Final Report GRADE 2010

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Nienke Kramer
Willem van Verseveld
Hessel Winsemius
Otto de Keizer
Simone Patzke

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Contents

1 Introduction

The workplan for the year 2010 consisted of a mixture of preparing the GRADE-Meuse system for the use in a pre-operational mode in the WTI procedure and improving the GRADE-Rhine system in order to bring it slowly up to the same level as GRADE-Meuse.

At the end of 2009 the conclusion was drawn that the GRADE-Meuse system was sufficiently developed to take it up one level and incorporate it in the process of the assessment of the design discharges as part of the WTI program, although still in a pre-operational mode. However, it was also clear that there were still some issues to be solved, as well as a number of actions needed to be made to make it acceptable to the WTI project to be incorporated in their program. Those issues were:

- Solve a water balance problem that occurs when using SOBEK for the flood routing on the main Meuse river instead of the build-in routing module of HBV;
- Establish an formal release version of GRADE-Meuse, built in FEWS in order to have a stable instrument and monitor developments;
- Elaborate a description of the GRADE-Meuse system to be used as a guide to the details of the system and its characteristics.

These issues were addressed during the year 2010 and it can be concluded now that GRADE-Meuse is completely ready to be used as part of the WTI program.

For the GRADE-Rhine the system still lacks behind as compared to GRADE-Meuse for a number of reasons.
In the first place most of the attention went until now to GRADE-Meuse as a test-case of the GRADE concept. Currently most attention in the GRADE project can be given to the system for the Rhine, while in parallel the application of GRADE-Meuse is tested in the WTI program.
In the second place the Rhine is a much more complicated river than the Meuse, the Meuse being comparable to a major tributary of the Rhine like the Mosel river. The Rhine has many large tributaries contributing to the main river and also with a different system in the upper part of the basin, in Switzerland, with snow melt, glaciers and major lakes that do hardly play a role in the Meuse river basin.
A third important issue is the major floodplains in the Rhine river basin that start to inundate at different discharge values along the main river, with most of them uncontrolled, but also with controlled inundation locations.
A fourth additional challenge for the Rhine are the many hydrodynamic models that are available for stretches the river Rhine and some of the tributaries. This makes it difficult to choose an optimum configuration for this river that is apt for the use in extreme situations that form the focus of GRADE.
Finally, the currently used calibration of the HBV-model for the Rhine basin has some drawbacks regarding transparency of the schematization and in particular flow routing. The 2009-calibration of the hourly HBV-model was more transparent, but gives worse results for Lobith, mainly because of a simplified routing procedure.

The confidence in the current calibration of the HBV-model for the Rhine basin is not yet high enough for GRADE applications. The Rhine River has already a fully-calibrated HBV model for all its subbasins, completely new since 2009, but the accuracy of this calibration for high discharges is debated. Other minor issues exist regarding the existing system, such as the use of a locally-produced hydrologic routing module (SYNHP) that presents limitations for the application in GRADE.

For these reasons, in 2010 a start was made with the solving of the most obvious problems in GRADE-Rhine and an inventory of the present status of the system regarding the various routing modules. Attention was also given to the way how to develop the GRADE-Rhine system in order to bring it up to the same level as GRADE-Meuse, with the aim of being able to use both systems in the year 2017 for the derivation of the design discharges (and related flood waves) in WTI. This means that there will be no official pre-operational application of the GRADE-Rhine system, although evidently the system will be tested extensively in the coming years, partly using the information that the pre-operational use of GRADE-Meuse will provide.

During the year 2010 the existing hydrologic routing module SYNHP was replaced by a Muskingum routing module. Minor issues regarding the water balance of the system were unravelled and corrected, with the result that the system is now able to run without the SYNHP routing. At the same time an inventory was made of the SOBEK models available for the Rhine river and also the coupling between the main river and the many tributaries of the Rhine were checked. During high discharges, a correction factor is used to correct for the impact of the flow on the main river on the discharge values of the tributaries ("Buiteveld correction"), which should be removed in the future and preferably replaced by an approach, based on full hydrodynamic modelling.

2 GRADE-Maas

2.1 Water balance issue SOBEK

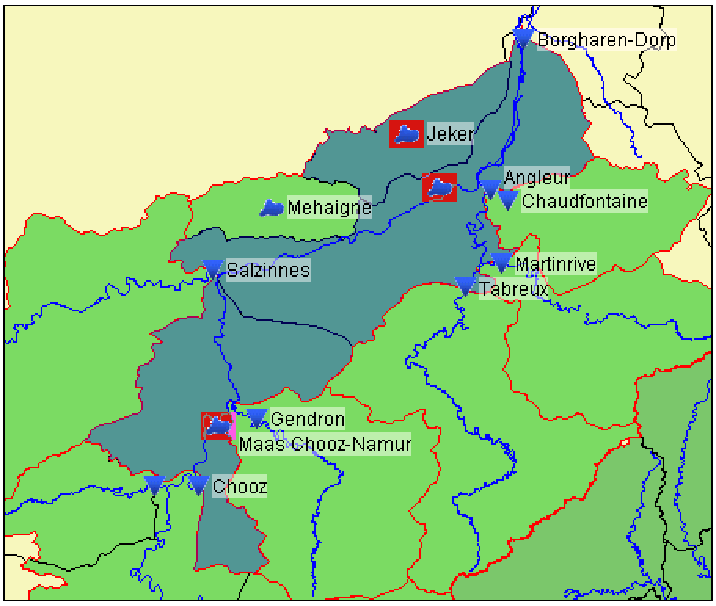
During the development and first applications of the GRADE-Maas system, it appeared that the discharge for the Meuse simulated by SOBEK downstream of gauging station Chooz, on the French-Belgian border, was too low compared to the HBV results. Especially at the location Borgharen the discharge peaks calculated with the SOBEK model were much lower then those calculated with HBV. Looking at the input to the SOBEK model it appeared that for some catchments the flows simulated by HBV were not passed to the SOBEK model at all. This was due to some configuration issues, which had to be resolved in order to pass the correct flows to the SOBEK model. The part of the configuration where relevant changes had to be made comprised the data preparation step before running SOBEK. As a reference for the correct data preparation the most recent version of the configuration of FEWS-Rivieren was used (provided by Marc van Dijk, status 09-03-2010). Three configuration files had to be corrected to solve the issue, the files were the following module instances:

- GRADE_SBKdag_Maas_Merge_Update.xml
- GRADE_SBKdag_Maas_Interpolate_Update.xml
- GRADE_SBKdag_Maas_Update.xml

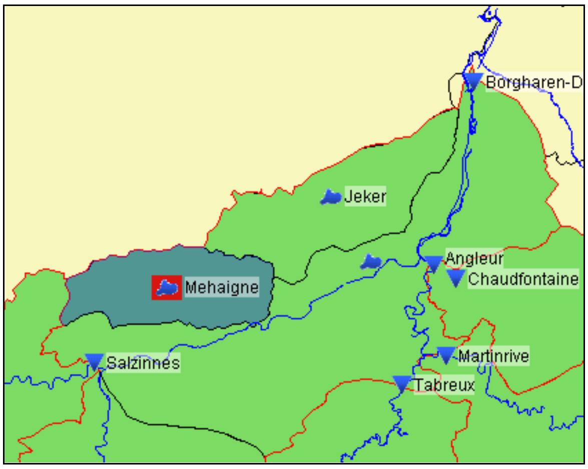
The corrections carried out in each of the files are described in the following.

2.1.1 GRADE_SBKdag_Maas_Merge_Update.xml

a) In the module instance GRADE_SBKdag_Maas_Merge_Update.xml a wrong reference to time series set was used in several transformations. This reference module instance name was corrected from “HBV_Update” to “GRADE_HBV_Update”. The erroneous configuration resulted in empty time series (flow equals zero) passed to the SOBEK model for the HBV catchments Jeker (I-MS-0015), Maas Chooz-Namur (I-MS-0007) and Maas Namur-Monsin (I-MS-0014), see figure below.



b) A copy of the time series for the HBV catchment Mehaigne (Lesse) was added to ensure that this flow is also passed to SOBEK.



An overview of all transformations carried out in the module instance is given below.

1. Make a copy of the discharge time series Q.uh - GRADE_HBVdag_Maas_Update to the discharge time series Q.uh - GRADE_SBKdag_Maas_Merge_Update

Name	Input	Output
Lesse	I-MS-0013	I-MS-0013
Jeker	I-MS-0015	I-MS-0015

2. Set minimum flow and make a copy of the discharge time series Q.uh - GRADE_HBVdag_Maas_Update to Q.uh – GRADE_SBKdag_Maas_Merge_Update

Name	Input	Min Flow	Output
Chooz	H-MS-0011	50	H-MS-0011
Lesse at Gendron	H-MS-0013	5	H-MS-0013
Sambre at Salzinnes	H-MS-0019	5	H-MS-0019
Ourthe at Tabreux	H-MS-0020	10	H-MS-0020
Ambleve at Martinrive	H-MS-0017	5	H-MS-0017
Vesdre at Chaudfontaine	H-MS-0010	5	H-MS-0010

3. Divide flow for Chooz-Namur and Namur-Monsion and make a copy of the discharge time series Q.uh - GRADE_HBVdag_Maas_Update to Q.uh – GRADE_SBKdag_Maas_Merge_Update

Name	Input	multiplier	Output
Maas Chooz-Namur	I-MS-0007	0,5	HBV07_1_50
Maas Chooz-Namur	I-MS-0007	0,5	HBV07_2_50
Maas Namur-Monsin	I-MS-0014	0,5	HBV14_1_50
Maas Namur-Monsin	I-MS-0014	0,5	HBV14_2_50

Remark: in FEWS NL some time series are lagged over a few hours (1, 2 or 4h) when copying to the input time series for SOBEK. As in GRADE all models are working with a daily time step this is neglected here.

2.1.2 GRADE_SBKdag_Maas_Interpolate_Update.xml

An interpolation step (linear interpolation) has been added for the discharge time series Q.uh for location set 'SBK_Maas_Inflows_updated'.

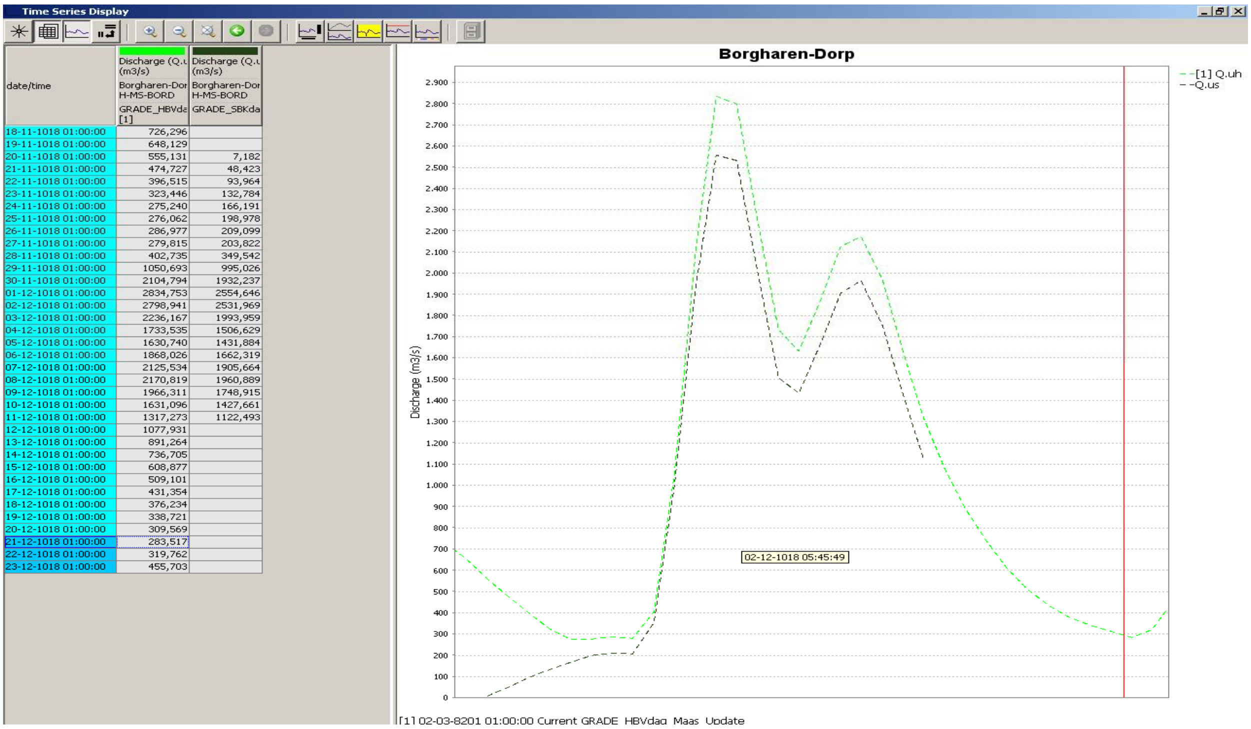
interpolationId	serialInterpolation		
Interpolation Q.uh	serialInterpolation (2)		
		serialInterpolationOption	gapLength
	1	linear	240
	2	extrapolate	240

timeSeriesInputSet		
moduleInstanceId	GRADE_SBKdag_Maas_Merge_Update	
valueType	scalar	
parameterId	Q.uh	
locationSetId	SBK_Maas_Inflows_updated	
timeSeriesType	simulated historical	
timeStep	unit	day
	multiplier	1
relativeViewPeriod	unit	day
	start	-14610
	startOverrulable	true
	end	0
readWriteMode	add originals	
expiryTime	unit	day
	multiplier	3

