**	**373**	**73**	**0.82**	**0.05**	**0.08**	**no**
10	10	20	20	2943	2800	910	368	0.83	0.05	0.14	no
20	20	20	20	4537	4966	910	806	0.80	0.08	0.12	no
Van Deursen parameterset				-	-	-	-	*0.88*	*0.004*	0.24	-
5	5	10	100	1220	1394	313	0	-	-	-	no
5	5	20	100	1220	1394	785	53	0.85	0.02	0.17	no
10	5	10	100	2943	1394	313	23	0.81	0.03	*0.08*	no
10	5	20	100	2943	1394	785	158	0.83	0.03	0.15	no
10	10	10	100	2943	2800	313	42	0.81	0.05	0.09	no
10	10	20	100	2943	2800	785	296	0.83	0.05	0.15	no
20	20	20	100	4537	4966	785	685	0.80	0.08	0.12	no

Table 3.5 Results sensitivity analysis of sub basin Vesdre (Chaudfontaine).

threshold			return period (year)	number of accepted parameter sets				mean value			Van Deursen parameter set accepted?
R2 (%)	RVE (%)	REVE (%)		R2 criteria	RVE criteria	REVE criteria	all criteria	R2 (-)	|RVE| (-)	|REVE| (-)	
Van Deursen parameterset				-	-	-	-	*0.80*	0.02	0.21	-
5	5	10	5	449	1215	855	1	0.78	*0.003*	0.10	no
5	5	20	5	449	1215	1759	37	0.79	0.03	0.17	no
10	5	10	5	1333	1215	855	23	0.75	0.03	*0.08*	no
10	5	20	5	1333	1215	1759	138	0.77	0.03	0.14	no
10	10	10	5	1333	2402	855	41	0.75	0.05	0.08	no
10	10	20	5	1333	2402	1759	255	0.77	0.05	0.14	no
20	20	20	5	3271	4444	1759	1062	0.72	0.08	0.11	no
Van Deursen parameterset				-	-	-	-	*0.80*	*0.02*	0.22	-
5	5	10	10	449	1215	792	0	-	-	-	no
5	5	20	10	449	1215	1678	21	0.79	0.03	0.17	no
10	5	10	10	1333	1215	792	10	0.75	0.02	0.09	no
10	5	20	10	1333	1215	1678	110	0.77	0.03	0.15	no
10	10	10	10	1333	2402	792	20	0.75	0.05	*0.08*	no
10	10	20	10	1333	2402	1678	205	0.77	0.05	0.15	no
20	20	20	10	3271	4444	1678	940	0.72	0.08	0.12	no
Van Deursen parameterset				-	-	-	-	*0.80*	*0.02*	0.23	-
5	5	10	20	449	1215	743	0	-	-	-	no
5	5	20	20	449	1215	1613	17	0.79	0.03	0.17	no
10	5	10	20	1333	1215	743	7	0.75	0.02	*0.09*	no
10	5	20	20	1333	1215	1613	95	0.76	0.03	0.15	no
10	**10**	**10**	**20**	**1333**	**2402**	**743**	**11**	**0.75**	**0.05**	**0.09**	**no**
10	10	20	20	1333	2402	1613	175	0.76	0.05	0.15	no
20	20	20	20	3271	4444	1613	862	0.72	0.08	0.12	no
Van Deursen parameterset				-	-	-	-	*0.80*	*0.02*	0.24	-
5	5	10	100	449	1215	666	0	-	-	-	no
5	5	20	100	449	1215	1514	13	0.79	0.02	0.18	no
10	5	10	100	1333	1215	666	7	0.74	*0.02*	*0.09*	no
10	5	20	100	1333	1215	1514	77	0.76	0.02	0.16	no
10	10	10	100	1333	2402	666	7	0.75	0.06	0.09	no
10	10	20	100	1333	2402	1514	140	0.76	0.05	0.16	no
20	20	20	100	3271	4444	1514	758	0.72	0.08	0.13	no

Out of the sensitivity analysis the following conclusions can be drawn:

- As could be expected, varying the thresholds affect the number of accepted parameter sets. The more lenient the criteria, the more accepted sets.
- Most parameter sets failed on the REVE criterion. This criterion indicates whether a fitted extreme-value distribution based on the model simulation corresponds with the fitted extreme-value distribution based on the yearly measured discharge maxima.
- In all cases the parameter set of Van Deursen did not meet the criteria, caused by rejection through the REVE criteria.
- When the error percentages increase the mean values of R^2 decreases and the mean values of |RVE| en |REVE| increase.
- The model performance is not very sensitive for changes in return period.

The percentages and the return period of 20 years used by Weerts and Van der Klis (2006) seem to be reasonable. However, the percentage of the REV criteria can be lowered to 5% without affecting the results too much. When calibrating a model it is important to simulate the volume balance correctly. Using a percentage of 10% for the RVE criteria only a small percentage of the sets are rejected through the Relative Volume Error, which means that this criterion has almost a negligible effect on the parameter set selection. Therefore, it is recommended to continue with a threshold percentage of 10%, 5% en 10% for the R^2, RVE and REVE criteria, respectively. Because the model performance is not very sensitive to return period changes, the remainder of the analysis was carried out with a return period of 20 years.

3.4 Validation 2005-2008 with hourly time series sets

The performance of the selected parameter set was analyzed using hourly time series data. Modelling with hourly time series requires extensive computing time. For this reason only one parameter set for Ambleve and one for Vesdre were selected; the selected parameter set was the one which performed best using daily time series data. The selected parameter set also adhered to the threshold values of 10%, 5% and 10% for the R^2, RVE en REVE criteria, respectively. The selected sets are given in Table 3.6.

Table 3.6 Selected parameter sets for sub basin Ambleve and Vesdre out of the daily sensitivity analysis

Catchment	Parameter set nr.	fc	beta	lp	alfa	hq	hkq	R^2	REV	REVE T=20	REVE T=100
Ambleve	Deursen	270	1.80	0.68	1.10	3.50	0.15	0.80	-0.02	-0.23	-0.24
Ambleve	1158	153	2.59	0.71	0.88	2.65	0.11	0.80	-0.02	-0.05	-0.07
Vesdre	Deursen	210	1.90	0.68	1.00	3.40	0.10	0.88	-0.004	-0.23	-0.24
Vesdre	3778	189	1.36	0.50	1.16	1.76	0.13	0.74	-0.02	-0.07	-0.09

The discharge at Ambleve and Vesdre was simulated in FEWS-NL for the period September 2005 to March 2008, using the Van Deursen (2004) and new parameter sets. The rainfall, temperature and discharge data originates form KNMI-SYNOP, TTRR and MSW. Figure 3.3 to Figure 3.6 show that the traditional parameter set (red line) has a higher base flow and lower peaks when compared with the new parameter set (blue line). However the performance is worse for the volume balance and for low flows. Generally the new parameter set approaches the measured peaks (green line) closer than the original sets, but the results are worse when attention is paid to the volume balance and low flows. The latter, though, are not important for the aim of GRADE. The outliers in the discharge measurements can be regarded as measurement errors.

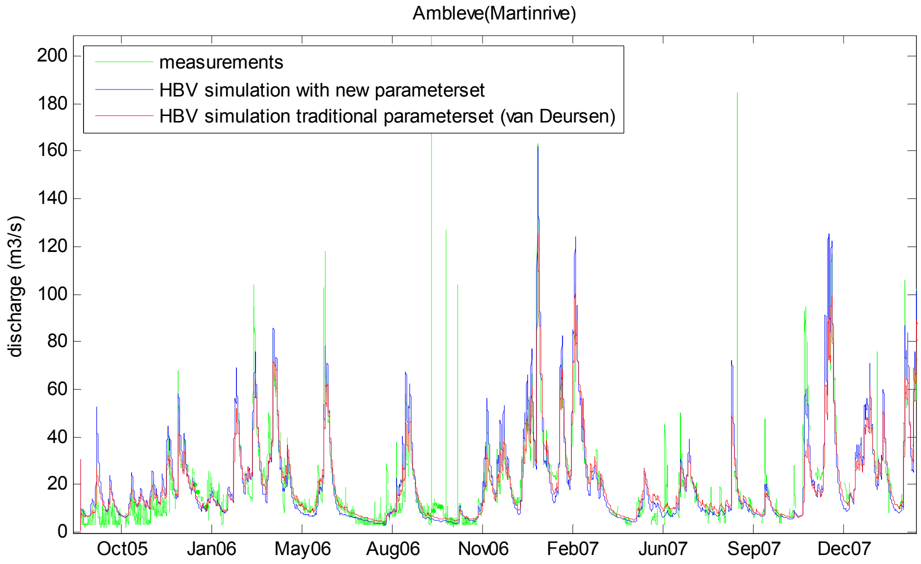

Figure 3.3 *Simulated discharges based on hourly data for subbasin Ambleve (Martinrive). (green line= measurements, red line= simulation using the parameterset of Van Deursen (2004), blue line= selected parameterset (Table 3.6)). (September 2006- March 2008)*

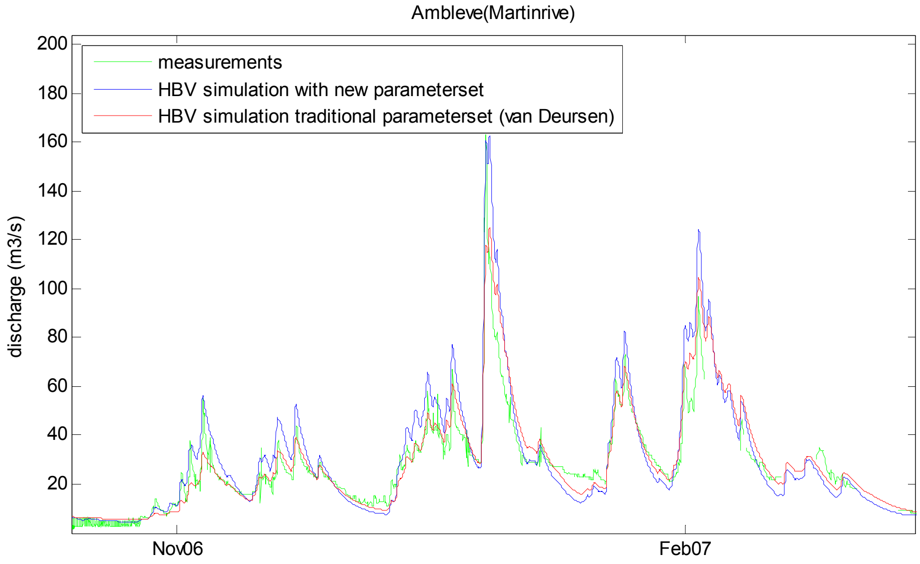

Figure 3.4 *Detail of Figure 3.3. (green line= measurements, red line= simulation using the parameterset of Van Deursen (2004), blue line= selected parameterset (Table 3.6)).*

