Generator of Rainfall and Discharge Extremes for the Rhine

Final report of GRADE-Rhine version 3.0

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Samenvatting

GRADE (**G**eneration of **R**ainfall **a**nd **D**ischarge **E**xtremes) is een combinatie van een stochastische weergenerator, een hydrologisch model en een hydrodynamisch model en wordt gebruikt voor het simuleren van extreme afvoeren in de Rijn bij Lobith en de Maas bij Borgharen. De ontwikkelingen van GRADE zijn gestart in 1998 en sinds 2014 (versie GRADE 2.0) wordt GRADE officieel toegepast binnen het Wettelijk Beoordelings Instrumentarium (WBI2017) voor het genereren van de afvoerstatistiek en golfvorm.

Sinds 2014 is er doorontwikkeld aan het GRADE instrumentarium om te komen tot een nieuwe versie (GRADE 3.0). In dit rapport worden deze nieuwe GRADE versie en de daaruit volgende resultaten gepresenteerd, inclusief de nieuwe afvoerstatistiek, de bijbehorende onzekerheidsband en de statistiek van golfvormen voor de Rijn bij Lobith. Voor de Maas bij Borgharen zijn de resultaten gepresenteerd in een separaat rapport (Hegnauer et al., 2022).

In het rapport worden de resultaten gepresenteerd voor het huidige klimaat. De nieuwe resultaten zijn gebaseerd op GRADE 3.0, met daarin een nieuwe versie van de weergenerator. De nieuwe weergenerator bevat een uitbereiding van de basis dataset (van 2007 tot en met 2015), een nieuwe methode voor het selecteren van een optimale reeks van 50,000 jaar uit een langere 500,000 jarige simulatie en enkele kleinere verbeteringen ten opzichte van GRADE versie 2.0. De nieuwe weergenerator (GRADE 3.0) geeft tot herhalingstijden van 100 jaar ongeveer dezelfde 4-daagse neerslagsom vergeleken met de vorige versie van GRADE (2.0). Voor langere herhalingstijden zijn de 4-daagse neerslagsommen in GRADE 3.0 iets lager vergeleken met GRADE 2.0.

GRADE 3.0 maakt gebruik van hetzelfde hydrologische model (HBV) als GRADE 2.0. Wel bevat GRADE 3.0 een verbeterd hydrodynamisch model voor de Duitse Rijn tussen Andernach en Lobith. Dit hydrodynamische model, een SOBEK3-1D2D model, simuleert het effect van overstromen van de Rijn in Duitsland tussen Andernach en Lobith op de berekende piekafvoeren bij Lobith. Dit effect begint bij afvoeren boven 14,000 m^3/s en zorgt ervoor dat de piekafvoeren bij Lobith veel lager worden vergeleken met de situatie zonder het meenemen van die overstromingen. Door het expliciet simuleren van de overstromingen tussen Wesel en Lobith, die plaatsvinden bij afvoeren boven de 17,000 m^3/s, worden de afvoeren bij Lobith onder aanname van de huidige inrichting van de rivier en dijken begrensd tot afvoeren rond 17,800 m^3/s. Dit is een nieuw inzicht dat GRADE 3.0 heeft opgeleverd ten opzichte van versie 2.0.

Voor GRADE 3.0 is de onzekerheidsanalyse voor het hydrodynamische model opnieuw uitgevoerd. De verbeterde onzekerheidsanalyse maakt expliciet onderscheid tussen modelonzekerheden en onzekerheid over het wel of niet nemen van noodmaatregelen. De modelonzekerheden zijn middels een Monte Carlo experiment afgeleid waarbij de ruwheid, de dijkhoogte en het wel of niet doorbreken van de dijken zijn meegenomen als stochasten. Het effect van noodmaatregelen op de afvoer bij Lobith is berekend aan de hand van enkele scenario’s van mogelijke noodmaatregelen. De modelonzekerheden werden gecombineerd met de onzekerheden van de weergenerator en het hydrologisch model en resulteren in het 95% betrouwbaarheidsinterval voor de afvoerstatistiek van Rijn bij Lobith. De scenario's voor noodmaatregelen kunnen worden gebruikt om aanvullende of alternatieve afvoerstatistieken af te leiden.

Voor herhalingstijden onder de 100 jaar is de afvoerstatistiek zonder onzekerheden vergelijkbaar met de WBI2017 resultaten. Voor herhalingstijden boven 1000 jaar zijn de GRADE’21 afvoeren ongeveer 5 tot 15% lager vergeleken met WBI2017.

Dit is het gecombineerd effect van de nieuwe weergenerator die lagere extreme neerslagsommen berekent, en het gebruik van het nieuwe hydrodynamische model van de Rijn.

De nieuwe 95% onzekerheidsband is voor kleinere herhalingstijden iets breder vergeleken met de onzekerheidsband in WBI2017, maar voor grotere herhalingstijden (>10,000 jaar) juist smaller. Dit is het gevolg van de verbeterde onzekerheidsanalyse die voor GRADE'21 is uitgevoerd.