2.1.3 GRADE_SBKdag_Maas_Update.xml

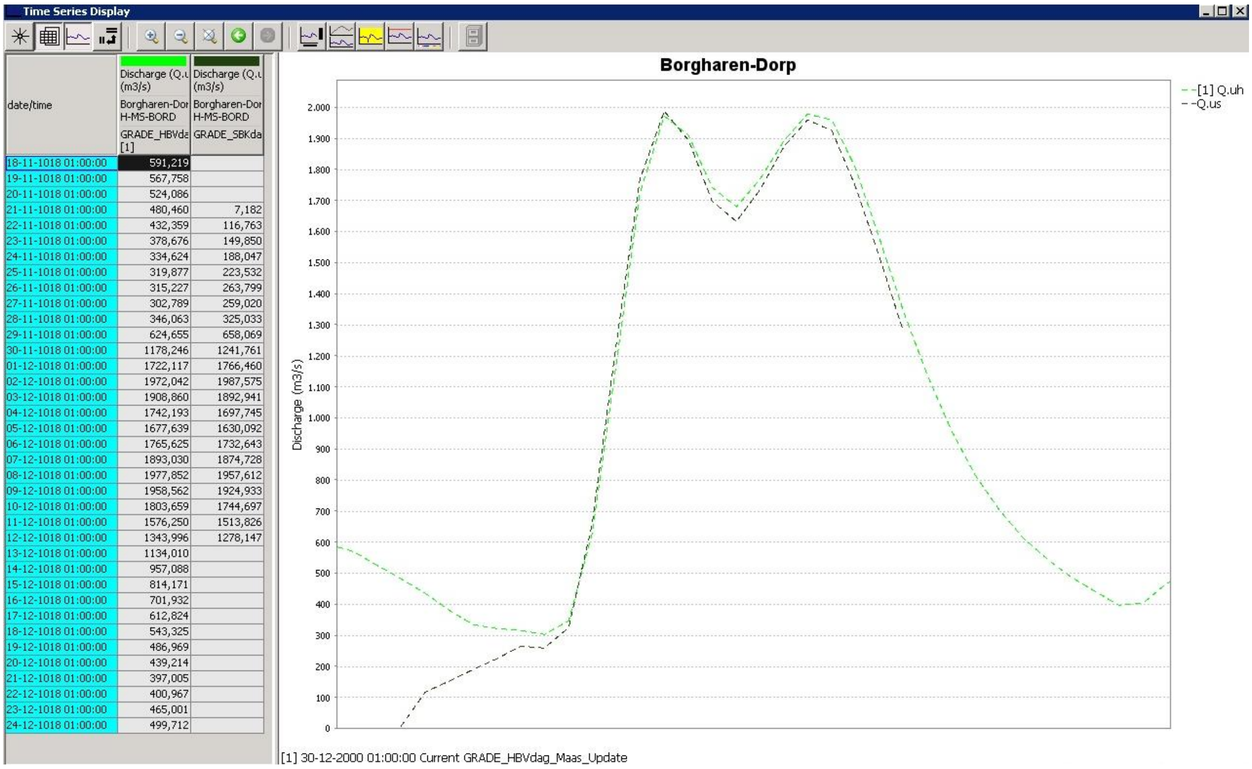
The read write mode of the exported time series was changed from 'editing visible to all future task runs' to 'read only'. This had no influence on the results of the SBK runs, but was adapted to be consistent with the concept of configuration.

With the corrections described above, the comparison of the discharge time series produced by SOBEK with the discharge times series produced by HBV gives much better results. In Figure 2.1 the HBV and Sobek results are given using the old configuration. The figure shows the underestimation of the Sobek results. Figure 2.2 shows the HBV and the Sobek results for the new configuration. The discharges calculated with Sobek approximates the HBV results. A remark must be made the height of the peaks in both figures cannot be compared, because different input values are used for both calculations.



date/time	Discharge (Q.u (m3/s) Borgharen-Dor H-MS-BORD GRADE_HBVda [1]	Discharge (Q.u (m3/s) Borgharen-Dor H-MS-BORD GRADE_SBKda
18-11-1018 01:00:00	726,296	
19-11-1018 01:00:00	648,129	
20-11-1018 01:00:00	555,131	7,182
21-11-1018 01:00:00	474,727	48,423
22-11-1018 01:00:00	396,515	93,964
23-11-1018 01:00:00	323,446	132,784
24-11-1018 01:00:00	275,240	166,191
25-11-1018 01:00:00	276,062	198,978
26-11-1018 01:00:00	286,977	209,099
27-11-1018 01:00:00	279,815	203,822
28-11-1018 01:00:00	402,735	349,542
29-11-1018 01:00:00	1050,693	995,026
30-11-1018 01:00:00	2104,794	1932,237
01-12-1018 01:00:00	2834,753	2554,646
02-12-1018 01:00:00	2798,941	2531,969
03-12-1018 01:00:00	2236,167	1993,959
04-12-1018 01:00:00	1733,535	1506,629
05-12-1018 01:00:00	1630,740	1431,884
06-12-1018 01:00:00	1868,026	1662,319
07-12-1018 01:00:00	2125,534	1905,664
08-12-1018 01:00:00	2170,819	1960,889
09-12-1018 01:00:00	1966,311	1748,915
10-12-1018 01:00:00	1631,096	1427,661
11-12-1018 01:00:00	1317,273	1122,493
12-12-1018 01:00:00	1077,931	
13-12-1018 01:00:00	891,264	
14-12-1018 01:00:00	736,705	
15-12-1018 01:00:00	608,877	
16-12-1018 01:00:00	509,101	
17-12-1018 01:00:00	431,354	
18-12-1018 01:00:00	376,234	
19-12-1018 01:00:00	338,721	
20-12-1018 01:00:00	309,569	
21-12-1018 01:00:00	283,517	
22-12-1018 01:00:00	319,762	
23-12-1018 01:00:00	455,703	

Figure 2.1 HBV and Sobek results using the old configuration.



date/time	Discharge (Q.u (m3/s) Borgharen-Dor H-MS-BORD GRADE_HBVda [1]	Discharge (Q.u (m3/s) Borgharen-Dor H-MS-BORD GRADE_SBKda
18-11-1018 01:00:00	591,219	
19-11-1018 01:00:00	567,758	
20-11-1018 01:00:00	524,086	
21-11-1018 01:00:00	480,460	7,182
22-11-1018 01:00:00	432,359	116,763
23-11-1018 01:00:00	378,676	149,850
24-11-1018 01:00:00	334,624	188,047
25-11-1018 01:00:00	319,877	223,532
26-11-1018 01:00:00	315,227	263,799
27-11-1018 01:00:00	302,789	259,020
28-11-1018 01:00:00	346,063	325,033
29-11-1018 01:00:00	624,655	658,069
30-11-1018 01:00:00	1178,246	1241,761
01-12-1018 01:00:00	1722,117	1766,460
02-12-1018 01:00:00	1972,042	1987,575
03-12-1018 01:00:00	1908,860	1892,941
04-12-1018 01:00:00	1742,193	1697,745
05-12-1018 01:00:00	1677,639	1630,092
06-12-1018 01:00:00	1765,625	1732,643
07-12-1018 01:00:00	1893,030	1874,728
08-12-1018 01:00:00	1977,852	1957,612
09-12-1018 01:00:00	1958,562	1924,933
10-12-1018 01:00:00	1803,659	1744,697
11-12-1018 01:00:00	1576,250	1513,826
12-12-1018 01:00:00	1343,996	1278,147
13-12-1018 01:00:00	1134,010	
14-12-1018 01:00:00	957,088	
15-12-1018 01:00:00	814,171	
16-12-1018 01:00:00	701,932	
17-12-1018 01:00:00	612,824	
18-12-1018 01:00:00	543,325	
19-12-1018 01:00:00	486,969	
20-12-1018 01:00:00	439,214	
21-12-1018 01:00:00	397,005	
22-12-1018 01:00:00	400,967	
23-12-1018 01:00:00	465,001	
24-12-1018 01:00:00	499,712	

Figure 2.2 HBV and Sobek results using the new configuration.

2.2 Preparation GRADE-Maas for WTI

In 2011 GRADE-Meuse will be applied in pre-operational mode as part of the WTI process to estimate the design discharge. This application in the official process is expected to result in feedback and consequently some improvements to the system for its actual usage. The formal application of GRADE-Meuse in the WTI process requires that some process steps of the system are being improved; the following themes have been analyzed:

- Version Control
- Input formats and metadata
- Post processing of results

Although the focus here has been on GRADE-Meuse, these activities also benefit GRADE-Rhine directly as they improve the management and process steps of the GRADE-system in general. As FEWS-GRADE is also used for climate change analyses each theme is analysed in such way to assure both facility as flexibility for use in specific projects.

2.2.1 Version control

Now that GRADE-Meuse is brought into the WTI project, a formalized management of its versions is needed. On the one hand it is important to main historical memory, e.g. being able to compare current results with results of a couple of years ago, as well as separate development improvements in process from the official version to assure only a tested version is used for official application like the WTI process. To this end, a proper version control of the instrument has been implemented. This has been implemented in SubVersion (SVN), a software that makes it easy to create separate development branches and later merge changes. A differentiation was made between the following components within the system:

- Official releases (to be used in WTI with fully tested features)
- Development versions (with new, yet to be tested features for WTI)
- Research versions (with research functionalities, outside the scope of WTI)

To this end, Deltares has put FEWS-GRADE (i.e. GRADE for both Meuse and Rhine) under version control. The principle of our version control is outlined in Figure 2.3.

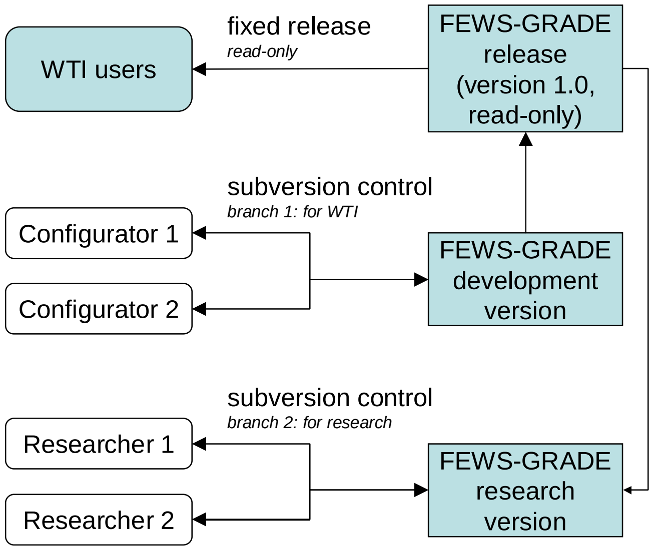


Figure 2.3. Principle of version control

SVN allows several users to work on one or several documents at the same time. A user can at all times go back to previous versions of the configuration, for instance when an error has been made in the configuration. SVN is frequently used to work together on configurations, software and text documents. Within Deltares it is commonly used to share FEWS configurations. If parallel configurations of the same system are being made, one can setup different so-called *branches* of that configuration. Currently, FEWS-GRADE has been placed under one SVN branch as a development version. This is our first branch under version control and editing of the configuration is only allowed to a limited amount of users that specifically configure the system for WTI use.