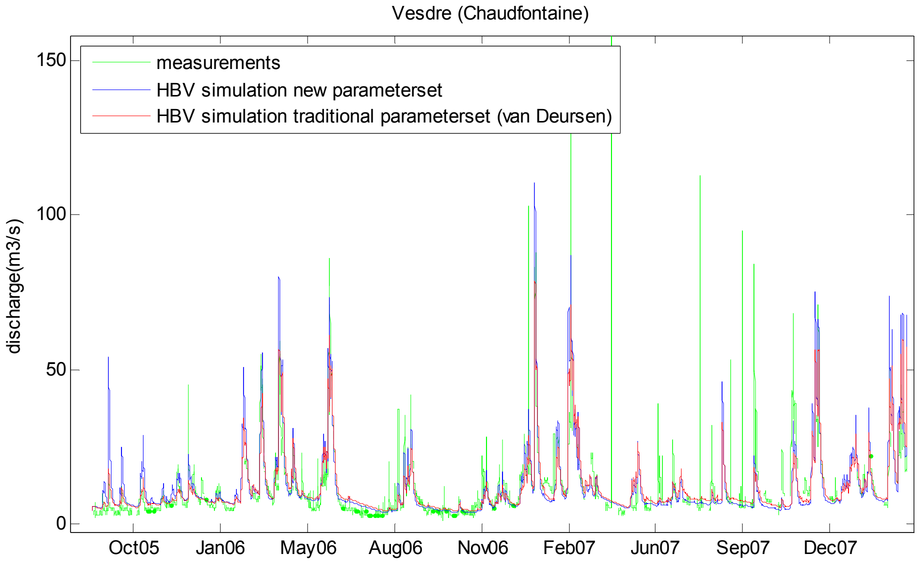

Figure 3.5 *Simulated discharges based on hourly data for subbasin Vesdre (Chaudfontaine). (green line= measurements, red line= simulation using the parameterset of Van Deursen (2004), blue line= selected parameterset (Table 3.6)). (September 2006- March 2008)*

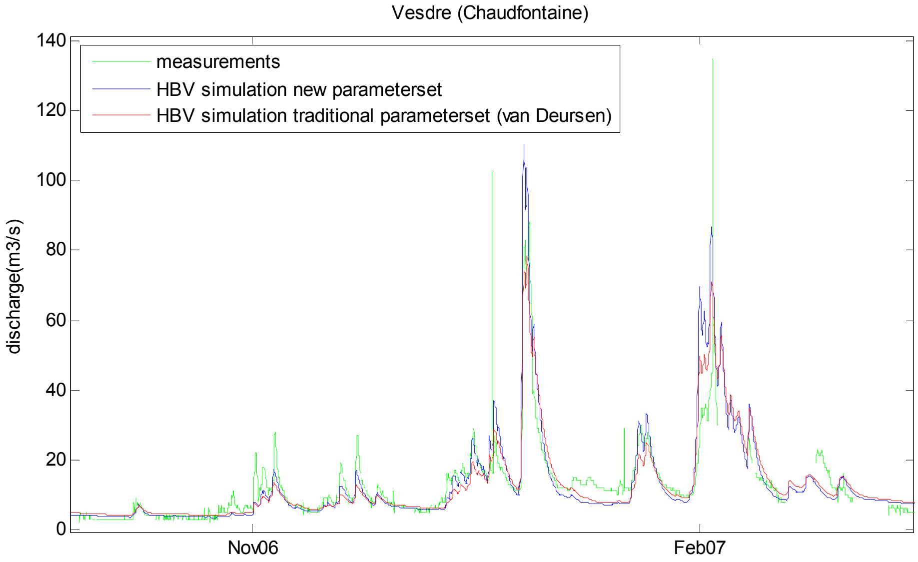

Figure 3.6 *Detail of Figure 3.5. (green line= measurements, red line= simulation using the parameterset of Van Deursen (2004), blue line= selected parameterset (Table 3.6)).*

3.5 GLUE analysis and food frequency curve for sub basins of the Meuse

In the previous paragraph the return period and acceptance interval of the criteria has been determined. These are used in the GLUE method, which is described in this paragraph.

3.5.1 GLUE analysis sub basins of the river Meuse

The GLUE analysis was carried out making use of the method described in Weerts and Van der Klis (2006). Differences in method are described below:

1. For the first sub basin (Maas, St-Mihiel) 7 parameters have been varied. The routing parameter “Maxbas” has been taken into account, too.
2. The acceptance interval (threshold) of the fit-criteria relative volume error RVE was changed into 5% (instead of 10 %).
3. For the gauging stations St-Mihiel, Carignan, Stenay, Membre, Treigne, Gendron and Moha some new discharge measurement series have been used.
4. The sub basins 1, 2, 3, 5 and 6 (see Figure 3.2) were calibrated independently. In Weerts and van der Klis the sub basins 2, 3, 5 and 6 were calibrated on the discharge series of Chooz.
5. To perform the GLUE analysis for sub basin 14 the parameters in the sub basins sets 1 to 6 were fixed in the same order like they were accepted in the GLUE analyse for Chooz.
6. To determine the flood frequency curve for Borgharen all parameters sets were fixed in the same order as they were accepted in the GLUE analysis for sub basin 14. This was not done in Weerts and van der Klis (2006) and caused the lower discharge measurements to fall outside confidence interval.

The GLUE analysis of the 14 sub basins of the Meuse river basin resulted in an ensemble of parameter sets per HBV sub model. Table 3.7 shows the number of parameter sets accepted (i.e. those that meet all fit criteria).

Table 3.7 number of accepted parameter sets per sub basin.

sub basin nr.	River	Location	Number accepted
1	Meuse	St-Mihiel	372
2	Chiers	Carignan	28
3	Meuse	Stenay	57
4	Meuse	Chooz	1344
5	Semois	Membre	739
6	Viroin	Treignes	38
7	Meuse	Chooz-Namur	2949
8	Lesse	Gendron	42
9	Flor./Salz.	Sambre	2949
10	Ourthe	Tabreux	23
11	Ambleve	Martinrive	40
12	Vesdre	Chaudfontaine	6
13	Mehaigne	Moha	53 *
14	Meuse	Monsin	2949

**For Mehaigne (Moha) an acceptance interval of 10 % for the RVE criteria has been used. The normal threshold values resulted in less accepted numbers.*

3.5.2 Flood frequency curve subbasins Meuse

The ensemble of HBV parameter sets per sub basin was used to make a flood frequency curve per sub basin. The flood frequency curve of every basin independently is showed in Appendix B.

3.6 GLUE analysis and flood frequency curve for Borgharen

3.6.1 GLUE analysis sub basins Meuse

All parameters sets, which were accepted in the GLUE analysis on the basis of the measurement at sub basin 14 have been used to generate a 3000-year discharge series at Borgharen using the HBV model. As input for the HBV model the rainfall series 3090 (smallwindow, 30sim1) obtained with the rainfall generator (Aalders et al., 2004) has been used.

3.6.2 Flood frequency curve Borgharen

The objective of this study is to quantify the effect of uncertainty in the model parameters of the HBV model on the flood frequency curves of the Meuse discharge at Borgharen.

For all of the 2949 set (selected for Monsin, see Table 3.7) 3000 year discharge series at Borgharen are generated using HBV. For each of these 3000-year discharge series the year maxima have been extracted and a Gumbel distribution has been fitted to these series of annual maxima. This resulted in 2949 samples of the flood frequency curve of the Meuse discharge at Borgharen. The spread in these samples represents the uncertainty in the frequency curve due to the uncertainty in the model parameters of HBV. Note that this is not the same as the uncertainty in the frequency curve.

This method results in an ensemble of 2949 flood frequency curves. The mean frequency curve and the 95% confidence interval, derived from the first 500 samples (500 instead of 2949, because of time consuming calculation time), are shown in Figure 3.7, together with the frequency curve obtained with the traditionally calibrated HBV model and the curve (i.e. fitted Gumbel distribution) based on the discharge measurements.

The measurements in Figure 3.7 have been plotted using the following 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)

The value of c = 0.44 results in the Gringorten plotting position that is typically used for the Gumbel distribution.

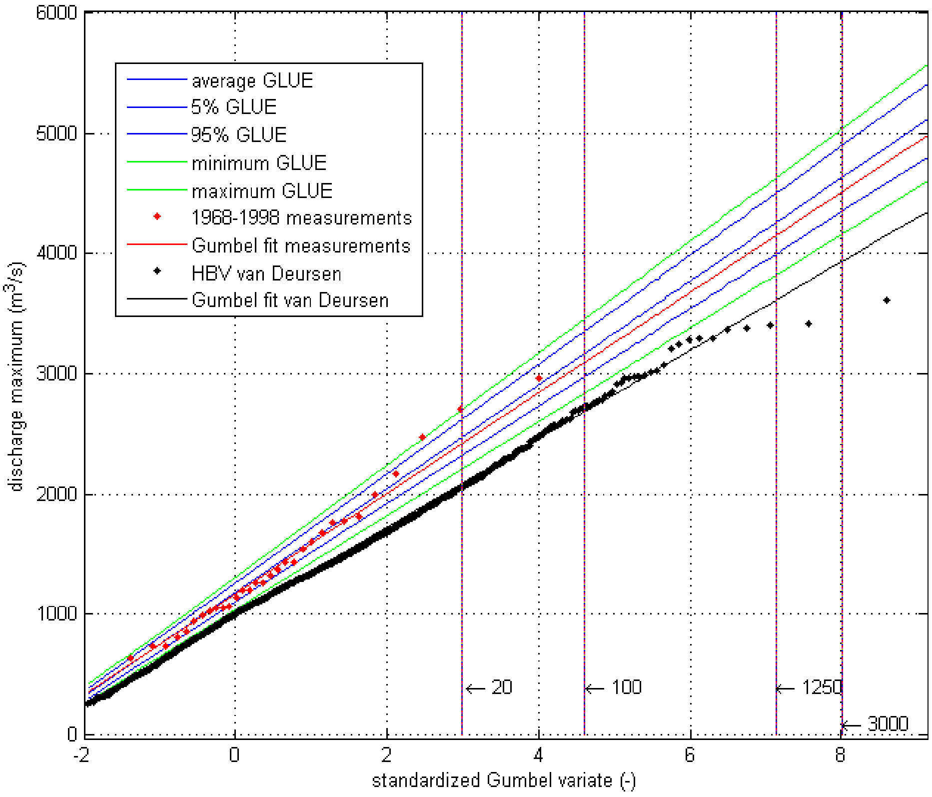

Figure 3.7 *Obtained mean and confidence interval of the flood frequency curve for the first 500 realizations (blue lines). The red line shows the resulting extreme value distribution using the measurements. The red dots show the measurements. The black lines shows fit using the traditional parameter set.*

This implies that the result of this study is not a single global optimum parameter set, but the result leads to multiple acceptable parameter sets. The figure shows that all measurements are located in the confidence interval of the mean flood frequency curve. According to the GLUE analysis the 1/1250-year mean discharge from a 3000 year time series is 4250 m^3/s and the two times the standard deviation is approximately 250 m^3/s.