De onzekerheidsband kan ook worden uitgeïntegreerd tot een afvoerstatistiek inclusief onzekerheden. Ook de afvoeren inclusief onzekerheden op basis van GRADE 3.0 zijn voor herhalingstijden groter dan 1000 jaar ongeveer 5 tot 10% lager dan de WBI2017 afvoerstatistiek inclusief onzekerheden. Voor herhalingstijden tot 100 jaar zijn beide statistieken nagenoeg gelijk.

Naast de afvoerstatistiek levert GRADE 3.0 ook nieuwe golfvormen op. De nieuwe gemiddelde golfvorm op basis van GRADE’21 is iets smaller dan de golfvorm in WBI2017. Dit heeft vermoedelijk te maken met het feit dat GRADE’21 door onder meer de nieuwe neerslaggenerator, iets lagere afvoeren produceert.

De resultaten zoals gepresenteerd in dit rapport bevatten relevante nieuwe inzichten die kunnen worden toegepast in het Beoordelings- en Ontwerp Instrumentarium 2023 (BOI2023) voor het beoordelen van de dijken en keringen langs de Rijn in Nederland. Deze inzichten zijn ook relevant voor andere projecten, zoals het Delta Programma, het Kennisprogramma Zeespiegelstijging en in de toekomst voor het berekenen van de afvoeren voor verschillende klimaatscenario’s.

Dit project is uitgevoerd in nauwe samenwerking met KNMI (het Koninklijk Nationaal Meteorologisch Instituut), Deltares en Rijkwaterstaat (WVL).

Summary

GRADE (**G**eneration of **R**ainfall **a**nd **D**ischarge **E**xtremes) is a combination of a stochastic weather generator, a hydrological model, and a hydraulic model to simulate the discharge of the Rhine at Lobith under extreme conditions. The development of GRADE started in 1998 and since was applied for the first time in 2014 (GRADE version 2.0) to derive discharge statistics and mean hydrograph shape for the Rhine at Lobith. GRADE (version 2.0) was used in the assessment of the primary flood defense measures in the Netherlands (WBI2017).

Since 2017 further development has been carried out leading to a new GRADE version (3.0). The goal of this report is to introduce the most recent update of the Generator of Rainfall and Discharge Extremes (GRADE) version 3.0 for the Rhine and to present the new results of discharge statistics (including uncertainties) and hydrograph shapes.

This report presents the results of the GRADE 3.0 simulations for the Rhine at Lobith for the current climate. The weather generator (WG) has been updated compared to the GRADE 2.0 simulations. The updates include the extension of the historical base period (from 2007-until 2015) used in the resampling procedure, the selection of an optimal 50,000-year simulation from a 500,000-year simulation and several (relatively minor) additional changes. The updated WG-Rhine for GRADE 3.0 gives very comparable 4-day precipitation extremes for return periods op to 100 years compared to the (previous) WG-Rhine for GRADE 2.0. For return periods longer than 100 years, GRADE 3.0 simulates slightly lower 4-day precipitation volumes compared to GRADE 2.0.

GRADE 3.0 uses the same hydrological model for the Rhine (HBV) as GRADE 2.0 but an improved hydraulic model (SOBEK3-1D2D) is used to better simulate the effect of flooding along the Lower Rhine in Germany. These effects start with discharges above about 14,000 m^3/s and have a large dampening effect of the discharge at Lobith. For discharges above 17,000 m^3/s at Wesel, dike overtopping and potential dike breach along the stretch between Wesel and Lobith results, under current conditions of the riverbed and the dikes, in an upper limit of the discharge at Lobith of around 17,800 m^3/s. This is a new insight derived by using GRADE 3.0 compared to GRADE 2.0.

With the updated weather generator, the HBV model and the updated SOBEK3-1D2D model new discharge statistics for the Rhine at Lobith were constructed. The result peak discharges without considering uncertainties based on GRADE 3.0 are somewhat lower than those based on GRADE 2.0 (also known as the WBI2017 results), especially for longer return periods.

The uncertainty analysis for the Rhine was (partly) redone. An improved uncertainty analysis for the hydrodynamic model was done. A major change compared to GRADE 2.0 is that the model uncertainties and uncertainties resulting from emergency measures were split in the analysis. The model uncertainties were assessed by performing a Monte Carlo experiment, where roughness, embankment heights and dike breach processes were considered as stochastics. The uncertainties from emergency measures were assessed by running different scenarios. The model uncertainties were combined with the other uncertainties from the weather generator and the hydrological model. The scenarios for emergency measures can be used to derive additional or alternative discharge statistics.

When including the uncertainties in the discharge statistics, the reference statistics for GRADE’21 are comparable to the WBI2017 results for return periods up to 100 years. The GRADE’21 discharges are approximately 5 to 15% lower for return periods above 1000 years. This is the combined effect of the new weather generator that calculates lower extreme precipitation sums, and the use of the new hydrodynamic model of the Rhine.