At the moment all the required features and workflows are tested (expected to be finalized in January 2011), and this will lead to release FEWS-GRADE version 1.0 (described extensively in the technical description report). With this version it is possible to run a full 20.000 year series as a continuous time series and to make such runs for the five (GLUE) parameter sets of the HBV model of the Meuse river using one workflow.

This version will be used for the WTI background run and will remain available as a read-only configuration (i.e. this is a fixed version 1.0). As soon as FEWS-GRADE version 1.0 is released, a second SVN branch may be generated, containing FEWS-GRADE 1.0 as a basis configuration. This branch can then be used to develop research versions of GRADE, e.g. for specific research programs such as Rheinblick. The users of this branch will not have access to the WTI development branch. If more research projects are initiated an alternate 3rd or 4th branch may be generated.

2.2.2 Input formats and metadata

During the development of GRADE, outputs of the weather generator of KNMI were always delivered in the form of ascii files with no significant header information. This brings along the risk that it is unknown how certain input files were generated (e.g. with which version of the weather generator, which configuration options, which base time series for rainfall, precipitation, potential evaporation). During 2010, discussion has taken place between KNMI and Deltares to find a solution to this risk. As a solution the NetCDF format (rather than ascii) was proposed by Deltares to share data, with the CF-conventions for storage of metadata.

The advantages are:

- NetCDF is commonly used as a data format at both Deltares and KNMI
- NetCDF format can store data with any number of dimension (space, time, ensembles, scenario's) and is therefore also suitable for future inputs, e.g. in case GRADE will switch to running with grids rather than spatially averaged time series.
- NetCDF can store unlimited amounts of metadata. By making use of this feature, it will always be known what the origin of the used synthetic series is.

The so-called 'Climate and Forecast' (CF) – conventions give a number of standard naming conventions for variables, and some standard metadata entries. These are listed in Table 2.1 and Table 2.2 below along with a suggestion for the values of these entries. The actual metadata descriptions will be selected in 2011 in discussion with KNMI.

Table 2.1 CF-conventions for variable names and units. These names and units are not compulsory, but merely a suggestion from the CF-conventions.

Variable	CF-convention name	CF-convention unit
Rainfall	rainfall_rate	$m\ s^{-1}$
Temperature	air_temperature	K
Potential evaporation	water_potential_evaporation_flux	$kg\ m^{-2}\ s^{-1}$

Table 2.2 CF-conventions for metadata. The given entries are commonly used.

Attributes	Suggested value
Title	Weather time series from KNMI weather generator for Rhine and Meuse
Institution	Royal Netherlands Meteorological Institute
Source	e.g.: weather generator model version X.X, base dataset, interpolated observations from year x until year y (including any other necessary details that distinct the dataset, e.g. was the 'noRep' functionality used yes/no, features in the feature vector used)
References	Published or web-based references that describe the data and/or the weather generator (latest status)
Comment	Miscellaneous information about the data or weather generator (latest status)

2.2.3 Postprocessing of GRADE-Meuse results

To support the background run of GRADE-Meuse for WTI 2011, a GRADE post-processing tool in the computer language R has been build. The post-processor is able to translate the very long time series of daily flows at Borgharen, generated in GRADE-Meuse, to results that are directly suitable for the WTI process (for instance a cumulative density function of annual extreme values), but also to results that may provide new insights. The post-processor has been brought under version control as well and is an integral part of FEWS-GRADE (i.e. a workflow is included within FEWS to run the post-processor).

It is the target of the GRADE team to provide WTI with tailor-made information for the WTI process. This section gives the first results of the post-processor along with short descriptions of the results of this post-processor. After the background run of GRADE-Meuse in WTI 2011 has been carried out, the post-processor may be changed or extended according to the experience obtained and the wishes of WTI.

Below, the outputs of the post-processor are given. All results are given for a synthetic simulation of 20 000 years. This is a satisfactory length, given that the return period of interest

(1250 years) is an order lower than the length of the series. For each output generated in the post-processor, a figure is given, providing the visualisation of the output, along with a short description:

2.3 Empirical extreme value distributions of peak flows and volumes

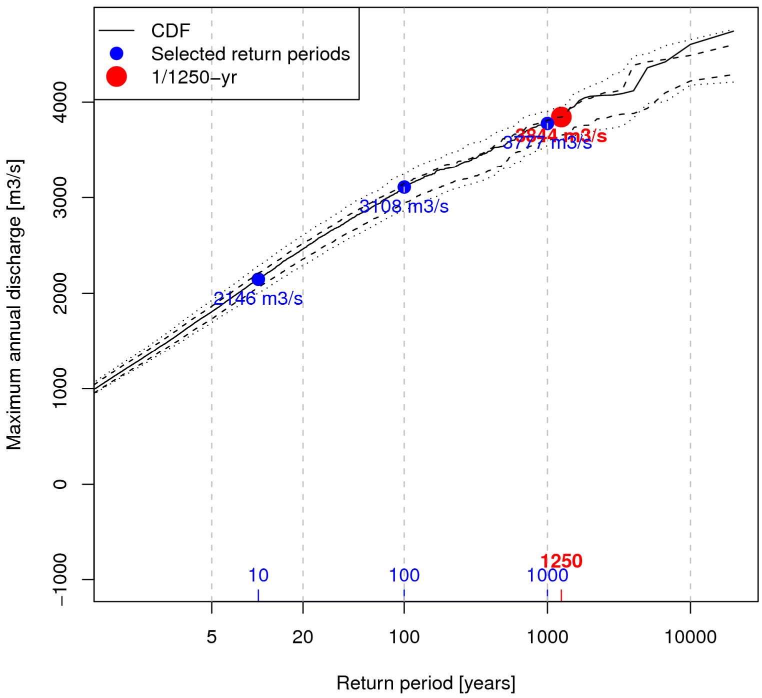


Figure 2.4. The empirical extreme value distribution of peak discharges at Borgharen using the 50%-GLUE parameterset (CDF). The dotted lines gives the extreme value distribution for the 5%, 25%, 75% an 95% parametersets.

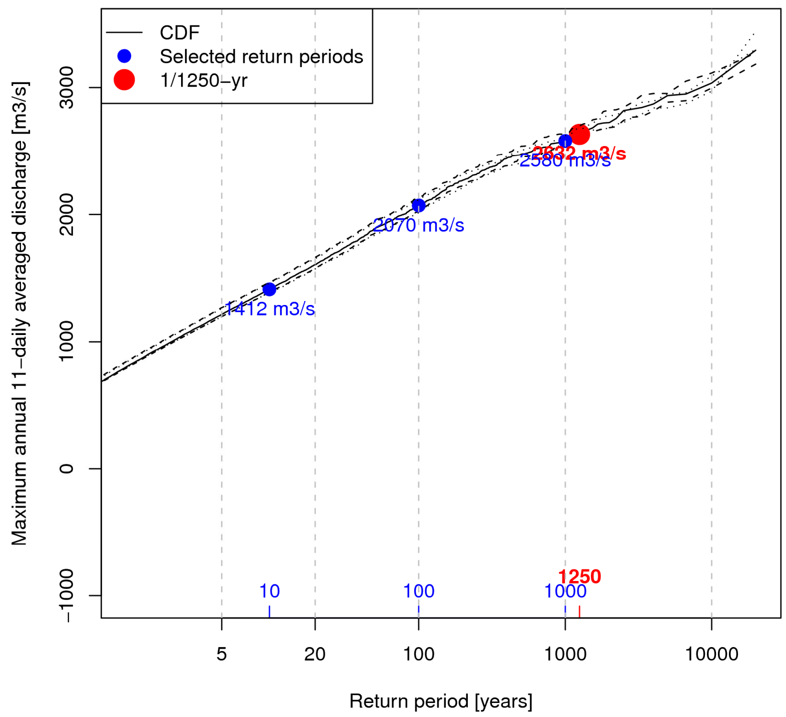


Figure 2.5. Same as Figure 2.4, but with 11-day averaged discharge, rather than peak discharge. This provides an estimate of return periods of flood volumes.

Figure 2.4 and Figure 2.5 display the *empirical* extreme value distributions of the GRADE results. In the original extreme value analysis, that is classically performed in WTI, the extreme value distributions need to be parameterised (e.g. using a Pearson-III or Gumbel fit) and extrapolated to the desired return period (see e.g. Tijssen, 2009), simply because the observation series are by far not long enough to capture a once in 1250-year occurring discharge. With GRADE, we can extend the generated time series significantly, which means that extrapolation of fitted parameterized distributions is not necessary. Instead, the once in 1250 year discharge is contained within our available series and simply looked up within the empirical distribution function.

In the figures above, 5 distributions are plotted, which are associated with 5 parameter sets of our HBV hydrological model, all giving slightly different empirical distribution functions. The 5 parameter sets contain information about the hydrological model uncertainty and can be considered in the derivation of designs (e.g. the worst case parameter set could be used, rather than the middle parameter set). The blue numbers indicate discharges at several return periods, the red number is the value belonging to return period of 1250 years.

2.4 Empirical extreme value distributions of flow durations above a threshold

Similar to the approach above, we can extract how long a certain high flow period lasts. This is additional information, which can be provided by GRADE, in addition to traditional extreme values of peaks. Long-duration high flow periods can be an essential loading on a dike body, and such information is also used in '*Voorschrift Toetsen op Veiligheid*' (see e.g. Geerse, 2009). Only continuous -above threshold- periods are considered here. The principle is explained in the schematic graph below (Figure 2.6).

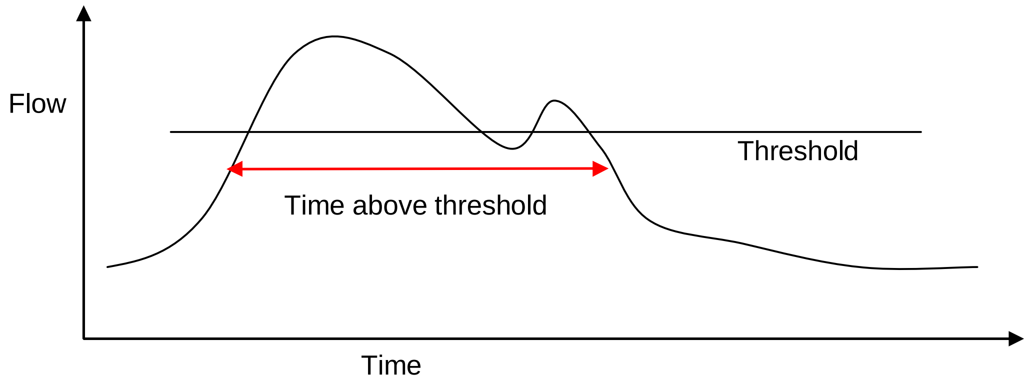


Figure 2.6 Principle to compute duration of a flood wave above a certain threshold. If the flow underspends the threshold for one day, but exceeds the threshold afterwards, the flood wave will still be treated as one event.

Similar to extreme value analysis, we can perform an ‘extreme high flow period analysis’ using the above displayed principle. For each year, we yield the highest continuous duration of flow above a threshold. Below, resulting graphs for a threshold of 1000 m^3/s and 2000 m^3/s are given. These graphs are automatically produced by the post-processor when FEWS-GRADE is run for the Meuse.