De Wit and Buishand (2007) shows a systematic underestimation of HBV for average floods peaks in the Meuse of 10% of the discharges (in that study the parameters of Van Deursen are used). The underestimation is also shown in the flood frequency curve (black line). Using this it can be concluded that the underestimation is among other things caused by the parameter choice. The figure shows that all GLUE parameter sets give a better approximation of the measured flood frequency curve at Borgharen than the flood frequency curve obtained with the parameter set as determined by Van Deursen (2004).

A note have to be made about the flood frequency curve. Figure 3.8 shows for a limited amount (12) of accepted parameter sets the yearly maxima and the flood frequency curve (Gumbel fit). The figure shows that the simulated yearly maxima dots bend away, whereas the fit is a straight line. This is caused by the choice of a Gumbel distribution function. For extreme discharges the Gumbel fit will give higher results than the simulated yearly maxima.

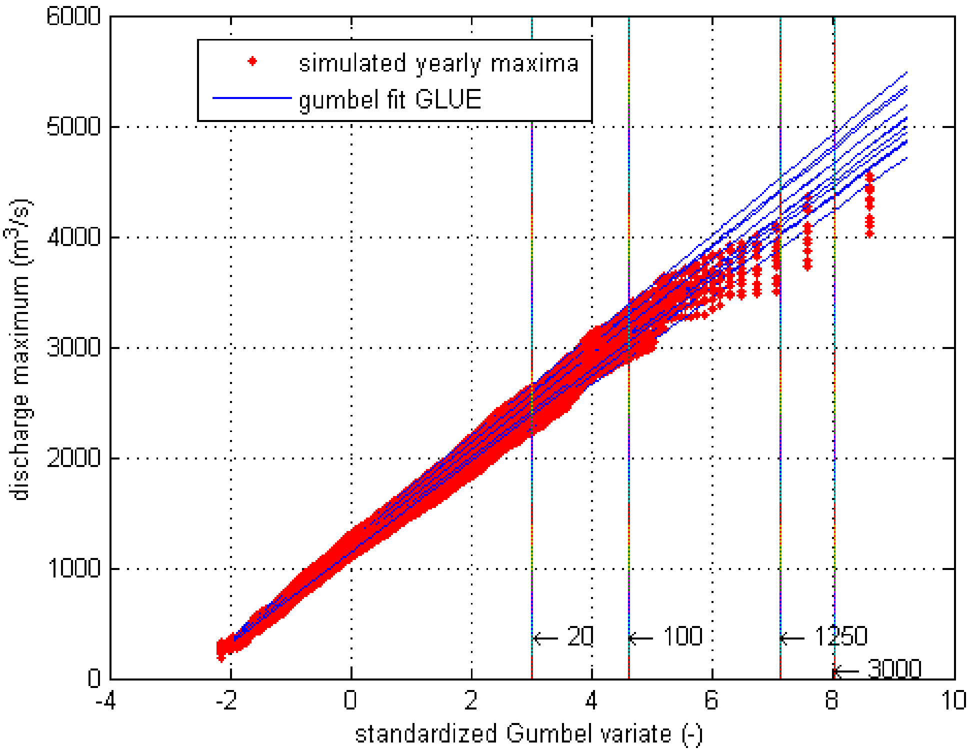

Figure 3.8 *The blue lines shows the extreme value distribution for the first 12 parameter sets using the yearly-maxima of the simulated 3000 year timeseries (red dots).*

4 Conclusions

This report is divided in 2 parts:

- Part D: Uncertainty caused by the limited length of precipitation data series used for the stochastic rainfall generator.

- Part E: Uncertainty in the parameter choice of the hydrological component (HBV model). – GLUE analysis.

In part D the following uncertainties are determined:

- The 20.000 reference time series shows a systematic underestimation of the extreme discharges compared to the observations and the usual exponential fit (‘werklijn’). This bias is partly due to the fact that the resampled time series are based on daily averages (instead of instantaneous values), but this effect cannot explain the total difference. The most plausible cause is that the HBV model underestimates the peak discharges, because it is calibrated on the full time series instead of on the peaks.

- The sampling error of the 1/1250-year discharge from this 20,000 year time series is approximately 100 m^3/s. The daily discharge with a return period of 1250 years is 3300 m^3/s.

- From the difference between the reference and 12 alternative time series it is concluded that the exclusion of observations from 1984 or 1995 and the pre-selection of wet and dry winters have an effect on the normative discharge. The variation of the 1/1250-year discharge is approximately 300 m^3/s (RMSE).

The following conclusions can be draw concerning part E:

- In the GLUE analysis an ensemble of HBV-parameter sets was determined. Every parameter set resulted in a flood frequency curve (using a 3000-year HBV simulation). These flood frequency curves (figure 4-1), correspond well with the flood frequency curve fitted through the measured yearly maxima. All measured yearly maxima are located in the 95% confidence interval of the GLUE analysis flood frequency curves. The measured yearly maxima are determined from a daily discharge dataset of the period 1968 to 1998 at Borgharen.

- In the GLUE analysis it was shown that the original parameter set as calibrated by Van Deursen (2004) underestimates the discharge for yearly maxima.

- The 1/1250-year mean discharge, determined with the different hydrological models resulting from the GLUE analysis and a 3000 year time series of rainfall and evaporation, is 4300 m^3/s. Two times the standard deviation is approximately 250 m^3/s. The standard deviation is a measure of the hydrological uncertainty in the 1/1250 year discharge.

5 Proposed activities for Part F of the GRADE project

Although the Part F of the GRADE project only aims at providing a synthesis of the results of the foregoing studies (especially Parts D & E), a number of follow-up activities are recommended to be performed in Part F based on the results of Part D& E:

- The GLUE analysis showed that the parameters as determined by Van Deursen (2004) underestimate the yearly maximum peak discharges. The parameters sets selected in the GLUE analysis describe the yearly maximum peaks better. Because the parameter set determined by van Deursen (2004) is also used in the operational system these should also be updated. One possible way to do this would be to select a limited number of parameters sets (start with three describing the mean and the upper (95%) and lower (5%) percentiles at Borgharen) and use these three selected parameter sets in the operational system. In order to further analyse whether the selected parameter sets give a good approximations of reality, it is recommended to recalculate the flood events of December 1993, January 1995, November 1998, March 1999, December 1999, March 2000, January 2001, February 2002, January 2003, and January 2004 as calculated by Weerts (2007), using the three parameter sets as described above and compare the outcome with the results obtained with the parameter set as determined by Van Deursen (2004).

- In order to determine the total uncertainty in GRADE (hydrological + meteorological) it is necessary to combine the different hydrological models (resulting from the GLUE analysis) with the different meteorological inputs (as described in part D). Given the limited amount of time and resources, it maybe practical to start with a limited number of hydrological model simulations (again start with the three as mentioned above) and combine these with the different 10,000 year meteorological time series to get an impression of the total uncertainty in the 1/1250 year discharge determined with GRADE.

6 References

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http://voies-hydrauliques.wallonie.be/opencms/opencms/fr/hydro/annuaires/index.html

Banque Hydro : http://www.hydro.eaufrance.fr/

A Selection measured discharge series

In this Appendix a comparison has been made between the original, Walloon and French measures discharge series to select per station the most useful discharge series.

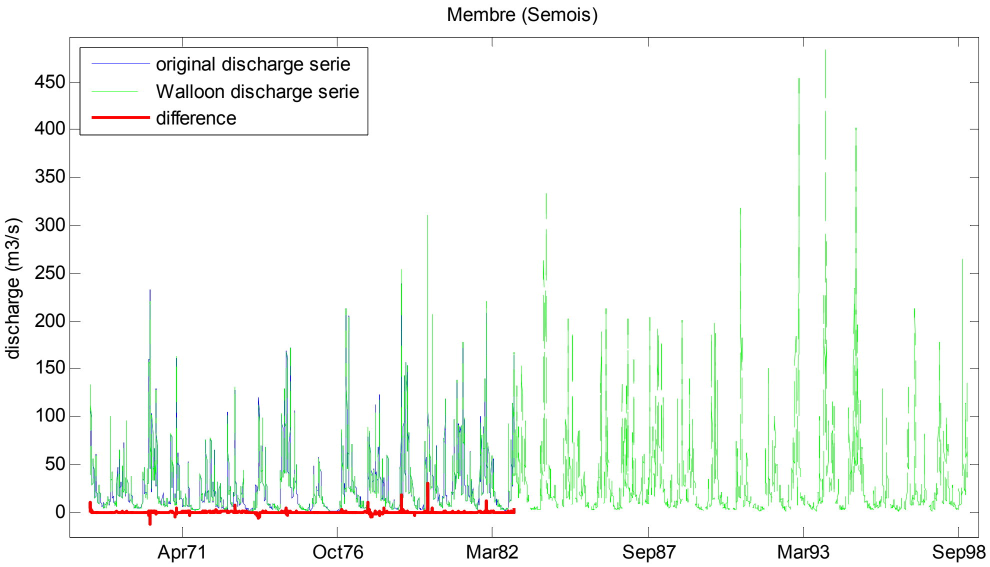
Original measured discharge series
The original discharge series as it is used in Weerts (2007). In the table below the length of the available time series is given.