The 95% uncertainty interval of the GRADE’21 results is slightly larger for shorter return periods, but smaller for longer return period (>10,000 year) when compared to the WBI2017 uncertainty interval. This is the result of the improved uncertainty analysis that was done for GRADE’21.

The uncertainty of the discharge statistics, and more precisely the 95% uncertainty interval around the discharge frequency curve, can be ‘integrated’ yielding to a ‘discharge frequency curve including uncertainty’. When comparing these frequency curves, the resulting discharges for GRADE’21 are comparable to those of WBI2017 for return periods up to 100 years and around 5-10% lower compared to WBI2017.

Besides discharge statistics, GRADE 3.0 also produces new hydrograph shapes. The newly derived averaged hydrographs shape (GRADE’21) is slightly smaller, compared to the WBI2017 hydrograph shape. This could be caused by the fact that the new weather generator, in combination with the new hydrodynamic model, produces slightly lower peaks compared to GRADE 2.0.

The results presented in this report provide valuable new insights which are relevant for assessing the primary flood defense measures in the Netherlands in the Assessment and Design Tool, (in Dutch: Het Beoordelings en Ontwerp Instrumentarium, (BOI) in 2023. These insights are also relevant for other studies like the Delta Program, Integral river management and the Knowledge Program Sea Level Rise and for the design of flood defense measures under BOI 2023, in these cases (also) for scenarios under climate change conditions.

This project was carried out in close cooperation between KNMI (the national meteorological institute, Deltares and Rijkswaterstaat (WVL), an agency of the Ministry of Infrastructure and Water Management.

Contents

1 Introduction

1.1 Background

In the late 1990s Rijkswaterstaat adopted the idea of developing an alternative method of determine the design discharge for the flood protection system in the Netherlands (Parmet and Van Bennekom, 1998). Back then, the design discharge for the Rhine river was based on extreme value statistics using the measured flood peak discharges of the Rhine at Lobith since 1911. Besides the design discharge corresponding to a return period of 1250 years a flood hydrograph associated with this peak discharge was calculated using the hydrographs of measured flood waves.

With the start of a new policy of assessing the primary flood defense systems in the Netherlands in 2017 (WBI2017) a new method called GRADE (**G**eneration of **R**ainfall **a**nd **D**ischarge **E**xtremes) was used for the first time to derive discharge statistics and mean hydrograph shape for the Rhine at Lobith. The use of GRADE in WBI2017 followed the advice from the ENW (Expertise Netwerk waterveiligheid, www.enwinfo.nl) in 2015 (ENW, 2015).

Meanwhile flood policy in the Netherland had been changed, asking for using the whole range of the discharge statistics up to very high return periods of 10,000 years and much higher including associated flood hydrographs. This made the step forward to a new method more urgent.

The developments after the ENW advice in 2015 on GRADE2.0 have led to the most recent version GRADE3.0 which is described in this report. This new version is used in the most recent method of assessing the primary flood defense systems (Beoordelings- en Ontwerp Instrumentarium 2023 (BOI2023)) and other studies like the Delta Program, Integrated River Management, and the Knowledge Program Sea Level Rise.

GRADE is a combination of a stochastic weather generator, a hydrological model, and a hydraulic model to simulate the discharge of the Rhine at Lobith under extreme conditions. These simulations are used to derive discharge statistics and mean hydrograph shape for the Rhine at Lobith. The modelling chain has been developed and validated using observations. In Figure 1-1 an overview of the GRADE components is shown.