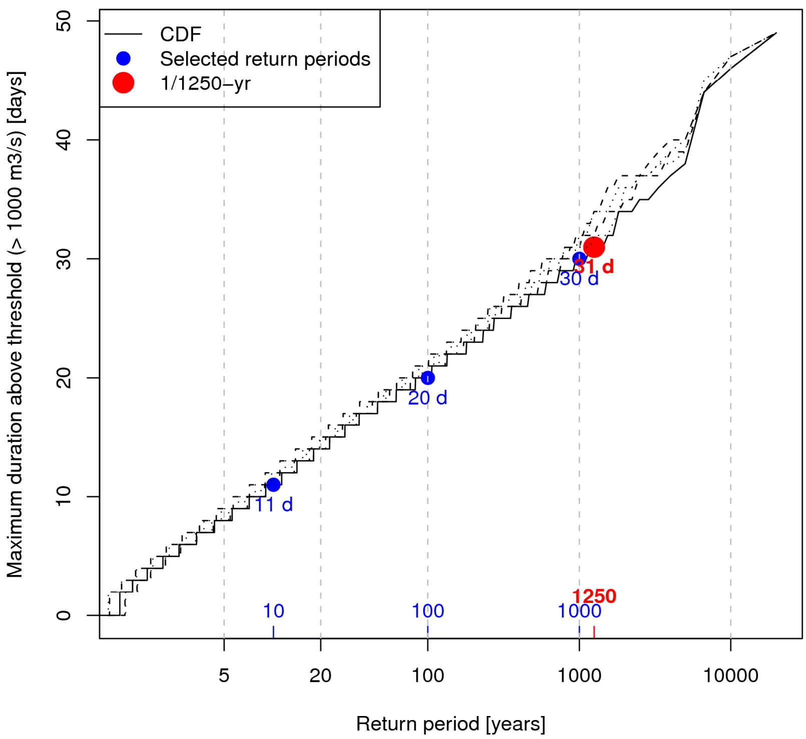


Figure 2.7. Extreme duration value distributions above a threshold of 1000 m^3/s using the 50%-GLUE parameterset. . This function has a step-wise increase because durations have a resolution of 1 day. (The dotted lines gives the extreme value distribution for the 5%,25%, 75% an 95% parametersets)

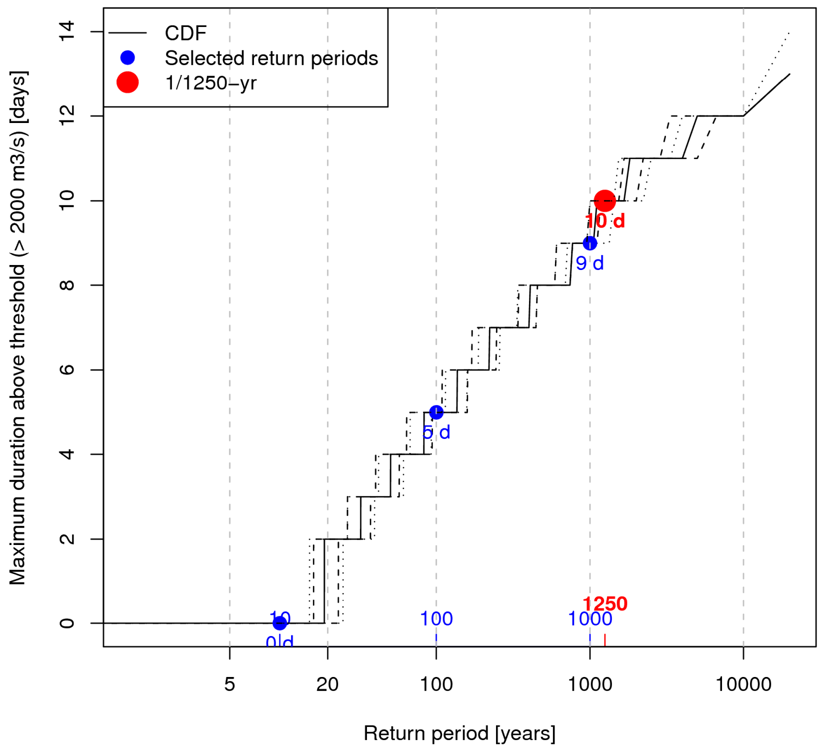


Figure 2.8. Same as Figure 2.7 but for a threshold of 2000 m3/s.

2.5 Bi-variate distributions of stochasts

Co-variable information about river flows has so far not been available in the WTI process. Instead, the design flood wave has been considered as being static in terms of wave peak, volume and shape. However, for the design of dike bodies, the concurrence of an event for instance having a high peak and a long duration can be of a more serious nature than an event with only a high peak or only a long duration. Such an event may for instance mobilize several failure mechanisms at once, for instance failure of the dike's outer stability for the peak flow, and piping for long duration events.

With GRADE we have the ability to present co-variable information on all these stochastic processes. GRADE allows us to construct multi-variable distributions.

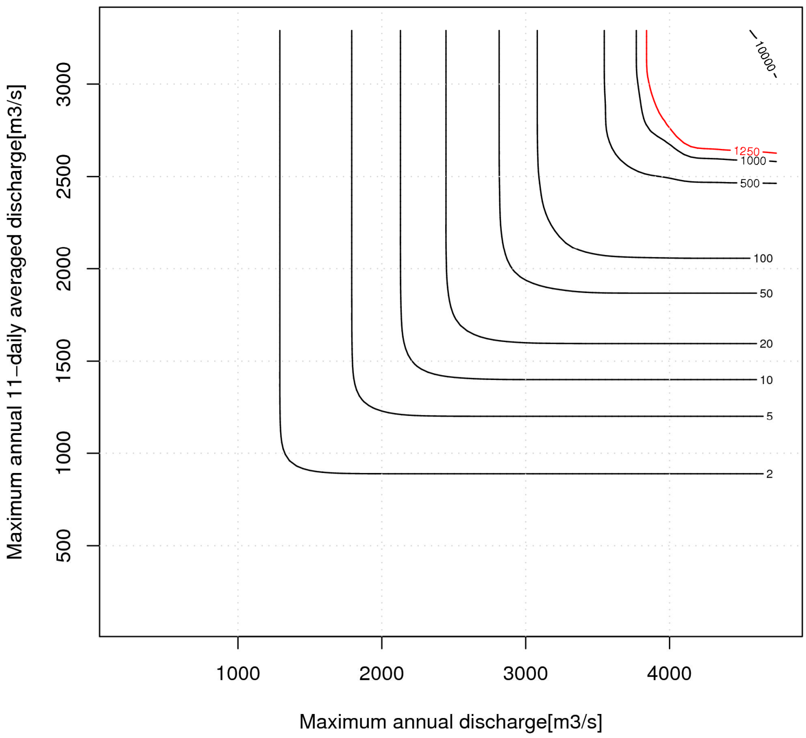


Figure 2.9. Bi-variate distribution of peak discharges and 11-day discharges, expressed as return periods.

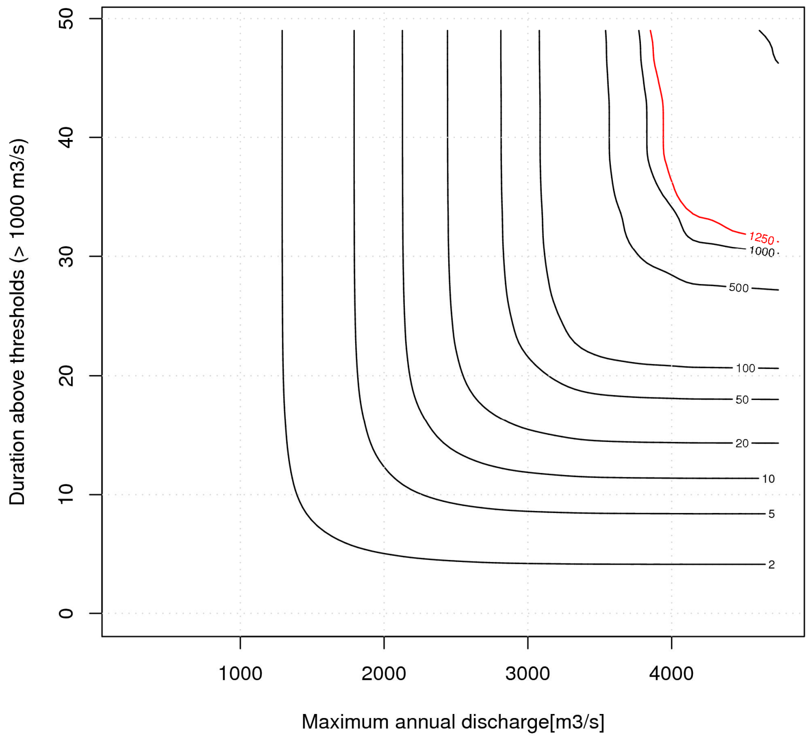
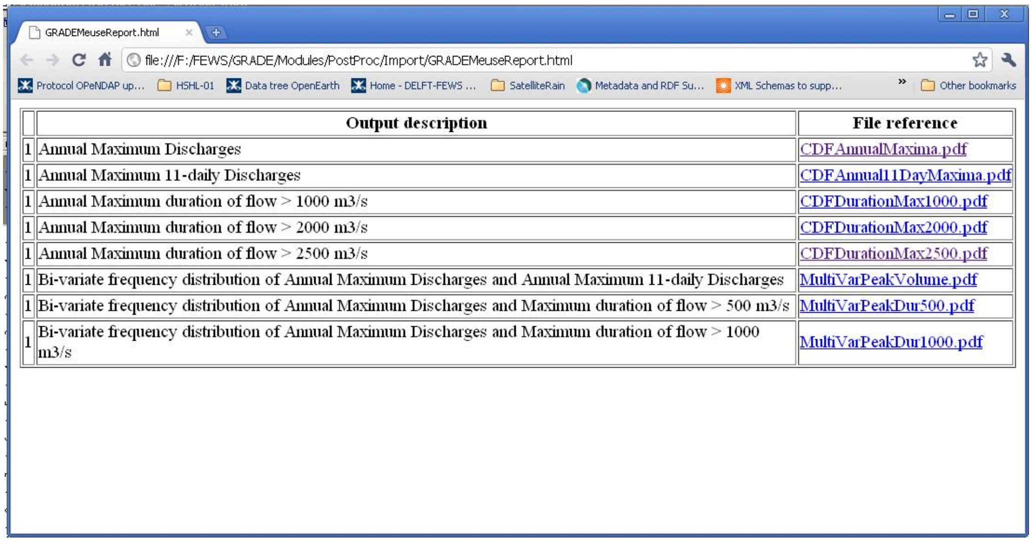


Figure 2.10. Bi-variate distribution of peak discharges [m3/s] and duration above a threshold of over 1000 m^3/s flow [days], expressed as return periods of exceedance of either the maximum discharge or the duration above thresholds.

In Figure 2.9, the bi-variable distribution of exceedance of *either* the annual peak discharges or the 11-day averaged discharges is plotted. The 1250 year return period of exceedance either one of the two processes is given as a red line. Figure 2.10 provides a similar plot for exceedance of annual peak discharges or duration of a flood wave above a certain threshold of discharge.

Of course, other important combinations of stochastic variables can be presented as well, if deemed important for WTI. One of the discussion points was the computation of duration *before* the occurrence of a flood peak, rather than just the full duration. The long duration before the peak may cause piping, while the peak may cause the actual failure. Also, similar co-variances may be generated showing the exceedance probability of *both* processes at once. The WTI 2011 background run should provide insight in what type of information is required in addition to the currently post-processed information.

After a FEWS-GRADE run has been performed, an HTML-file will open automatically, which presents links to the figures, produced so far within the post-processing module (see Figure 2.11).



	Output description	File reference
1	Annual Maximum Discharges	CDFAnnualMaxima.pdf
1	Annual Maximum 11-daily Discharges	CDFAnnual11DayMaxima.pdf
1	Annual Maximum duration of flow > 1000 m3/s	CDFDurationMax1000.pdf
1	Annual Maximum duration of flow > 2000 m3/s	CDFDurationMax2000.pdf
1	Annual Maximum duration of flow > 2500 m3/s	CDFDurationMax2500.pdf
1	Bi-variate frequency distribution of Annual Maximum Discharges and Annual Maximum 11-daily Discharges	MultiVarPeakVolume.pdf
1	Bi-variate frequency distribution of Annual Maximum Discharges and Maximum duration of flow > 500 m3/s	MultiVarPeakDur500.pdf
1	Bi-variate frequency distribution of Annual Maximum Discharges and Maximum duration of flow > 1000 m3/s	MultiVarPeakDur1000.pdf

Figure 2.11. Screenshot of HTML-report, with links to the figures along with a short description of the figures' content.

2.6 Documentation GRADE-Maas for WTI

GRADE-Meuse currently has a mature enough stage to use it next to the frequency analysis method in the project 'Wettelijk Toets Instrumentarium 2011 (WTI2011)'. An extensive documentation has been prepared (Winsemsius & Kramer, 2010) that provides background information about the instrument, its accuracy, and its potential with respect to the currently used frequency analysis. This document can be used to inform ENW about the current status of GRADE-Meuse and as background information for the WTI team. Furthermore, a short manual of FEWS-GRADE version 1.0, describing the workflows and procedures to estimate the flow duration curves along with all additional information that FEWS can currently provide, has been included.