sub-basin	**river**	**measurement location**	**period**
1	Meuse	St-Mihiel	1980-1997, with missing values
2	Chiers	Carignan	*not available*
3	Meuse	Stenay	1980-1997, with missing values
4	Meuse	Chooz	1986-1997
5	Semois	Membre	1968-1982
6	Viroin	Treignes	*not available*
8	Lesse	Gendron	1986-1998
9	Flor./Salz.	Sambre	*not available*
10	Ourthe	Tabreux	1986-1998
11	Ambleve	Martinrive	1986-1998
12	Vesdre	Chaudfontaine	1986-1998
13	Mehaigne	Moha	1969-1996
14	Meuse	Monsin	1986-1998
15	Jeker	Maastricht	1980-1993, with missing values
	Meuse	Borgharen	1986-1998

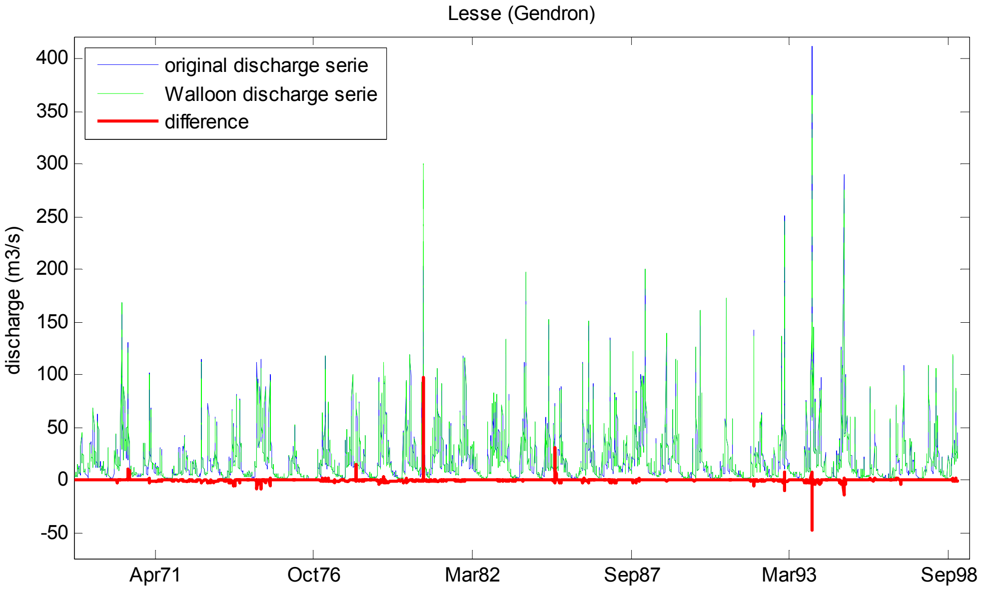
Walloon discharge series

The Walloon measured discharge originates from Région wallonne (http://voies-hydrauliques.wallonie.be/opencms/opencms/fr/hydro/annuaires/index.html). In the following table and figures the difference between the original and Walloon dataset is further explained. No data available for basins 1 – 4 & 9 (French Meuse).

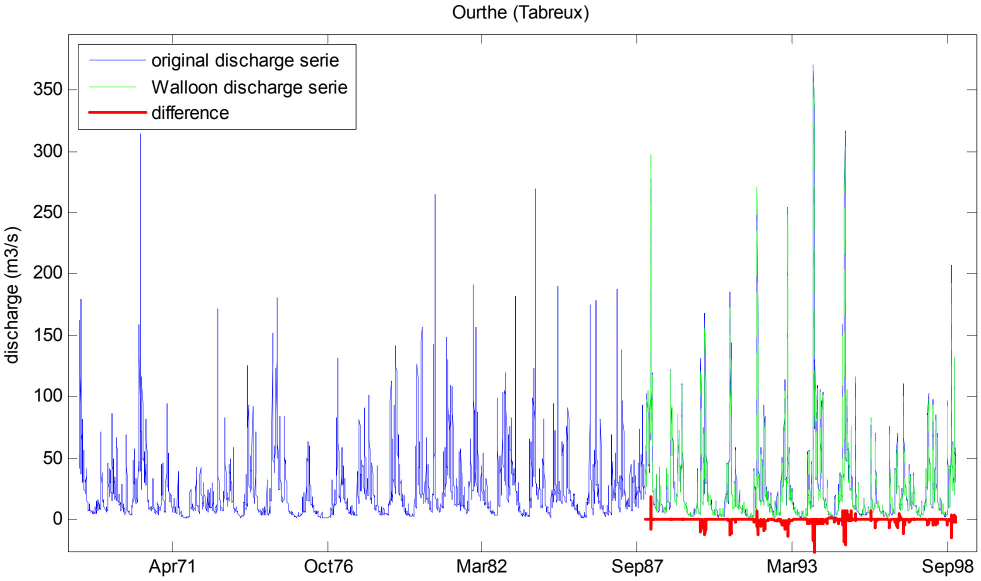
sub-basin	river	measurement location	period	difference with original dataset
5	Semois	Membre	1968-2006	- extended discharge set - peak correction
6	Viron	Treignes	1974-2006	- no original dataset available
7	Meuse	Chooz	1990-2006	- extended discharge series
8	Lesse	Gendron	1968-2006	- peak correction
10	Ourthe	Tabreux	1988-2006	- small differences in discharge - extended discharge series
11	Ambleve	Martinrive	1974-2006	- small differences in discharge - extended discharge series
12	Vesdre	Chaudfontaine	1992-2006	- small differences in discharge - extended discharge series
13	Mehaigne	Moha	1974-2000	- original set start at earlier timestep, Walloon data ends at later time



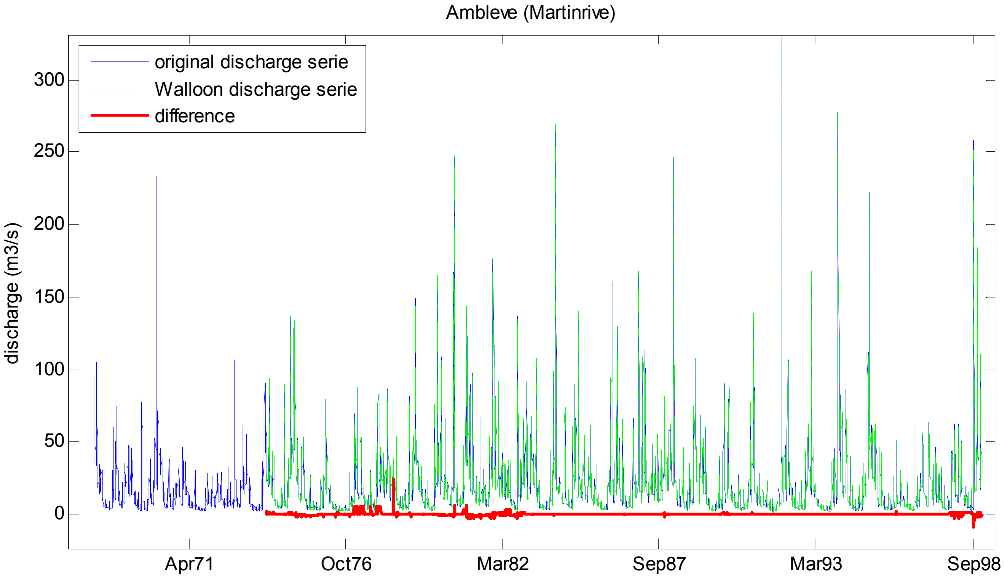
Semois (Membre)



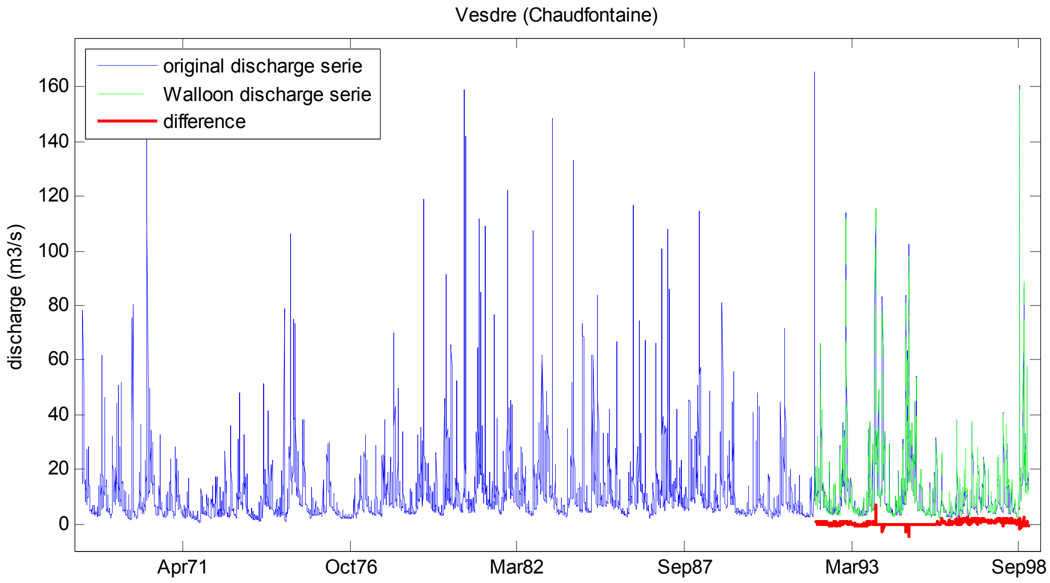
Lesse (Gendron)