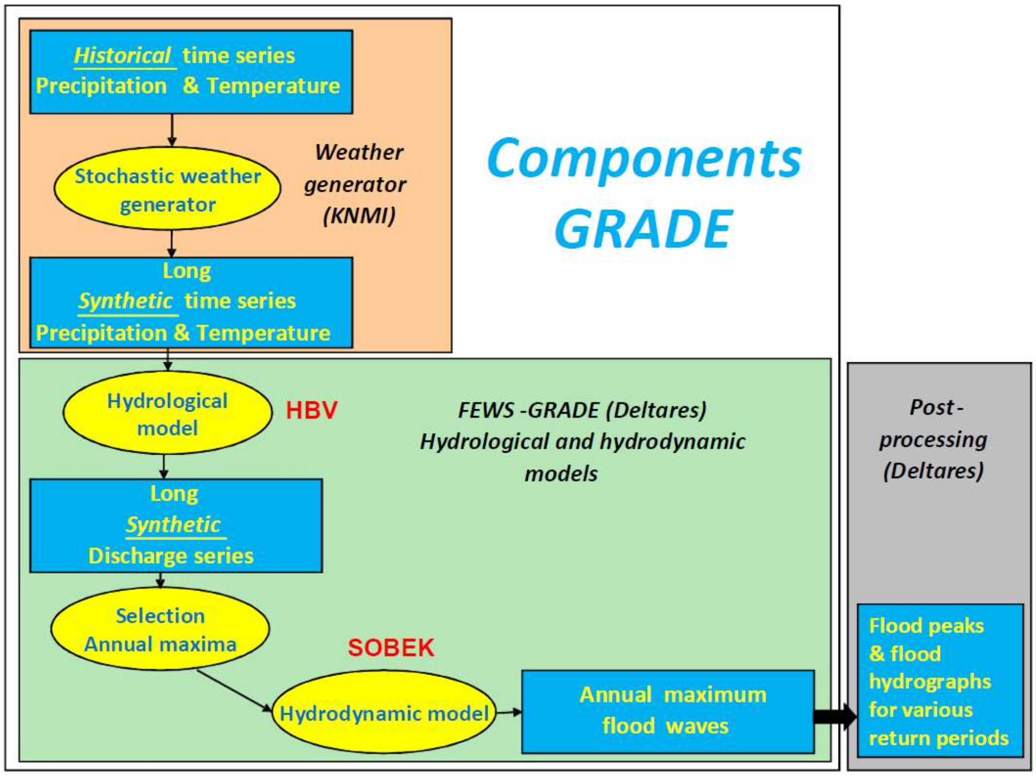

Figure 1-1 Schematic overview of GRADE components.

1.2 About this report

The goal of this report is to introduce the most recent update of the Generator of Rainfall and Discharge Extremes (GRADE) version 3.0 for the Rhine. This report will highlight the differences between GRADE 2.0 and 3.0 and will present the results of the GRADE 3.0 simulations for the Rhine. For a detailed description of GRADE and its components we refer to the GRADE 2.0 report (Hegnauer, et al. 2014).

In Chapter 2 this report presents the stochastic weather generator. In Chapter 3 the hydrological and hydraulic models are presented. In Chapter 4 the final GRADE 3.0 results are presented. Finally, in chapter 5 a summary and the conclusions are given.

2 Stochastic Weather Generator

2.1 Introduction

The weather generator (WG) is the first component of GRADE. It is used to simulate long records of daily weather data. The WG is based on a nonparametric resampling technique known as nearest-neighbor resampling. Daily rainfall amounts are resampled from the historical record with replacement. The WG does not generate rainfall at a single site but rainfall and temperature at multiple locations simultaneously. A major advantage of resampling historical days at multiple locations simultaneously is that both the spatial association of daily rainfall over the drainage basin and the dependence of daily rainfall and temperature are preserved without making assumptions about the underlying joint distributions. More details of the resampling procedure can be found in the GRADE 2.0 report (Hegnauer et al., 2014), Buishand and Brandsma (2001) or Schmeits et al. (2014). For the WG for the Rhine basin these multiple locations are the 134 (major HBV) sub basins of the Rhine upstream of Lobith (chapter 3).

Basically, the methodology of the weather generator for the Rhine basin is unchanged compared to the methodology used in the GRADE 2.0 (Hegnauer et al., 2014). There are however some changes and improvements which are described in the subsequent sections:

- Extension of the base period and meteorological input data (section 2.2)
- Selection of an optimal 50K-year slice (section 2.3)

2.2 Extension of the base period and changing the meteorological input data

2.2.1 Extension of base period

First, the historical base period used for the weather generator is extended with the most recent (available) historical data, effectively 2007-2015. This was one of the main reasons for producing a new reference WG simulation for the Rhine basin for GRADE 3.0 (i.e., the 2021 version of GRADE).

2.2.2 Active and passive data

In the WGs for the river basins, the meteorological data that are used for performing the resampling procedure (the so-called active data) are not necessarily identical to the data that are used in the final timeseries that are coupled to the hydrological model (the so-called passive data). A possible difference is that the passive data can consist of more meteorological elements (e.g., evaporation) than those that are used for the resampling procedure (precipitation and temperature), but typically the passive dataset consists of a dataset that has a better underlying resolution, i.e., for which (much) more measurement stations were available. This distinction stems from the time when for the active data (i.e., precipitation and temperature) only a relatively small number of precipitation and temperature stations within the basin were available. For the simulation sequence, i.e., for the order of the resampled historical dates, this is fine but for coupling the resulting time series with the hydrological model the most accurate estimates of daily averages at the sub-basin scale are required, which requires in turn as many underlying stations as possible, especially for precipitation which has a large spatial variation.

Another advantage of the distinction between passive and active data is more flexibility with respect to extending the historical base period with the most recent years (in general, the resampling benefits from an as-long-as-possible recent base period). This is typically easier (and in practice usually available earlier) for the 'low-resolution' active data than for the 'high-resolution' passive data. When extended active data are available but the corresponding extended passive data not (yet), it is still possible to use these extended active data. This can be done by introducing a second resampling step to the resampling procedure that links a newer date in the active data (i.e., a date that is thus not available in the passive data) to the date of a similar day in passive data (i.e., a date that is available in the passive date). Such a second resampling step was used in the GRADE 2.0 version of the Rhine WG because the base periods of the active and passive data did not exactly match. For the GRADE 3.0 update of the Rhine WG such a second resampling step is no longer needed since the active data (E-OBS (Cornes, 2018)) and the passive data (HYRAS (Razafimaharo, 2020))) are available for the same base period (1951-2015)[1]. But this situation of availability of data might change again in the future (and may also become different for active and passive data needed for the WG's for the different river basins).