2.7 Start development new method 'golfvorm'

In 2010, a start was made to identify needs for generation of wave shapes from GRADE. As mentioned in Section 2.2.3, GRADE may deliver recurrence times of several features of wave-shapes, however, in the WTI and VTV process, a single standard wave is required (Den Heijer, personal communication). In order to progress to the selection of a standard wave shape, the postprocessor, described in section 2.2.3, was extended, so that it can also deliver the flood waves, concurring with peak discharges. Figure 2.12 shows the 25 most extreme flood waves from the 20 000 year no-rep simulation from GRADE 2009. These waves have been classified from least to most severe, by using the most extreme value in the flood wave. It is reasonable to assume that when a different aspect of the flood wave (e.g. flood volume, duration above threshold) would be used to classify from least to most severe events, a different set will result, although probably with some overlap. In 2011 further study will be needed on the impact of the flood wave shape by selecting different classification criteria, or by using multi-variate criteria. However especially the use of multi-variate classification criteria will require a much longer simulation period than 20 000 years, although this does not need to be a continuous series. We therefore recommend that 5 series of 20 000 years are generated with FEWS-GRADE to further analyse how flood wave shapes may be selected in the future within WTI.

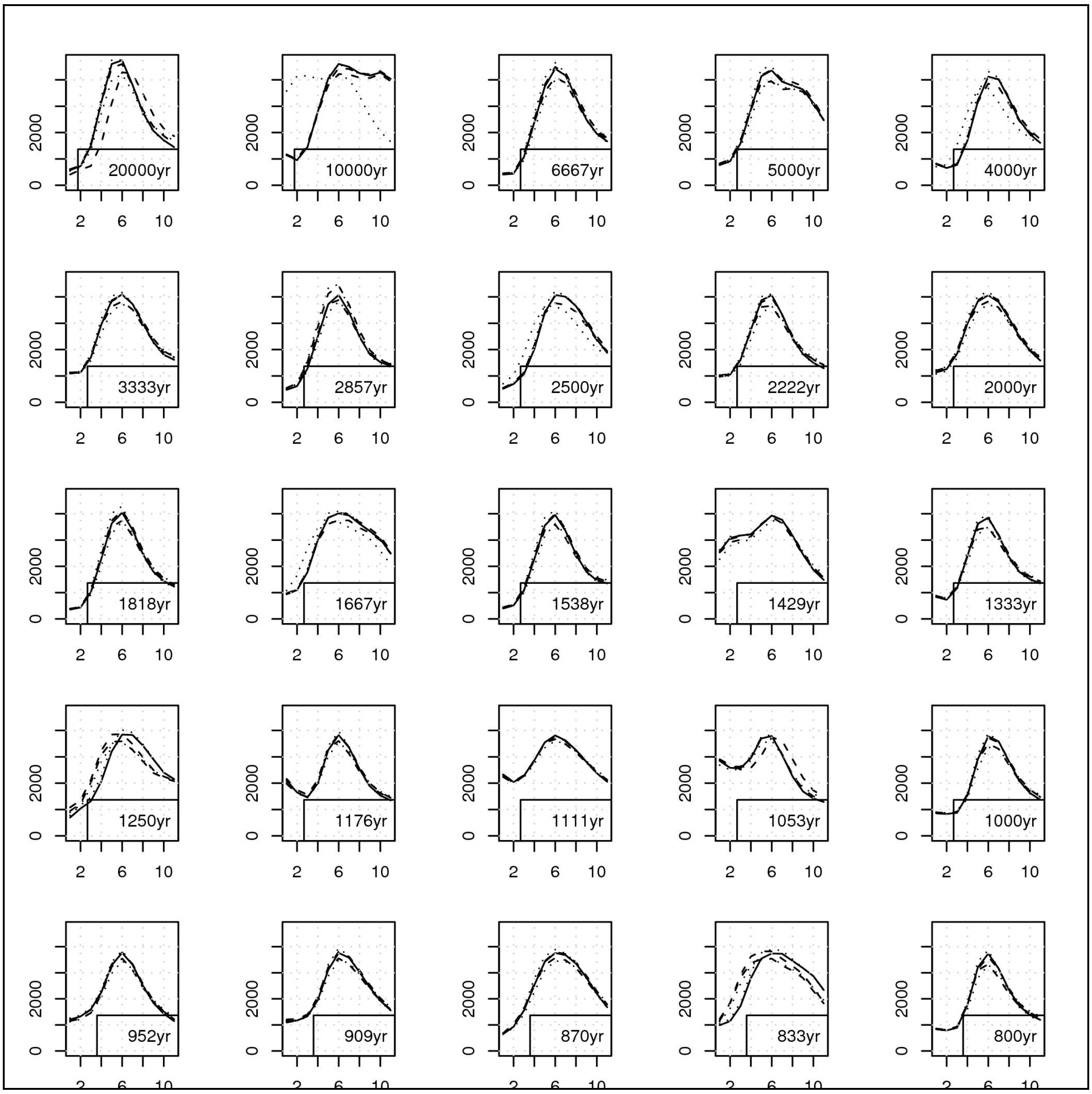


Figure 2.12 Representation of the 25 most extreme flood waves in a 20 000 year simulation. In this case, the flood waves have been selected based on the most extreme discharge value, occurring within the flood period.

3 GRADE-Rhine

The present model system of GRADE Rhine has been developed some years ago. Since then actualised models have become available and need for improvements have been found during recent research (for example Goergen et al. 2010). Therefore, GRADE-Rhine has to be actualised. As a first step a short review of existing models has been done and the coupling of the hydrologic with the hydraulic modelling was analysed. Finally the SYNHP routing module used in the present model system of GRADE-Rhine is replaced by a Muskingum model for several reasons. In the coming years 2011 – 2013 most of the attention in the GRADE project will be shifted towards the application of the Rhine.

3.1 Inventory existing models of the Rhine River basin with respect to GRADE

In 2010 an inventory of available models in the Rhine river basin has been carried out by the Steering Group Model Administration of the BfG, Deltares and Waterdienst cooperation with LANUV-NRW as joined partner. The mandate of this steering group is to stimulate within the 4 partner organisations the use of an agreed set of software and schematisations for the Rhine basin. Although the inventory is not finalised yet, mainly with respect to the FEWS-systems, they came to a large amount of model schematisations (7 HBV models for the whole catchment or parts of it, 47 SOBEK models for different Rhine stretches upstream Lobith and main tributaries, 23 coupled SOBEK-models and 3 WAQUA models). Additionally, there are models available in the Rhine catchment, which are not part of this inventory such as SYNHP, because none of the 4 partner organisations is owner of these models. In the following Chapter, an overview of the models is presented from the perspective of GRADE-Rhine.

3.1.1 HBV

There are two types of HBV models used by BfG and Deltares/Waterdienst: models based on a hourly timestep and models based on a daily timestep. GRADE makes use of HBV based on a daily timestep. The current version of HBV used in GRADE differs from the HBV- daily timestep-model used by BfG only with respect to the routine used to calculate reference evapotranspiration. The version applied by Deltares uses a simple temperature dependent routine; the version used within BfG applies the Penman-Wendling equation with global radiation as additional input series. Note that in contrary to the HBV-Meuse model the reference evaporation is not given directly as a separate time series. For operational forecasting a recalibration of the hourly model was made in 2009; as shown in the GRADE report of 2009 this calibration resulted in too many problems in the high discharges to be used directly for the calculation of extreme flood peaks at Lobith.

3.1.2 Flow routing

For the Rhine-River stretch between Basel and Maxau up to now GRADE made use of the flow routing model SYNHP. This is now replaced by a Muskingum model (see chapter 3.3). Both models are not part of the inventory of the Steering Group Model Administration.

3.1.3 SOBEK

The (coupled) SOBEK-model in GRADE-Rhine covers the stretch between Maxau and Lobith and the downstream part of some of the tributaries. Currently a SOBEK model for the Upper Rhine is being developed, which is expected to be finished at the end of 2012. In GRADE-Rhine only a flow routing model is used for this river stretch.

In GRADE-Rhine FEWS Rijn 2.01 and 2.02 (Van der Veen and Buiteveld, 2005) is used; FEWS Rijn 2.01 refers to the river section between Maxau and Lobith and FEWS Rijn 2.02

refers to the whole river section above Lobith. In FEWS Rijn 2.01 and 2.02 a coupled SOBEK-model is used consisting of 8 SOBEK models (Table 3.1) which were coupled with the program COMBINE (version 1.04). Two different versions of this model exist: a version that allows for retention and flooding and a version where flooding and retention is not allowed to occur by using an elevated position of triggers in SOBEK.

Table 3.1 The basic models used to build the complete SOBEK model for the Rhine in GRADE (taken from van der Veen and Buiteveld, 2005).

Name	prefix
Fews_Rijn Rhein Maxau-Mainz	MM1
Fews_Rijn Rhein Mainz-Andernach versie 2004.3	RM1
Fews_Rijn Rhein Andernach-Lobith Niederrheinstudie 2002_NRW_M	AL1
Fews_Rijn Rijntakken 2004.2	RT2
Fews_Rijn Neckar Rockenau-Muendung	NE1
Fews_Rijn Main Raunheim-Muendung	MA3
Fews_Rijn Lahn Kalkofen-Muendung	LA1
Mosel Cochem-Muendung	MO1

In FEWS-Rivers (flood early warning system for the rivers Rhine and Meuse) a more recent SOBEK model of the Rhine is used leading to , FEWS Rijn 3.01 and 3.02 (Table 3.2) . The following SOBEK models are different from FEWS Rijn 2.01:

- Fews_Rijn Neckar Rockenau-Muendung stuwen HYD control
- Fews_Rijn Main Raunheim-Muendung stuwen HYD control
- Fews_Rijn Lahn Kalkofen-Muendung stuwen HYD control
- Fews_Rijn Mosel Cochem-Muendung

Compared to FEWS Rijn 2.01 rules for different dams in these rives sections (Neckar, Main, Lahn and Mosel) have been added.

Table 3.2 The basic models used to build the complete SOBEK model for the Rhine in FEWS-Rivers (taken from van der Veen, 2007).

Name	prefix
Fews_Rijn Rhein Maxau-Mainz	MM1
Fews_Rijn Rhein Mainz-Andernach versie 2004.3	RM1
Fews_Rijn Rhein Andernach-Lobith Niederrheinstudie 2002_NRW_M	AL1
Fews_Rijn Rijntakken versie J06_4	RT2
Fews_Rijn Neckar Rockenau-Muendung stuwen HYD control	NE1
Fews_Rijn Main Raunheim-Muendung stuwen HYD control	MA3
Fews_Rijn Lahn Kalkofen-Muendung stuwen HYD control	LA1
Fews_Rijn Mosel Cochem-Muendung	MO1

During the last years new SOBEK-models were built up and calibrated for the River Rhine between Maxau and Lobith and several tributaries by the BfG, Deltares, Waterdienst and LANUV-NRW. Based on a pre-selection, appropriate SOBEK-models will be selected for an new version of GRADE-Rhine in the beginning of 2011 in consultation with BfG, Waterdienst and LANUV-NRW including the HVAL expert group of the ICPR. These SOBEK models allow to make hydraulic calculations without inundations. Partly they are also able to account for the effects of inundations on the flood wave, partly this has to be implemented by the further development of the new GRADE-Rhine.

3.2 Coupling hydrologic modelling– hydraulic river model

In FEWS-GRADE the flood waves in the stretch between Maxau and Lobith, and downstream parts of the Neckar, Main, Lahn and Moselle, are modelled with SOBEK. Flood routing processes can also be modelled with a simplified Muskingum approach in HBV. However, with SOBEK, river and floodplain processes can be modelled in more detail and as a result the simulation of the flood wave with SOBEK is more reliable (de Wit and Buishand, 2007).