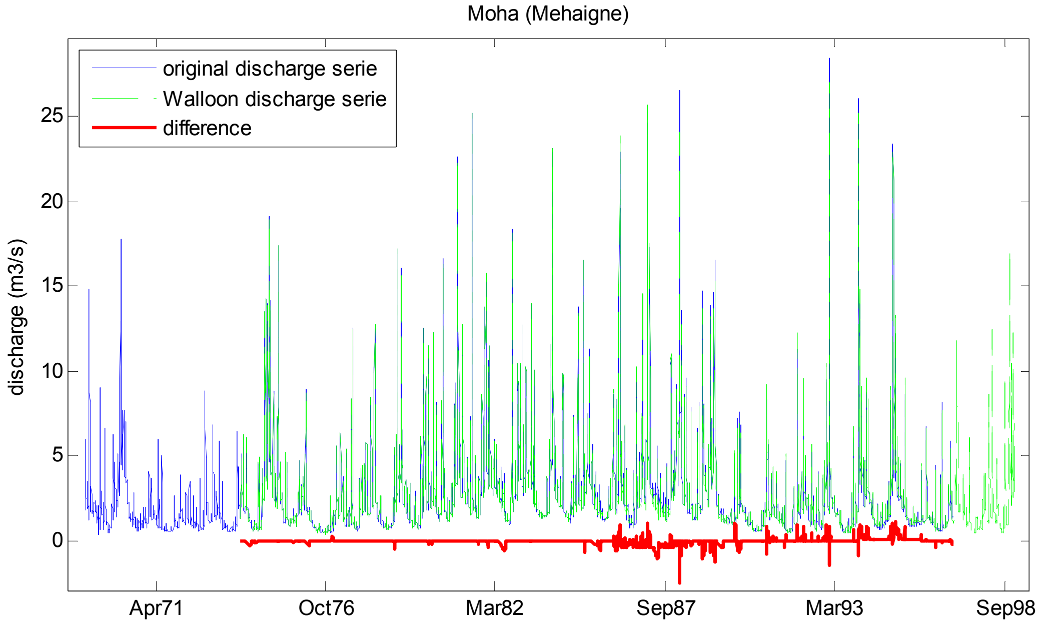
Ourthe (Tabreux)



Ambleve (Martinrive)



Vesdre (Chaudfontaine)

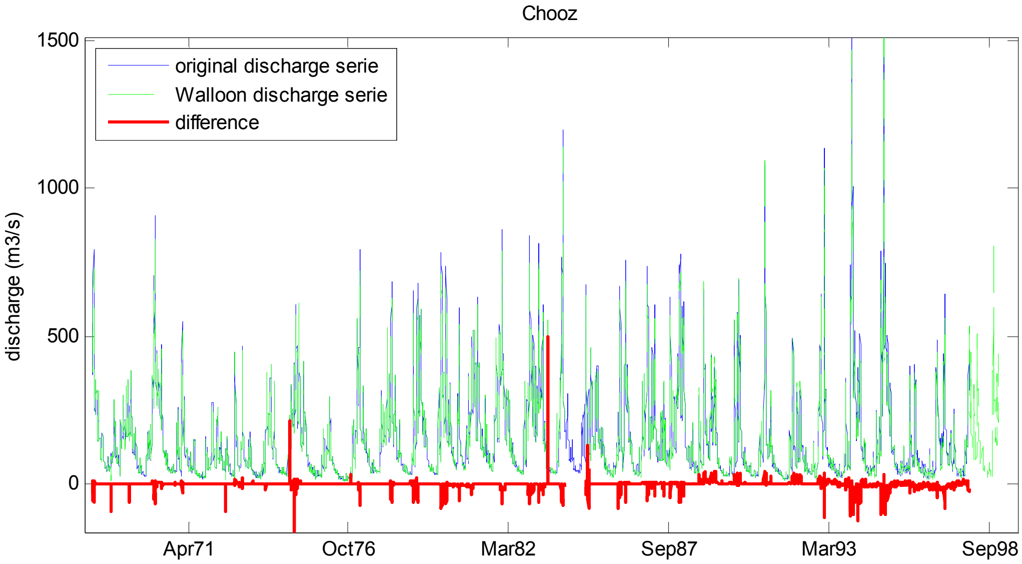


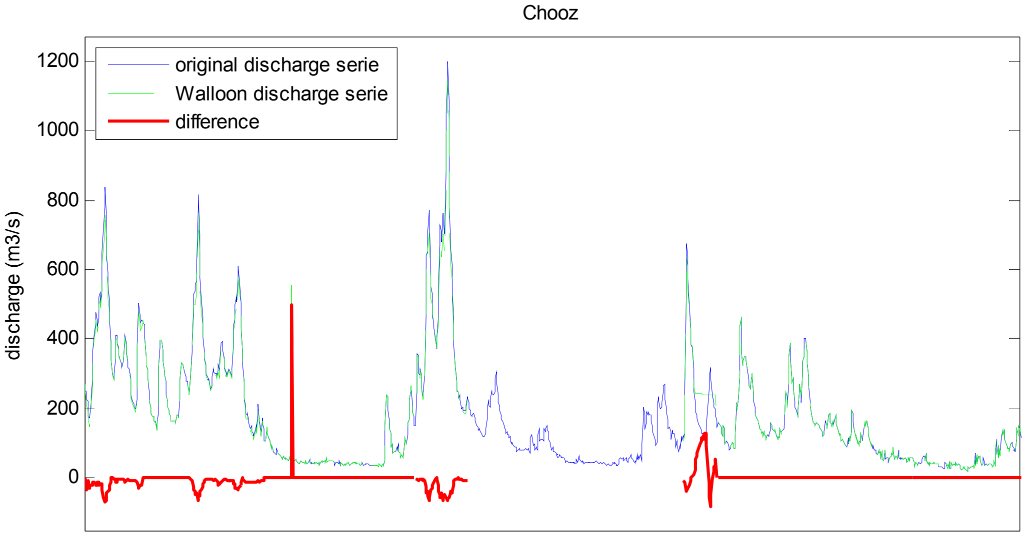
Moha (Meghaine)

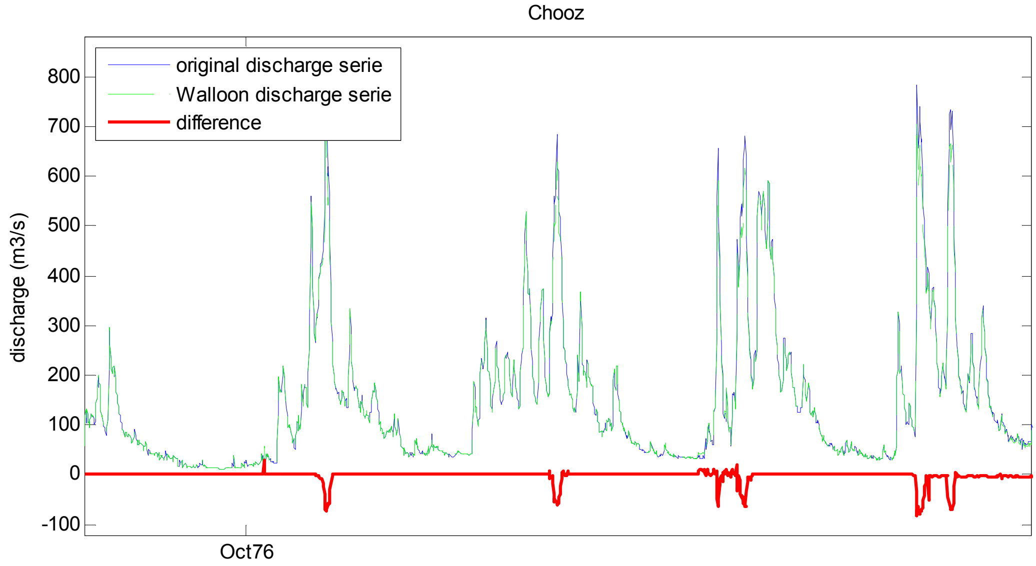
French discharge series

The French measured discharge originates from Eufrance (http://www.hydro.eaufrance.fr/). In the following table and figures the difference between the original and French dataset is further explained. Only data available for basins 1 – 4 (French Meuse).

sub-basin	river	measurement location	Id	period	difference with original dataset
1	Meuse	St.Mihiel	B2220010	1968-2008	- extended and more complete series
3	Meuse	Stenay	B3150020	1968-2008	- extended and more complete series
2	Chiers	Chauvency	B4601010	1968-2008 (missing values for '70, '75 en'77)	- no original dataset available
2	Chiers	Carignan	B4631010	1968-2008 (missing values for '83)	- no original dataset available
4	Meuse	Chooz	B7200010	1953-2008 (missing values in '84)	- peaks are lower - missing values for part of 1984, however this is a low flow period




Chooz
original discharge serie
Walloon discharge serie
difference
discharge (m3/s)
1200
1000
800
600
400
200
0


Chooz
original discharge serie
Walloon discharge serie
difference
discharge (m3/s)
800
700
600
500
400
300
200
100
0
-100
Oct76

Meuse (Chooz)

B Flood frequency curves

A further comparison is shown in the figures below; it shows the selected parameter sets per sub basin, after applying all three fit criteria. The flood frequency curves are obtained by fitting the Gumbel distribution function to the maximum discharges using the maximum likelihood method (***wgumbfit*** in the MATLAB WAFO toolbox developed by the Lund University).

The measurements in the figures have been plotted using the following formula:

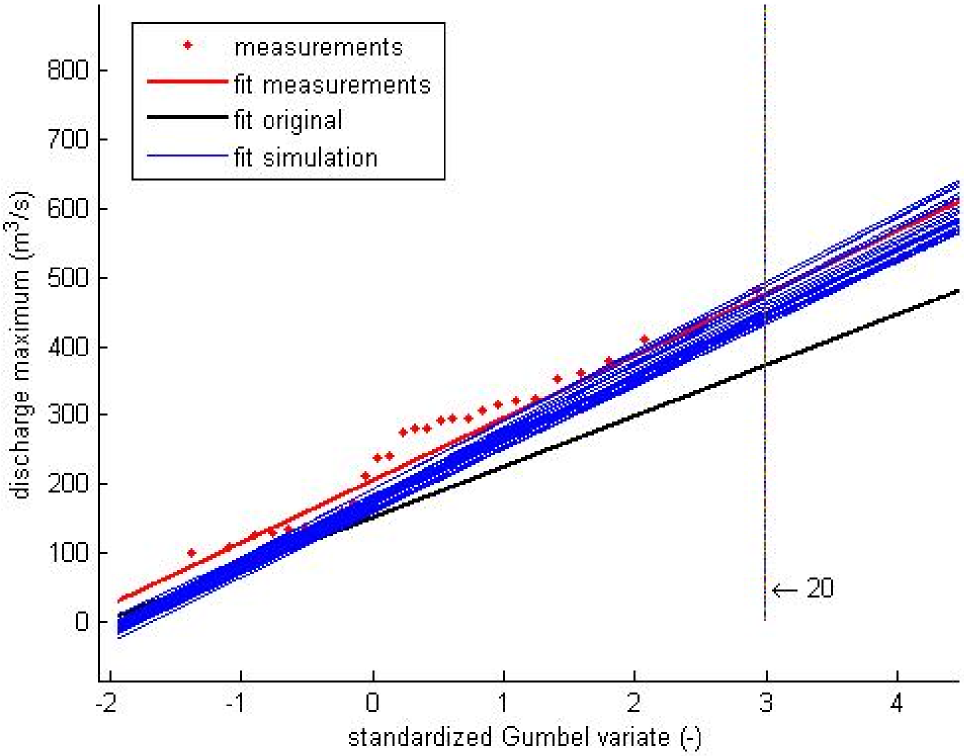
$$P = \frac{r - c}{N + 1 - 2c}$$

with:

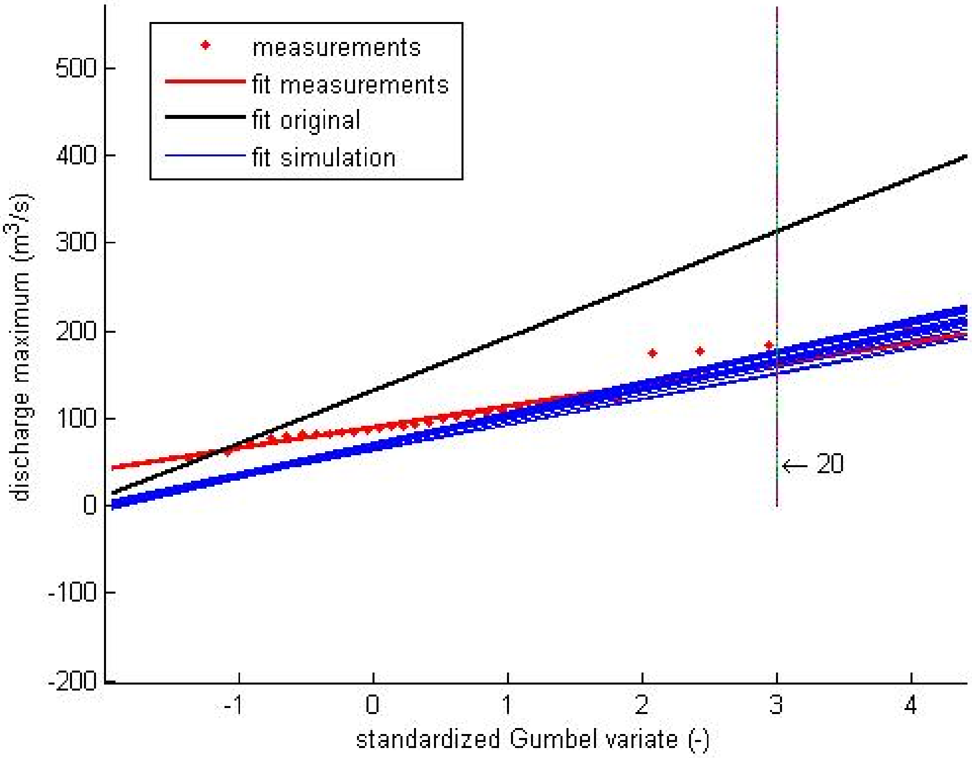
P = exceedance probability,
c = plotting constant (here c = 0.44),
N = number of time units (years),
1 = ranking number (1 for highest value, 2 for highest but one, etc)

The use of the value c = 0.44 implies that the Gringorten plotting position is used that is considered the most apt for graphs of the Gumbel distribution function.

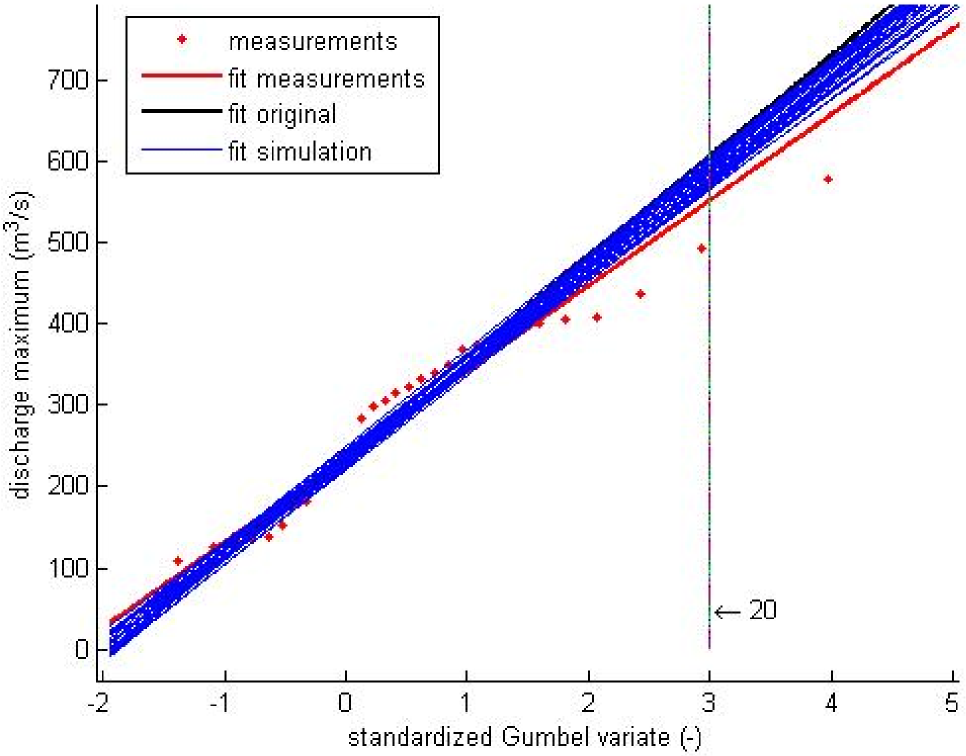
The blue lines show the resulting flood frequency curves from the accepted parameter sets, the black line shows the fit using the original parameter set and the red line shows the resulting extreme value distribution using the measurements. The red dots show the measurements.