*Table 2-1 Overview of the sources of the active and passive meteorological data used in the GRADE 3.0 and GRADE 2.0 versions of the WG for the Rhine basin. ** See KNMI Technical Report, TR-345 (Beersma et al, 2014).*

		active	**passive**
GRADE 3.0	precipitation	E-OBS v21.0e (1951-2015)	HYRAS v3.0 (1951-2015)
	temperature	E-OBS v21.0e (1951-2015)	E-OBS v21.0e (1951-2015)
	PET	-	ETF method ** (Internally calculated by HBV-Rhine, with the same ETF-coefficients as for GRADE 2.0)
GRADE 2.0 (2012 version of WG Rhine)	precipitation	E-OBS v7.0 ** (1951-2006)	HYRAS v2.0 ** (1951-2006)
	temperature	E-OBS v7.0 ** (1951-2006)	E-OBS v7.0 ** (1951-2006)
	PET	-	ETF method ** (Internally calculated by HBV-Rhine)

2.2.3 Potential evaporation GRADE 2.0 versus GRADE 3.0

In HBV-Rhine potential evaporation, or in short PET, has always been calculated internally by HBV-Rhine based on the so-called ETF-method (which is part of the HBV'96 model for the Rhine, see section 3) from the daily temperature. As from E-OBS v21.0e (the version used for GRADE 3.0) besides precipitation and temperature also Makkink-type PET is available as a daily meteorological variable. This E-OBS PET, which has the advantage that it is fully consistent with the E-OBS precipitation and temperature (and has no 'underlying', and therefore time-dependent, PET climatology like the ETF-method) could therefore be used as an alternative to the ETF-method in HBV-Rhine for GRADE 3.0.

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[1] The activate dataset is used for the sampling of days, because this data is updated more frequently and is available for more parameters. The passive dataset is used for the actual data used to force the hydrological model, since this dataset has higher resolution and of better quality.

Therefore, calculations were done with the hydrological model using the E-OBS PET data instead of the ETF-method. Both datasets were evaluated by doing an historical model run with the HBV model. Based on the results of both methods it was concluded that using the E-OBS PET data does result in reduced performance of HBV-Rhine (for GRADE 3.0), resulting is too low flood peaks and too high baseflow. It was therefore decided to not implement the improved PET in GRADE 3.0 without re-calibration of the hydrological model, although the change has clear benefits compared to the ETF method in terms of consistency and its potential for the use in climate change impact calculation. See section 3.1 and Appendix B for details.

2.3 Setup of the weather generator for the Rhine basin

There are several key parameters in the WG that must be chosen carefully to optimize the results.

- The first choice is the number of nearest neighbours that is chosen from (called k). The value of k=10 is unaltered with respect to the previous Rhine WG version.
- The second choice involves the (moving) window of calendar days around the day that must be resampled. Like the previous version a window of 61 days is used (30 days before and after the central value).
- The third choice involves the composition of the so called ‘feature vector' (FV) used for finding the nearest neighbours (i.e., for each day the most similar days). In the GRADE 2.0 version the FV consisted of 3 elements: the mean (daily) precipitation in the basin, the mean (daily) temperature in the basin and the (daily) fraction of the sub-basins with precipitation. In the GRADE 3.0 version a fourth element is added: a precipitation 'memory term’ of 6 days. This 6-day precipitation term is introduced to improve the lagged persistence of precipitation in the simulated series during the summer half year. By using this ‘memory term’ the WG for the Rhine basin becomes more similar to that for the Meuse, in which a 4-day memory term is included in both versions (GRADE 2.0 and GRADE 3.0). As of GRADE 3.0 the WGs for the Rhine and Meuse basins have the same number and type of FV elements.

Apart from these key parameters, all other steps in the resampling procedure are unchanged compared to the GRADE 2.0 version. This involves the weighting of the FV elements (inversely proportional to the variance of the FV elements) to determine a Euclidean distance which is needed to find the *k* nearest-neighbours, randomly selecting - for each simulated day - one of these nearest-neighbours using a decreasing kernel and finally, the standardization and subsequent de-standardization[2] procedure of the precipitation and temperature data (to better reproduce the annual cycle in the simulated precipitation and temperature time series).

Figure 2-1 shows the Gumbel plot of the maximum 4-day precipitation in winter (Oct-Mar) over the Rhine catchment according to the GRADE 2.0 (black) and GRADE 3.0 (blue) WG versions. Up to return periods of 100 years, the lines are similar; the difference for larger return periods are not significant and are largely related to the fact that the GRADE 3.0 version is based upon the optimal 50K-year slice from the longer 500K-year WG simulation, which leads to a smoother, "less noisy”, line. The latter is explained in the next section.

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[2] By de-standardization the reverse of the standardization procedure is meant, in other words the procedure to transform the value of a variable back to its original scale (and units).