For the period 1961 – 1995 de Wit and Buishand (2007) noticed that flood peaks at Lobith were systematically overestimated with the HBV/SOBEK/SYNHP combination. Also the flood volumes of the tributaries exceeded the flood volume at Lobith. Backwater effects at these tributaries during high water levels were suggested as a possible explanation for the exceedence of flood peaks at Lobith. As a first approximation, the simulated discharges at the tributaries (with HBV) have systematically been reduced with five percent (de Wit and Buishand, 2007). In FEWS-GRADE (Patzke, 2007) the so called ‘Zwischeneinzugsgebiete’ (ZWE) were set to zero because it was assumed that during high flows these areas barely have a chance to contribute to the Rhine total discharge (Table 3.4, Figure 3.4a and 3.4b). The factor for Maxau was set to 0.90, and the inflow of tributaries was lowered with 5% (except Mosel (3%)) as was done in the study of de Wit and Buishand (2007).

Table 3.4 Lateral inflows from HBV to the SOBEK model (Type B is boundary, D is diffuse inflow and P is point inflow) with factors used in FEWS-GRADE and factors used in FEWS-Rivers (from the original calibration (van der Veen and Buiteveld, 2005))

Lateral Inflow	SOBEK branch	Location	Type	Length	Factor (GRADE)	Factor (FEWS-Rivers)	Series ID
Maxau	Maxau-Neckar	0	B		0.90*	1.00	H-RN-0689
ZWE Maxau-Speyer	Maxau-Neckar	1	D	38232	0.00	1.00	I-RN-0080
Ettlingen (Alb)	Maxau-Neckar	8844	P		0.37	0.39	H-RN-0036
Berghausen (Pfinz)	Maxau-Neckar	18368	P		0.58	0.61	H-RN-0038
Siebeldingen (Queich)	Maxau-Neckar	22460	P		0.37	0.39	H-RN-0028
Neustadt(Speyerbach)	Maxau-Neckar	37833	P		0.58	0.61	H-RN-0031
ZWE Speyer-47616	Maxau-Neckar	38233	D	9383	0.00	0.34	I-RN-0081
ZWE 47616-Neckar	Maxau-Neckar	47616	D	18168	0.00	0.66	I-RN-0081
Rockenau (Neckar)	Neckar-Worms	1	P		1.05	1.00	H-RN-0659
ZWE Neckar-Worms	Neckar-Worms	1	D	14876	0.00	1.00	I-RN-0082
ZWE L Worms-Main	Worms-Main	1	D	53519	0.00	0.37	I-RN-0084
ZWE R Worms-Main	Worms-Main	1	D	53519	0.00	0.63	I-RN-0084
Lorsch (Weschnitz)	Worms-Main	11368	P		0.77	0.81	H-RN-0024
Eberstadt (Modau)	Worms-Main	30482	P		0.18	0.19	H-RN-0039
Raunheim (Main)	Main-Mainz	1	P		0.96	1.00	H-RN-1027
ZWE_Mainz_Nahe	Mainz-Nahe	1	D	31118	0.00	0.71	I-RN-0087
Oberingelheim (Selz)	Mainz-Nahe	20713	P		0.95	1.00	H-RN-0029
ZWE_Nahe_Kaub	Nahe-Kaub	1	D	16581	0.00	0.29	I-RN-0087
Grolsheim (Nahe)	Nahe-Kaub	10	P		0.95	1.01	H-RN-0913
Pfaffental (Wisper)	Nahe-Kaub	10861	P		0.95	1.00	H-RN-0026
ZWE_Kaub_Lahn	Kaub-Lahn	1	D	39311	0.00	1.00	I-RN-0088

Kalkofen (Lahn)	Lahn-Mosel	10	P		1.05	1.00	H-RN-0888
ZWE_Mosel_Andernach	Mosel-Andernach	1	D	21621	0.00	0.57	I-RN-0089
Saynbach	Mosel-Andernach	7643	P		0.41	0.43	I-RN-0089
Nettegut (Nette)	Mosel-Andernach	16494	P		0.95	1.01	H-RN-0052
Friedrichsthal (Wied)	Mosel-Andernach	18001	P		0.98	1.03	H-RN-0053
ZWE_Ande_Bonn	Andernach-Bonn	1	D	40999	0.00	1.00	I-RN-0093
Altenahr (Ahr)	Andernach-Bonn	15501	P		0.95	1.00	H-RN-0808
ZWE_Bonn_Koel	Bonn-Köln	1	D	33199	0.00	1.00	I-RN-0094
Menden (Sieg)	Bonn-Köln	4501	P		0.95	1.00	H-RN-0984
ZWE_Koel_Dues	Köln-Düsseldorf	1	D	56199	0.00	1.00	I-RN-0096
Opladen (Wupper)	Köln-Düsseldorf	15301	P		1.29	1.36	H-RN-1025
Neubruck (Erft)	Köln-Düsseldorf	52201	P		1.09	1.15	H-RN-0847
ZWE_Dues_Ruhr	Düsseldorf-Ruhrort	1	D	36599	0.00	1.00	I-RN-0097
Hattingen (Ruhr)	Düsseldorf-Ruhrort	35901	P		1.03	1.09	H-RN-0957
Hattingen (Ruhr)	Ruhrort-Wesel	1	P	33199	0.00	0.21	I-RN-0099
Koenigstrasse (Emscher)	Ruhrort-Wesel	17600	P		1.05	1.11	H-RN-1026
ZWE_Wese_Rees	Wesel-Rees	1	D	23399	0.00	0.79	I-RN-0099
Schermbeck (Lippe)	Wesel-Rees	401	P		0.98	1.02	H-RN-0900
ZWE_Rees_Lobi	Rees-Lobith	1	D	24799	0.00	1.00	I-RN-0100
ZWE_Cochem-Muendung	Mosel	1	D	52023	0.00	1.00	I-RN-0063
Cochem (Mosel)	Mosel	0	B		0.97	1.00	H-RN-0908

- in the FEWS-GRADE configuration (XML file) the factor is currently 1.0 (factors for FEWS-GRADE are taken from Patzke (2007))

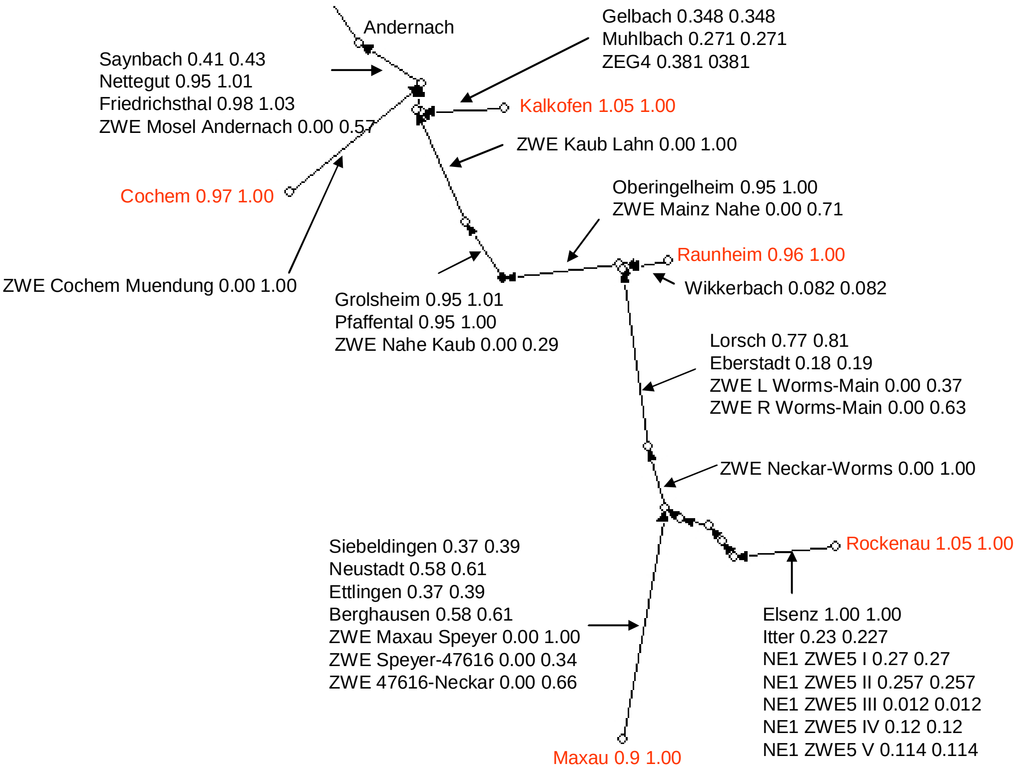


Figure 3.4a. SOBEK model between Maxau and Andernach with lateral inflows and factors, the first factor is used in FEWS-GRADE and the second factor is used in FEWS-Rivers

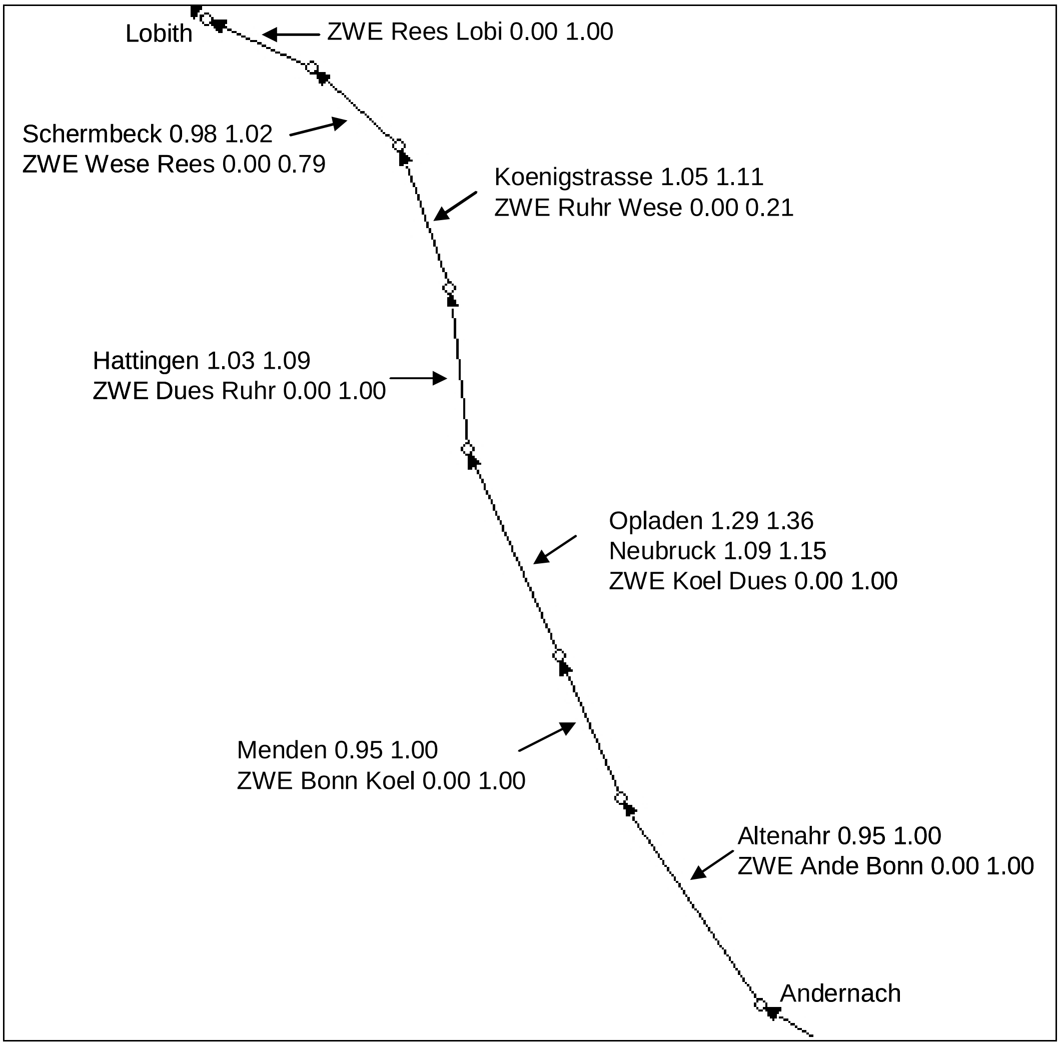


Figure 3.4b. SOBEK model between Andernach and Lobith with lateral inflows and factors, the first factor is used in FEWS-GRADE and the second factor is used in FEWS-Rivers (original calibration of SOBEK)

In order to get more insight into the impact of the factors that are used in FEWS-GRADE a comparison was made between HBV Rhine results (with factors from FEWS-Rivers/calibration of SOBEK, and factors from FEWS-GRADE) with measured lateral discharge. For the period 01-01-1992 – 13-12-1995 average volumes were compared (Table 3.2), and for the high flood period between 22-01-1995 and 09-02-1995 Nash-Sutcliffe Efficiencies (NSE) were calculated between measured lateral discharges and HBV Rhine results with factors used in FEWS Rivers and FEWS-GRADE respectively (Table 3.3).