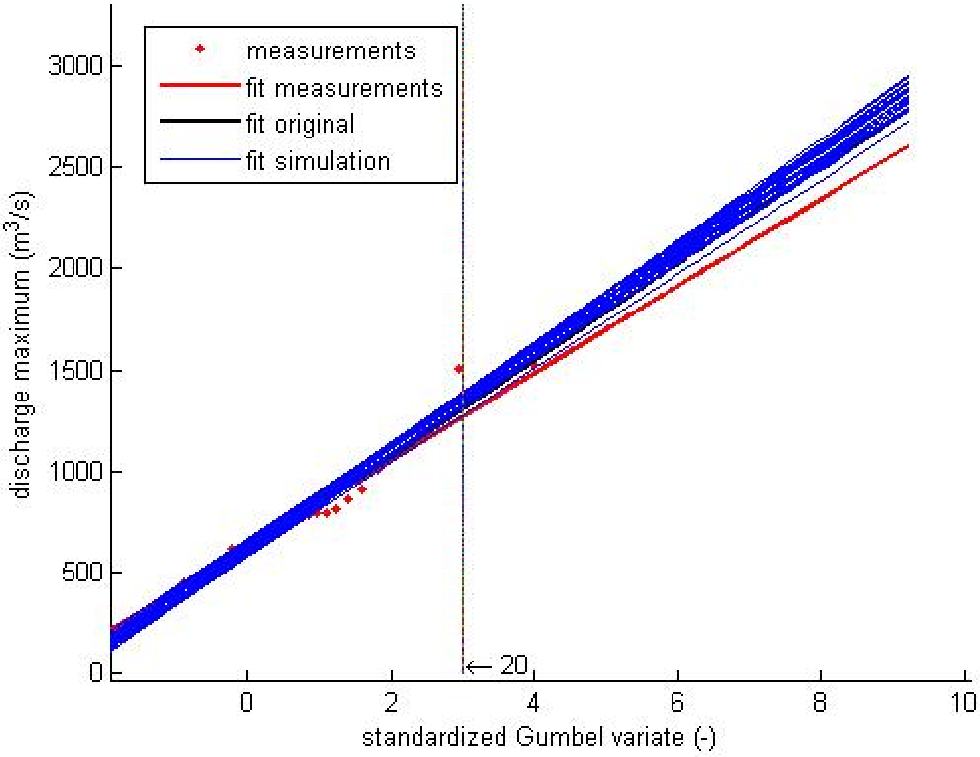
Sub basin 1



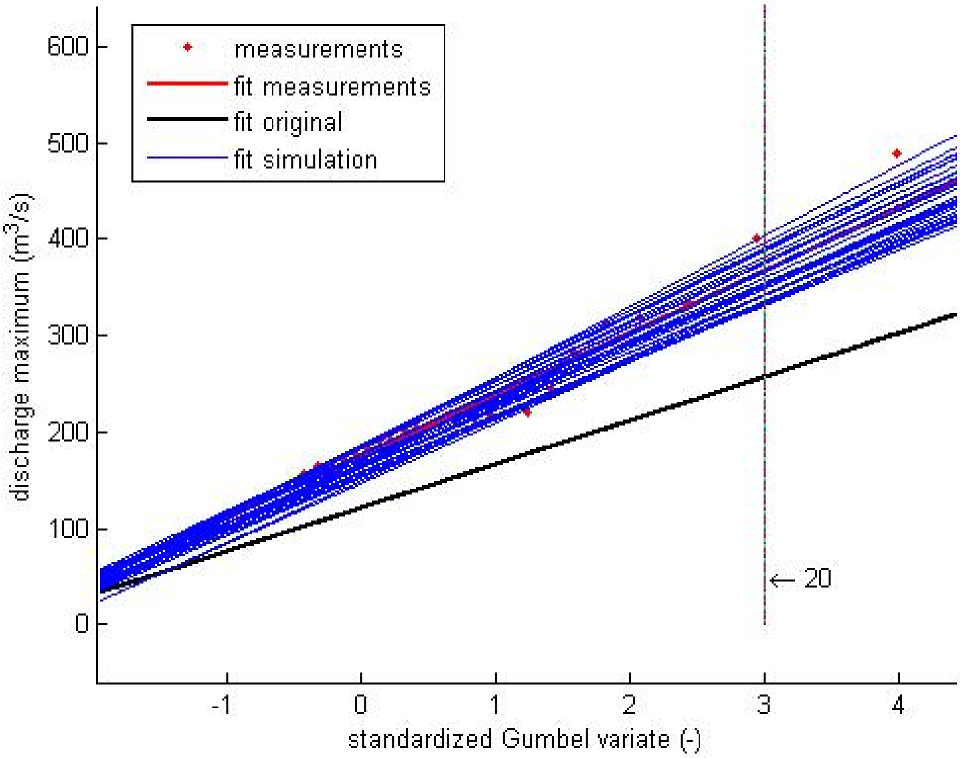
Sub basin 2



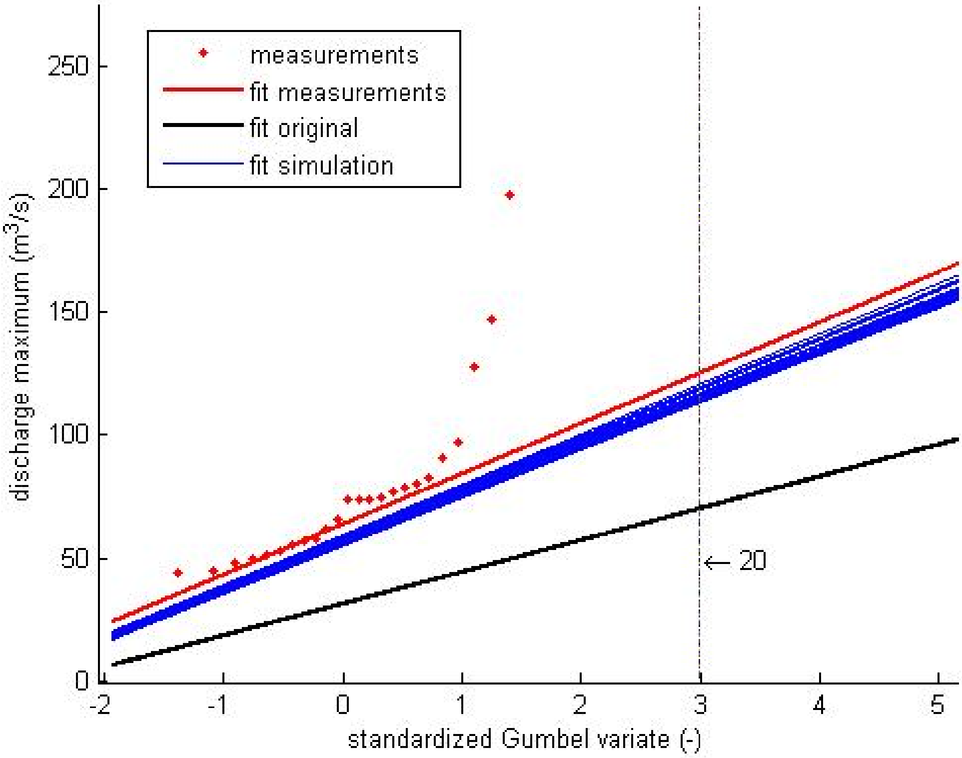
Sub basin 3



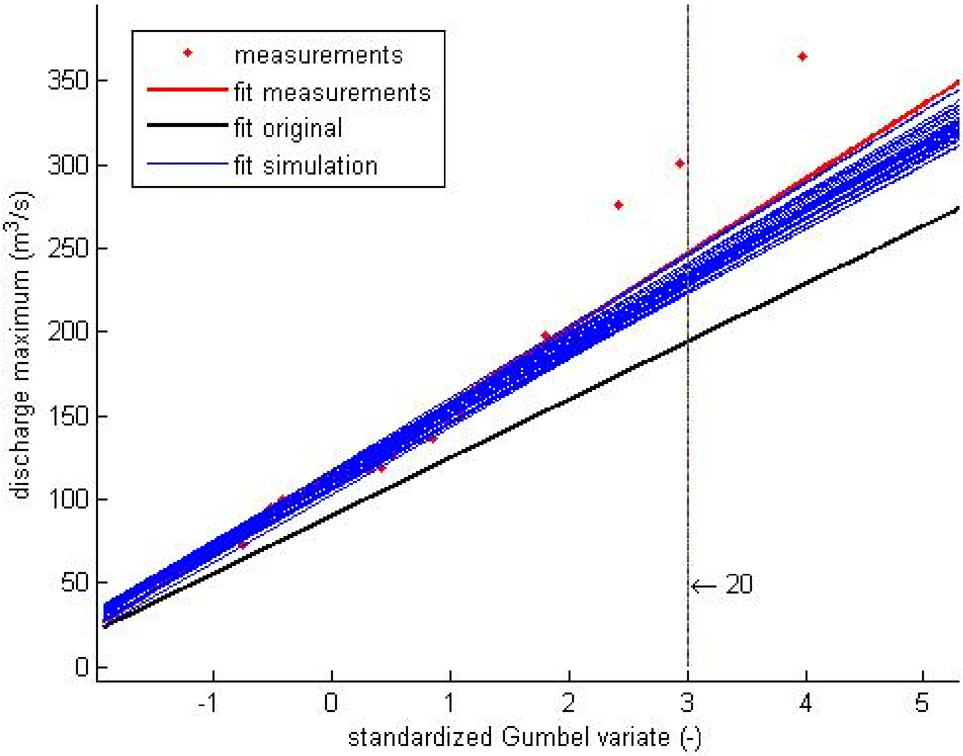
Sub basin 4



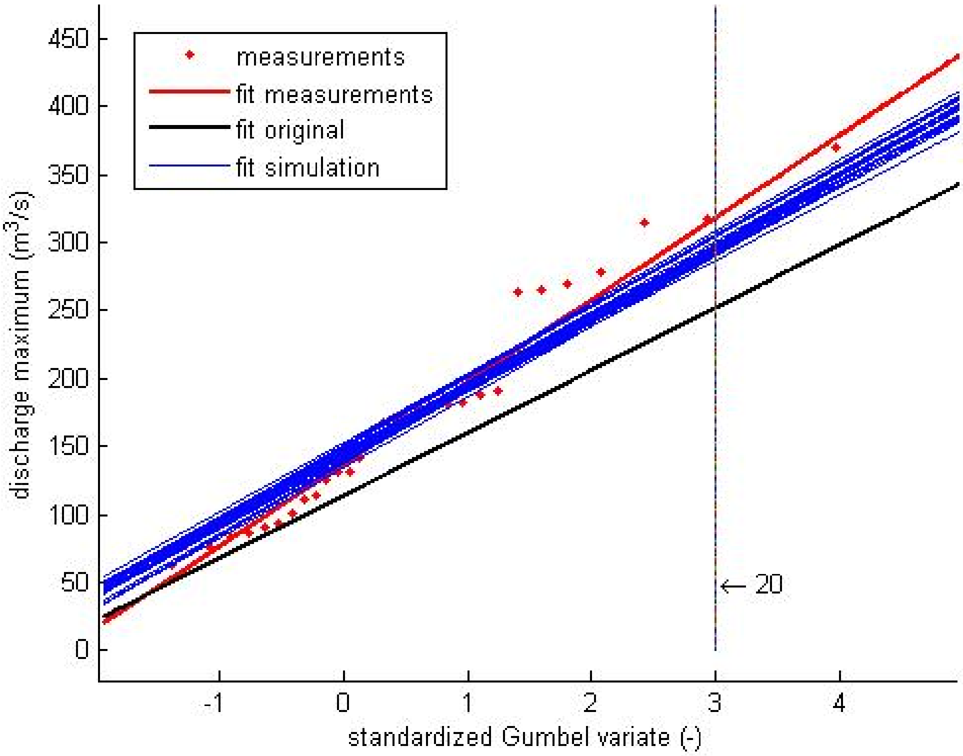
Sub basin 5



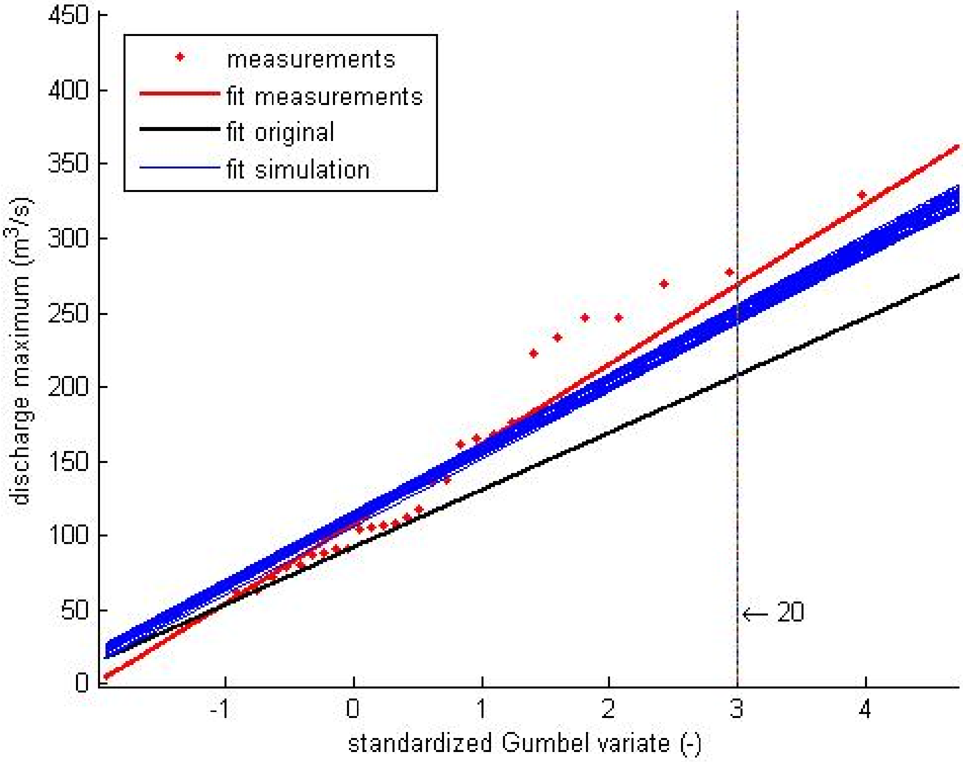