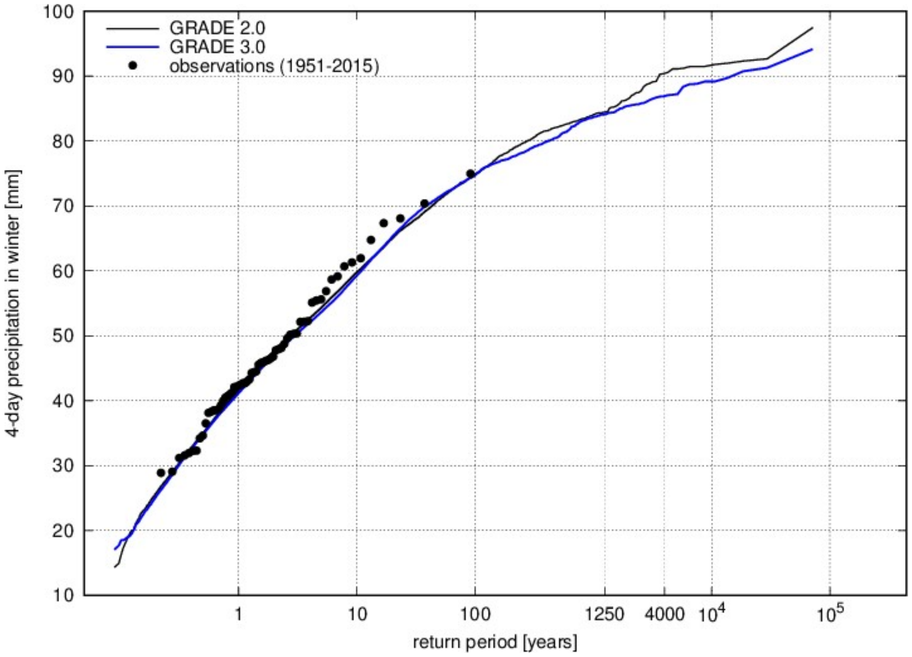

Figure 2-1 Gumbel plot of the maximum 4-day precipitation in winter (Oct-Mar) over the entire Rhine catchment according to the GRADE 2.0 (black) and GRADE 3.0 (blue) WG versions. The observations (HYRAS v3.0, 1951-2015) are indicated with the black dots.

2.4 Selection of an optimal 50,000-year slice

Resulting discharges from GRADE and related return periods are used for designing flood defense measures in the Netherlands. Because of the very high requirements for design discharges, discharges with very high return periods of 10,000 years up to 100,000 years and even higher are required. To avoid additional (statistical) extrapolation the simulation length should therefore be at least 10,000 years and preferable one order of magnitude longer. On the other hand, the hydrological modelling and especially the hydraulic modelling in GRADE are computationally expensive, therefore the length of the simulation should stay within acceptable limits. For practical reasons so far, a simulation length of 50,000 years was chosen, five times longer than the 10,000-year return period.

The largest event in a 50,000-year simulation has an approximate average return period of 50,000 year. But the actual return period of this largest event is statistically very uncertain. The 10th highest event in a 500,000-year simulation also has an approximate average return period of 50,000 year but the actual return period of this event is much less uncertain.

A considerable improvement of the new WG simulations (both for the Meuse and Rhine basins) is that they are obtained now from 500,000-year simulations, but that the 50,000-year period that is used in GRADE, is the 50,000-year slice from the 500,000 years that best resembles the statistics of the 500,000-year simulation up to return periods of 50,000 year. In this way we can profit optimally from the full length of the WG simulation of 500,000 years (in terms of a smaller uncertainty for the events that correspond with largest return periods in a 50,000-year simulation, say for return periods of 10,000 years and more), while effectively only using 50,000 years for which also the computationally expensive hydrological and hydraulic calculations must be performed. To summarize, the same (reduced) uncertainty as from a 500,000-year simulation is gained by using the 'best fitting’ 50,000 years for the subsequent GRADE simulations. The details of the selection of the optimal slice can be found in Appendix A.

2.5 Uncertainty analysis

For GRADE 3.0 no new uncertainty analysis of the weather generator for the Rhine basin is performed. The WG uncertainties, in the form of the calculated so-called Jackknife standard deviations (sigma's) for each return period, from the GRADE 2.0 WG uncertainty analysis are used to construct the complete uncertainty band for GRADE 3.0 (see Section 5.2). The details of the GRADE 2.0 WG uncertainty analysis are described in the GRADE 2.0 report (Hegnauer et al., 2014) and the GRADE uncertainty analysis report (Van den Boogaard et al., 2014). It was decided to refrain from a new WG uncertainty analysis because it was expected that the extension of the historical base period used for the WG would not have a large influence on the time series simulation with the WG. This is confirmed by the results in Figure 2.1.

3 Hydrological modelling

3.1 HBV model

The current hydrological model used in GRADE for the Rhine is based on the HBV'96 model concept. No major changes were made compared to the version of the model used in GRADE 2.0. A small difference is that the parameters for the snow melt have been altered slightly to prevent the model from crashing when running long (i.e., more than 10,000-year) simulations. This change does not affect the model results for extreme discharge conditions.