From Table 3.2 and Table 3.3 the following is observed for the most important contributors of lateral flow (>1%), as compared to FEWS-River:

- Simulated discharge at Maxau is overestimated (note that the factor in FEWS-GRADE and FEWS-Rivers is the same: 1.0).
- For Rockenau a higher factor (1.05) results in a lower performance (NSE), however maximum discharge is better estimated. The higher factor does not improve the simulation of average flow volumes.
- A higher factor for Kalkofen (1.05) both improves the simulation of average flow volumes and the flooding event in January 1995.

- A lower factor for Cochem (0.97) improves the simulation of the flooding event in January 1995.
- A lower factor for Grolsheim (0.95) does not improve the simulation of average flow volumes and the flooding event in January 1995.
- A lower factor for Menden (0.95) does not not improve the simulation of average flow volumes and the flooding event in January 1995.
- A lower factor for Opladen (1.29) does improve the simulation of the flooding event in January 1995, but it does not improve the simulation of average flow volumes.
- A lower factor for Hattingen (1.03) does not improve the simulation of the flooding event of January 1995 and the simulation of average flow volumes.
- A lower factor for Koenigstrasse (1.05) does improve the simulation of the flooding event of January 1995 and the simulation of average flow volumes.
- A lower factor for Schermbeck (0.98) does improve the simulation of the flooding event of January 1995 and the simulation of average flow volumes.

While lower factors (and a higher factor for Kalkofen) did improve the simulation of average flows and the high flood event of January 1995 for a number of lateral flows (for example Hattingen and Schermbeck) the question of course remains how these factors are applied.

Table 3.2 Simulated (with HBV Rhine using factors from FEWS-Rivers and factors from FEWS-GRADE) and measured total volumes of water for the period 01-01-1992 – 31-12-1995. The percentages refer to the relative contribution to the average flow volume at Lobith for this period (77.75 Bm^3/y). ZWE refers to the so called 'Zwischeneinzugsgebiete'.

		Average volume (Bm^3/y)		
		Factors FEWS-Rivers	Factors FEWS -GRADE	Measured lateral discharge
Maxau-Neckar	Siebeldingen (0.07%)	0.06	0.06	0.05
	Neustadt (0.10%)	0.09	0.09	0.08
	Ettlingen (0.11%)	0.07	0.06	0.08
	Berghausen (0.09%)	0.11	0.10	0.07
	ZWE	0.44	0.00	
	Maxau (55.53%)	45.28	45.28	43.02
Neckar-Worms	Rockenau (6.35%)	5.11	5.37	4.92
	ZWE	0.54	0.00	
	Elsenz	0.26	0.26	
	Itter	0.16	0.16	
Worms-Main	Lorsch (0.12%)	0.08	0.08	0.10
	Eberstadt (0.03%)	0.02	0.02	0.02
	ZWE	0.26	0.00	
Main-Mainz	Raunheim (8.21%)	7.60	7.29	6.36
Mainz-Nahe	Oberingelheim (0.02%)	0.03	0.03	0.02
	ZWE	0.08	0.00	
Nahe-Kaub	Grolsheim (1.54%)	1.06	1.00	1.19
	Pfaffental (0.04%)	0.04	0.04	0.03
	ZWE	0.03	0.00	
Kaub-Lahn	ZWE	0.10	0.00	0.10
Lahn-Mosel	Kalkofen (2.23%)	1.80	1.73	1.72
	Gehlbach/Muhlbach/ZEF4	0.14	0.00	

Mosel	ZWE	0.24	0.00	
	Cochem (15.92%)	12.60	12.10	12.33
Mosel-Andernach	Friedrichsthal (Wiede) (0.35%)	0.31	0.30	0.27
	Nettegut (0.10%)	0.10	0.09	0.07
	Friedrichsthal (Saynbach) (0.11%)	0.06	0.06	0.08
	ZWE	0.08	0.00	
Andernach-Bonn	Altenahr (0.32%)	0.27	0.25	0.25
	ZWE	0.16	0.00	
Bonn-Koln	Menden (2.26%)	1.73	1.64	1.75
	ZWE	0.16	0.00	
Koln-Duesseldorf	Opladen (0.98%)	0.71	0.68	0.76
	Neubrueck (0.43%)	0.92	0.87	0.33
	ZWE	0.40	0.00	
Duesseldorf-Ruhrort	Hattingen (3.86%)	2.94	2.78	2.99
	ZWE	0.22	0.00	
Ruhrort-Wesel	Koenigstrasse (0.80%)	0.67	0.64	0.62
	ZWE	0.06	0.00	
Wesel-Rees	Schermbeck (2.16%)	1.93	1.86	1.67
	ZWE	0.22	0.00	
Rees-Lobith	ZWE	0.22	0.00	

Table 3.3 Nash-Suttcliffe Efficiency (NSE) and maximum discharges for simulated lateral flows with HBV Rhine (with FEWS-Rivers factors and FEWS-GRADE factors)

Laterals	**NSE**	**NSE**	Maximum discharge (m^3/s)		
	FEWS-Rivers factors	FEWS-GRADE factors	FEWS-Rivers factors	FEWS-GRADE factors	measured
Maxau	-0.01	-0.01	4750.95	4750.95	3770.00
Siebeldingen	-2.99	-2.28	10.89	10.34	7.83
Neustadt	-8.39	-6.73	17.04	16.20	7.28
Ettlingen	0.54	0.54	3.23	3.07	5.39
Berghausen	-1.51	-1.09	5.06	4.81	3.21
Rockenau	0.66	0.59	975.67	1024.45	1130.00
Lorsch	0.49	0.48	24.23	23.04	32.4
Eberstadt	0.37	0.38	5.68	5.39	9.63
Raunheim	0.80	0.87	2323.19	2230.26	2040.00
Oberingelheim	0.61	0.59	2.27	2.16	3.47
Grolsheim	0.61	0.63	630.94	593.46	764.57
Pfaffental	0.19	0.34	15.37	14.46	11.20
Kalkofen	0.72	0.77	624.09	599.12	551.00
Cochem	0.79	0.82	3757.82	3607.51	3437.00
Friedrichsthal (Wiede)	0.38	0.42	81.72	77.75	90.74
Nettegut	-0.95	-0.54	28.13	26.46	27.00
Friedrichsthal (Saynbach)	0.18	0.12	17.05	16.26	28.19
Altenahr	-0.76	-0.57	151.96	144.36	111
Menden	0.74	0.75	553.05	525.40	625
Opladen	0.65	0.69	183.96	174.49	164.36

Neubrueck	-8.19	-6.17	53.68	50.88	29.90
Hattingen	0.69	0.68	923.73	872.88	921.05
Koenigstrasse	0.19	0.30	189.46	179.22	183.17
Schermbeck	-0.15	0.07	520.62	500.20	334.56

The overall conclusion, which can be drawn from these results is, that it seems to be necessary to start a thorough inventory of the various correction factors used in GRADE-Rhine and how to replace them for example by using as much as possible straightforward hydrodynamic modelling of the main river and the ultimate (downstream) parts of the major tributaries.

3.3 Replacement SYNHP routing module

For flow routing upstream from Maxau the SYNHP model was part of GRADE-Rhine. The model is managed by the LUBW of the German state Baden Wurtenberg. Baden Wurtenberg did not give permission to use SYNHP, since they considered it as inadequate for calculating extreme peak discharges on a daily basis. This is due to the retention measures being managed on a time scale smaller than one hour. Other disadvantages in the use of SYNHP where that the compiled configuration of SYNHP is unknown to Deltares and the number of years that SYNHP could be run in one simulation is too small.

In order to improve the transparency of GRADE-Rhine, an analysis was made of the possibility to replace the existing flow routing between Basel and Maxau by a transparent Muskingum routing. An uncalibrated Muskingum routine was already in place in GRADE-Rhine, based on the SAMRT model code (Werner, 1997), but this module had not been used so far.

The following has been done:

- Comparison between a selected time series, simulated by SYNHP, and simulated by Muskingum. Checks for mass conservation between inputs and outputs and checks of temporal consistency of the outputs at Maxau;
- Based on the previous, investigate reasons for discrepancies;
- Analysis of discharge calculations for Maxau

3.3.1 Comparison between SYNHP and Muskingum outputs

For a one-year period, the HBV, SYNHP and the uncalibrated Muskingum models were run. As input, synthetic time series from the ESSENCE climate run were used. In this experiment, SYNHP and Muskingum receive precisely the same input time series, all generated from the upstream HBV models. Flow series from 13 HBV subcatchments are provided to both models.

Some of these series were directly generated by the HBV models in upstream catchments, others are flows from intermediate catchments, not modelled by HBV. Instead, these are approximated by means of multiplications of flow series, generated by the HBV models.

The 13 inflow time series mentioned above were reported from GRADE-Rhine, together with the output as generated by SYNHP and by Muskingum. Time series plots of the sum of all contributing catchments, as well as the SYNHP and Muskingum outputs were made and double mass plots of the sum of contributing time series and the outputs from SYNHP and

Muskingum were made (see Figure 3.1 and Figure 3.2). These figures clearly show that SYNHP is mass conservative (i.e. the amount of water that flows into the model, also flows out of the model).

Muskingum however, is not mass conservative, but has a consistent bias with respect to the inputs.

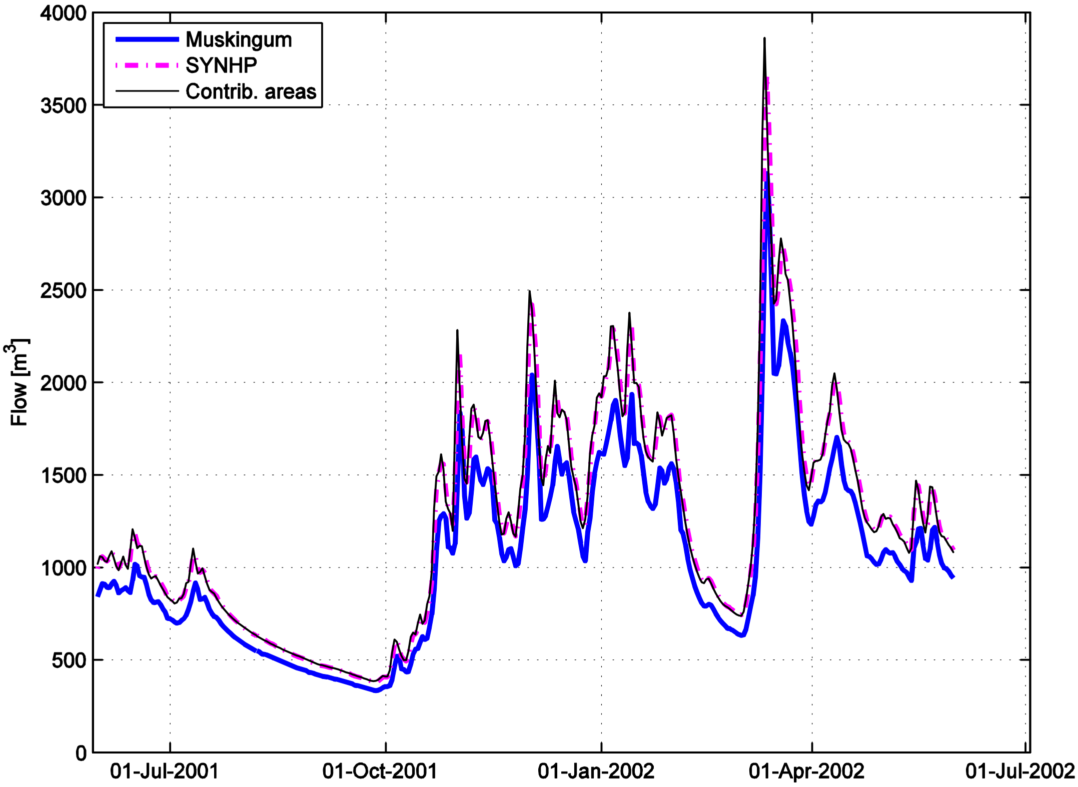


Figure 3.1. Time series plot of total flows from contributing areas, SYNHP and Muskingum output at Maxau