Sub basin 6



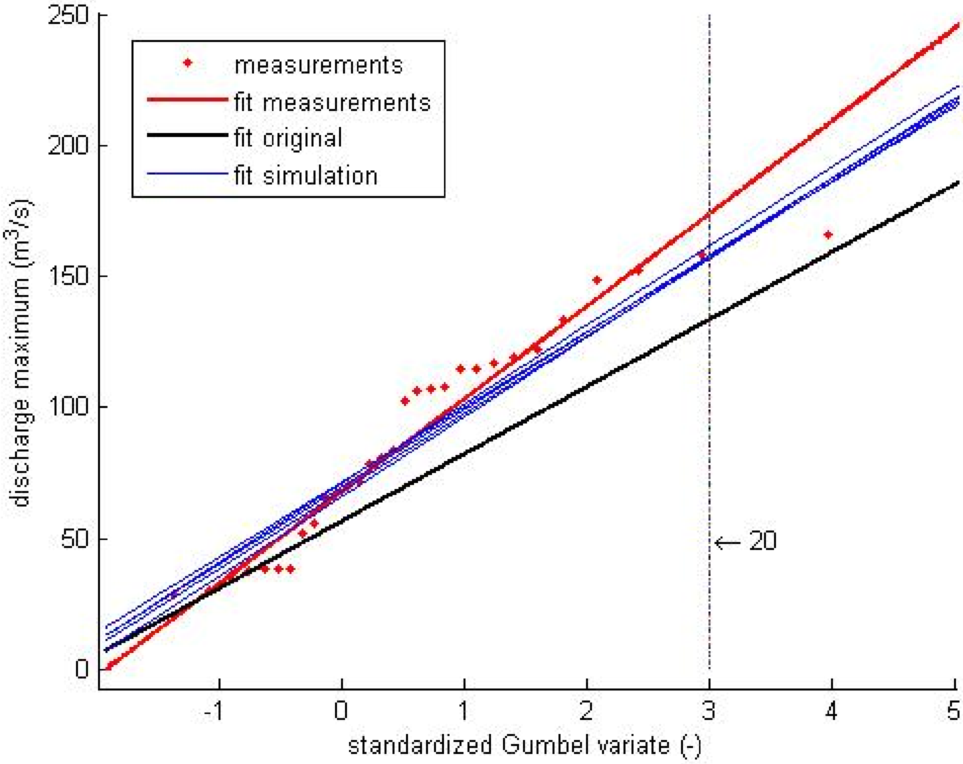
Sub basin 8



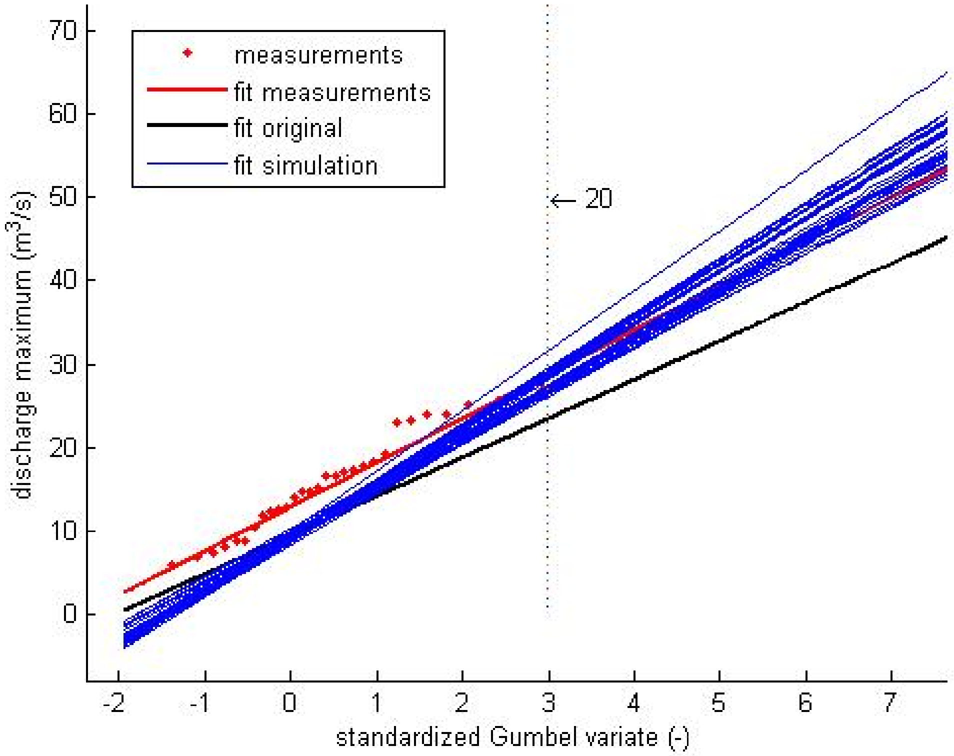
Sub basin 10



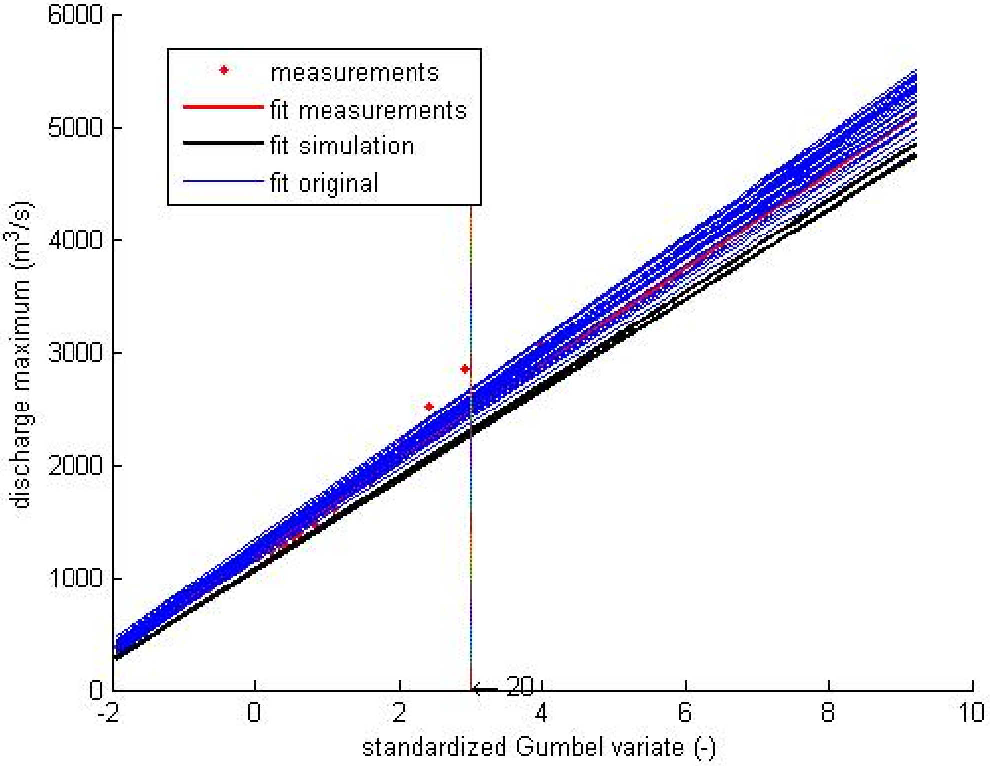
Sub basin 11



Sub basin 12

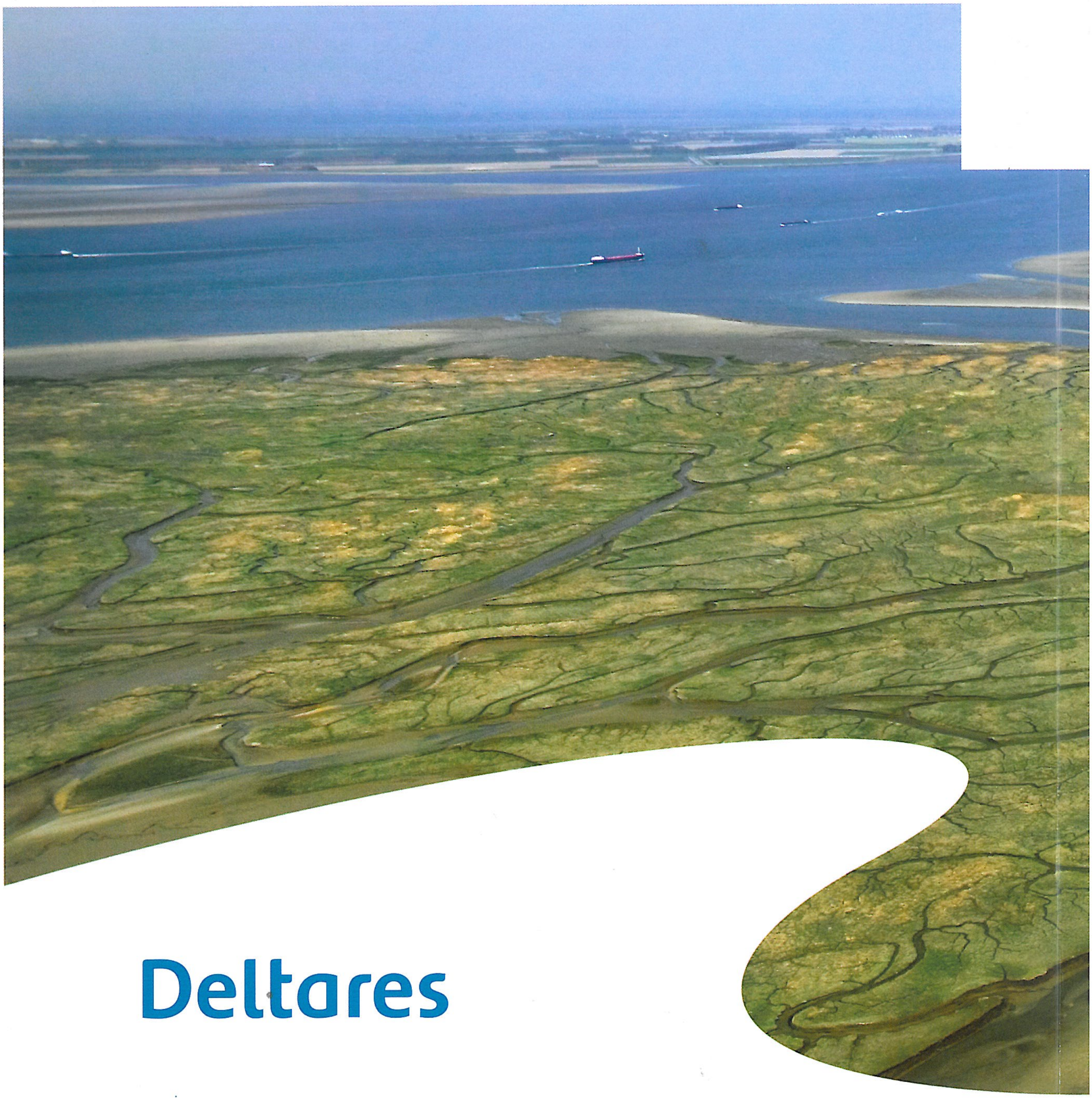


Sub basin 13



Sub basin 14

www.deltares.nl



Deltares