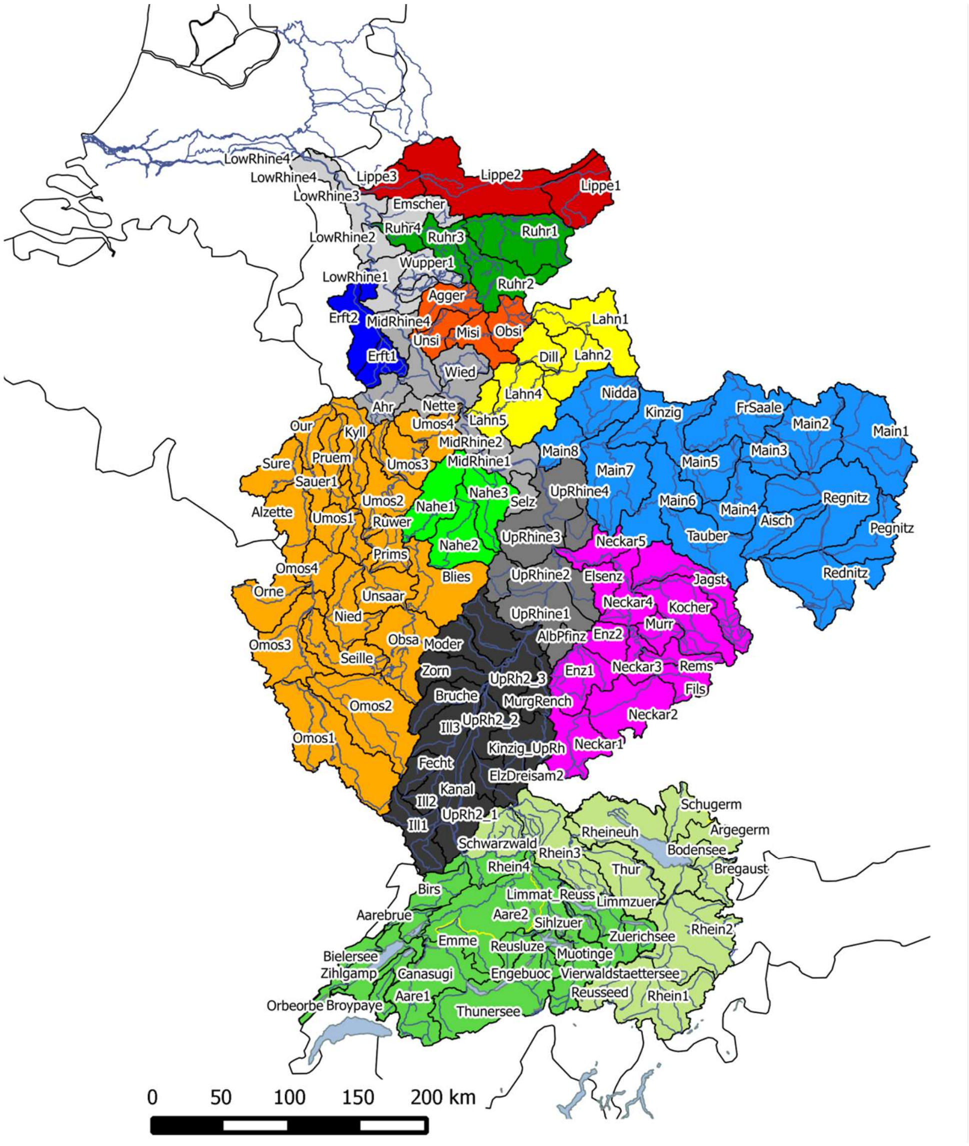

Figure 3-1 Overview of the HBV'96 model schematization for the Rhine.

In the process of preparing new weather generator time series for the Rhine basin, tests were done with replacing the original (and internal) HBV-Rhine ETF method which calculates the potential evaporation from the temperature by (the newly available) potential evaporation in the E-OBS v21.0e dataset (based on the Makkink formula using measured temperature and global radiation data). The latter is theoretically preferable since the daily evaporation is not solely determined from the daily temperature and no fixed (monthly) evaporation climatology and daily evaporation factors are used. The point is however that HBV-Rhine was calibrated using the original ETF method. Consequently, theoretically better evaporation does not automatically lead to better HBV performance. Based on the differences between the two results, it was decided that for GRADE 3.0 the original ETF method in HBV_Rhine is not replaced by the E-OBS v21.0e potential evaporation (externally provided to HBV-Rhine like precipitation and temperature). The results of this analysis are presented in Appendix B.