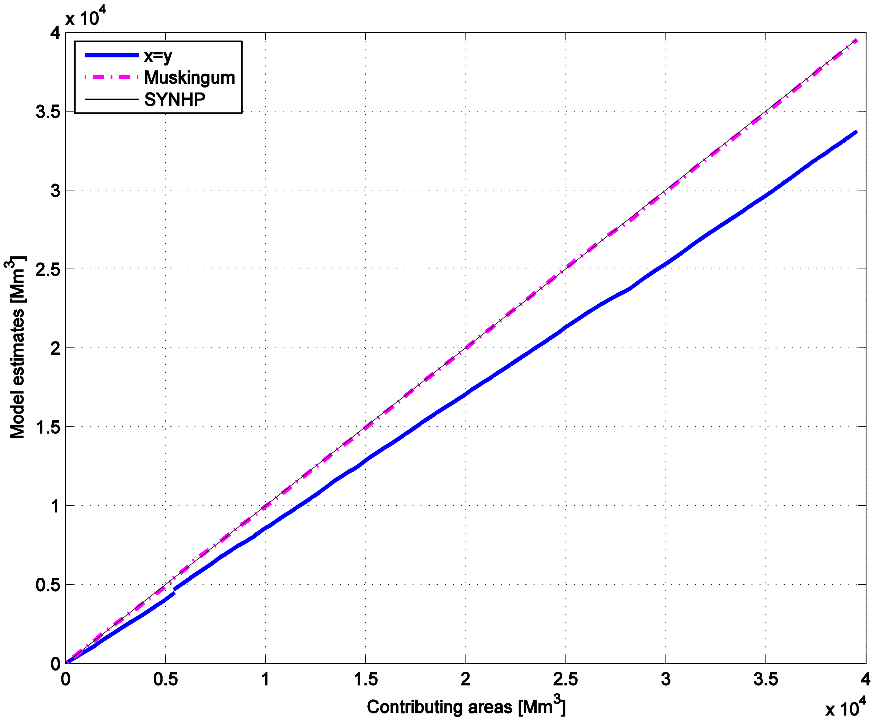


Figure 3.2. Double Mass curve of the sum of all contributing catchments, against both SYNHP and Muskingum model estimates

3.3.2 Reconfiguration and calibration of the Muskingum model

The configuration of the Muskingum model has been checked in order to identify the reason why the model is not mass conservative. SAMRT has an option to route percentages of input flows over different stretches of the river. It was found that the separation of the flow over different stretches was already computed in FEWS, resulting in 13 contributing time series to SAMRT. The same separation in contributions was followed for SYNHP. However, within SAMRT only certain percentages of the incoming flows were used as input to the routing equations, rather than the total flow. Since this step is already taken in the data preparation step in FEWS, it needed to be removed. The following percentages were found for each of the 13 contributions:

Basel:	90 %
Wiese:	39 %
Leop-k:	100 %
Zwe_1:	23 %
Ill-Ent:	70 %
Kinzig:	88 %
Ill:	30 %
Ach_Renc:	30 %
Zwe_2:	12 %
Moder:	100 %
Zwe_3:	8 %
Murg:	70 %
Sauer:	56 %

The Muskingum equation assumes that the water storage within a channel reach is a function of weighted inflow and outflow and reads as follows:

$$S = \frac{1}{K}\left[\theta I + \left(1-\theta\right)Q\right], \qquad (3.1)$$

where *S* [L^3] is the storage within the river channel, *K* [1/T] is a reciprocal of a residence time, approximating the time travel of a flood wave, *I* [L^3/T] is the inflow into the channel over a time window, *Q* [L^3/T] is the outflow and θ [-] is the weighting coefficient.

The parameter θ has been set to 0.2 for all reaches. This default value has also been used in all other Muskingum models throughout FEWS-GRADE. Parameter *K* strongly influences the timing of peaks and has therefore been calibrated manually. Calibration was based on time series of 35 years of observed precipitation and temperature data (1961-1995), available to FEWS-GRADE, averaged at sub-catchment locations. The calibration was performed on discharge estimates, based on water level observations, at Maxau. To estimate the goodness of fit, the coefficient by Nash and Sutcliffe (1970) has been used. To emphasize the resemblance of the peaks of observed and simulated values, the correlation coefficient has also been computed (between SYNHP and Muskingum output). The results are given in Table 3.2. The results of different values for K are very close to each other. The difference can hardly be seen on a hydrograph plot that has been omitted here for this reason.

Table 3.4 Calibration results for residence time parameter K in Muskingum model. The best result is highlighted in black

K [1/day]	Nash [-]	correlation coeff. [-]
0.1	0.98	0.99
0.2	**0.99**	**0.99**
0.3	0.98	0.99
0.4	0.96	0.98
0.6	0.91	0.96

A residence time of 1 / 0.2 days gives the best resemblance between observed and simulated discharge values although the differences are quite small. Therefore, *K* has been set to 0.2 for all reaches.

The SYNHP model has been replaced by this updated configuration in FEWS-GRADE for the Rhine.

3.3.3 Analysis of discharge calculations for Maxau

As has been shown by Goergen et al. (2010), flood peaks at Maxau are significantly (> 20%) overestimated by the HBV model at Maxau. This seems to be partly caused by over-estimation of the precipitation in the CHR observational dataset for the Ill watershed area that is partly situated in France.

Also flood routing may contribute to the overestimation of peak values. As mentioned before, SYNHP was used until recently in FEWS-GRADE but is now replaced by the Muskingum flow routing model. Here we give some insight about the performance of the models for discharge calculations at Maxau.

Figure 3.3 shows the flow duration curve for discharges at Maxau with focus on the high discharges, which are relevant for GRADE. All models overestimate the observed discharges that have an exceedance probability of less than 1%. The Muskingum and SYNHP routing models perform clearly better than the HBV-routing, although overestimation of the higher discharges is still significant.

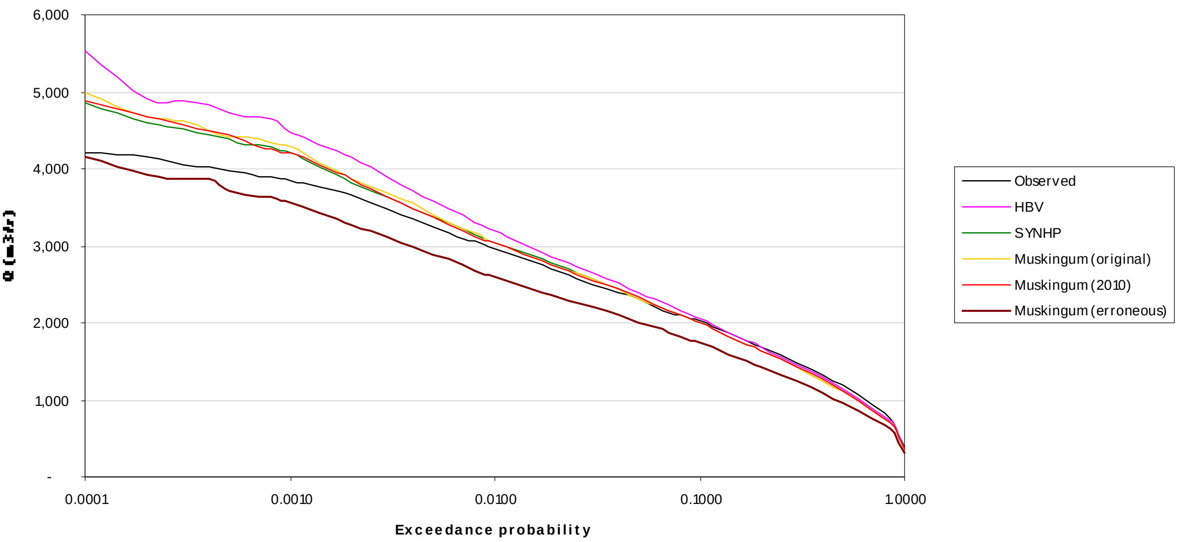


Figure 3.3 Flow duration curve for river discharges at Maxau

Table 3.5 shows some characteristics of the model outputs as compared to the observed discharge series at Maxau. The HBV-routing as well as the SYNHP routing produce less water volume over the 1961-1995 period than results from observed discharges. For the volumes resulting from the Muskingum flow routing it strikes that they are exactly the same as observed; apparently the percentages shown in paragraph 3.2.2 are tuned to the overall water balance of the CHR observational dataset. In addition, the characteristics of the "erroneous" Muskingum model where the percentages were applied 2 times are shown in the table.

Table 3.5 Characteristics of modelled time series for Maxau

	Volume (%)	**R^2**	**Nash Sutcliffe**
HBV	98,9	0,92	0,82
SYNHP	97,4	0,91	0,80
Muskingum (original)	100,0	0,95	0,89
Muskingum (2010)	100,0	0,96	0,90
Muskingum ("erroneous")	86,7	0,95	0,75

As can be expected the Nash Sutcliffe coefficient is rather low for the models that are not mass conservative. The Muskingum routine results to be an improvement to the HBV-routing as well as to the SYNHP routing model; also the new calibration performs slightly better then the standard calibration. To solve the significant bias in the results for high flows further analysis is needed to improve discharge calculations at Maxau, flow routing does not seem to be due to the remaining differences.

Points for further research may include:

- Actualisation of the CHR observational dataset to the HYRAS dataset that is currently being finalized. It is expected that the HYRAS dataset solves mismatches in precipitation estimates at the German border areas as is the case for the Ill river basin.
- Analysis of contributions from upstream subbasins to discharge at Maxau. As explained in paragraph 3.2.2, only certain percentages from discharge values are taken for subbasins upstream of Maxau. Does HBV indeed produce discharges that are too high, can these values be explained by other reasons and do these values effect the discharge contribution during flood events?

These questions will be picked up in the GRADE research in 2011 – 2013.

4 Conclusions and recommendations

4.1 Conclusions

- The water balance problem that was found to occur in the version of GRADE-Meuse that makes use of the SOBEK model for the flood routing came out to be caused by errors in the configuration and could easily be solved.
- The flood routing of the flood waves on the Upper Rhine river, which were made using an external routing module (SYNHP), has been replaced by a similar routing module based on the Muskingum method as SYNHP is not permitted to be used anymore for GRADE.
- Promising options have been developed for the post-processing of the GRADE simulations and further development will need to be made using the results of the pre-operational use ("schaduwdraaien") with GRADE-Meuse as part of the WTI project during 2011.
- A first start has been made with the development of a methodology for the derivation of the design hydrograph corresponding to the design flood peak for various return periods based on the same simulations series from GRADE. A large number of forms may occur and longer series with more flood waves are necessary to start the actual process of the derivation of a design hydrograph.
- Many correction factors are used by the coupling of the hydrologic (HBV) and hydraulic (SOBEK) model that obscure whether or not the actual processes are well represented in the models.

4.2 Recommendations

- The pre-operational use of GRADE-Meuse will form an excellent test case for the planning of the implementation of the GRADE-Rhine system
- It is necessary to start a thorough inventory of the various correction factors used in GRADE-Rhine and how to replace them for example by using as much as possible straightforward hydrodynamic modelling of the main river and the ultimate (downstream) parts of the major tributaries
- There is the necessity of a thorough update of GRADE-Rhine taking into account things as a good database (precipitation and discharge) for calibration and verification of models, improving HBV and SOBEK and coupling of both as well as improving the facilities for the use of GRADE for WTI
- A thorough inventory of the existing models of the Rhine river is urgently needed in order to make well-balanced choices among the various existing model systems made by the cooperation partners BfG, Waterdienst, Deltares and LANUV-NRW. With the inventory started in 2010 by the steering group model administration a first step has been done, but this inventory had to be finished and has to be updated regularly.
- The use of multi-variate classification criteria in the derivation of the standard flood wave will require a much longer simulation period than 20,000 years, although this does not need to be a continuous series. We therefore recommend that 5 series of 20,000 years are generated with FEWS-GRADE to further analyse how flood wave shapes may be selected in the future within WTI.

5 Literature

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