3.2 Uncertainty analysis

In GRADE 3.0 no new uncertainty analysis of the HBV model was done. The reason for this decision was that the HBV model used in GRADE 3.0 did not change comparing to GRADE 2.0. Additionally, the total uncertainty is dominated by the uncertainties in the other GRADE components (i.e., the weather generator and in the hydraulic model). Also, no new insights regarding the hydrological model and its uncertainties are currently available, reducing the need to re-calculate the uncertainties. The uncertainties, in the form of the calculated sigma for each return period, which were calculated for GRADE 2.0 were (re-)used to construct the complete uncertainty band. The way this was done is described in the GRADE 2.0 report (Hegnauer et al., 2014) the GRADE uncertainty analysis report (van den Boogaard et al., 2014).

4 Flood routing

In this Chapter the flood routing models for the Rhine are presented (Section 4.1). Next to the introduction of the different models, also the usage of the models to calculate the flood peaks and flood waves is presented (Section 4.2).

4.1 Routing models

In Figure 4-1 an overview of the main river of the Rhine from Basel until Lobith is presented. The flood routing of the Rhine is split over different models, each covering a separate reach of the river. The reach between Basel and Maxau is covered by a Muskingum routing model. From Maxau till Lobith a 1D SOBEK-RE model is used for the routing. This model includes the effect of retention and flooding behind dikes using retention-basins to calculate the effect of flooding on the discharges in the river. For the final reach between Andernach and Lobith a detailed SOBEK3-1D2D flood model is used. This model calculates the effect of flooding behind the dikes using a 2D flood model which is coupled to the 1D model covering the river between the dikes. In comparison with the 1D SOBEK-RE model the SOBEK3-1D2D model gives a better performance in calculating the flooding behind the dikes namely at very extreme circumstances including potential flood areas just upstream of Lobith. The three models will be presented in more detail in the following sections.

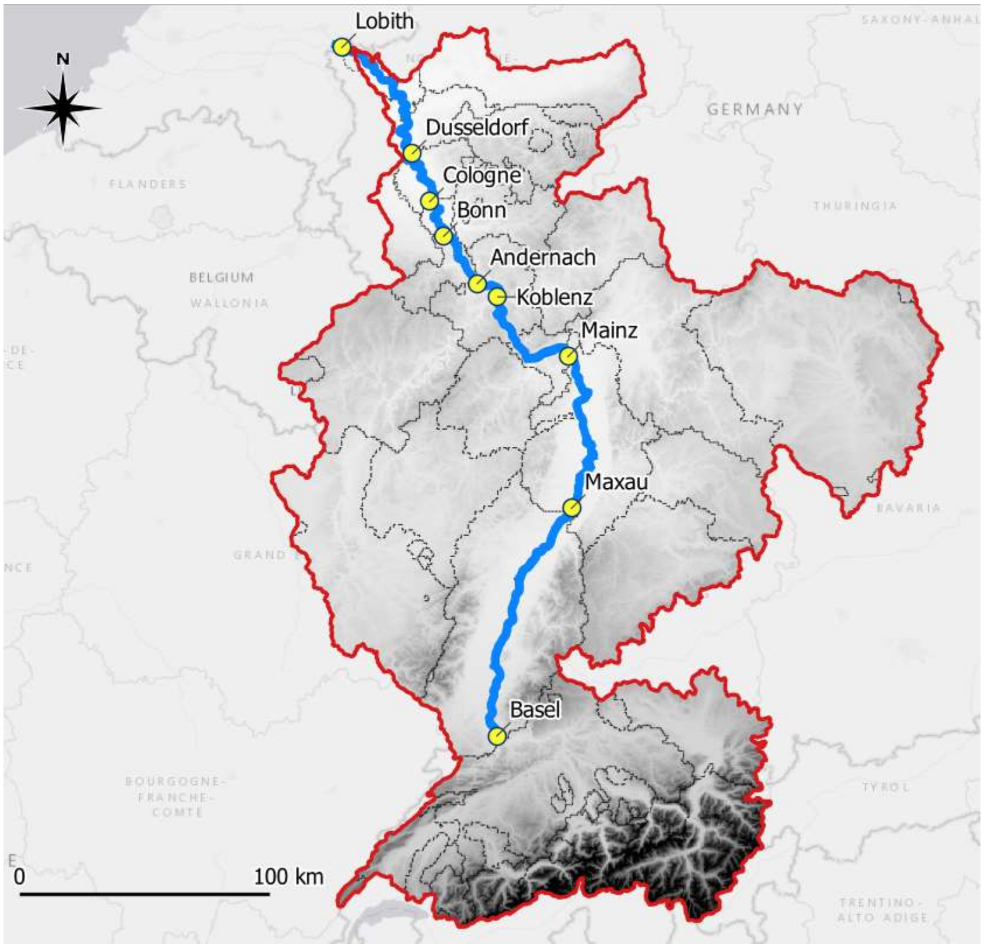

Figure 4-1 Overview of the main Rhine River, starting from Basel and ending at Lobith.

4.1.1 Muskingum model for Basel – Maxau

For the section between Basel and Maxau (as illustrated in Figure 4-2) no hydrodynamic model is available yet. Instead, use is made of the Muskingum routing model to simulate the flow at Maxau. The Muskingum model was calibrated on the results of a more detailed SYNHP model from the German state of Baden Württemberg.

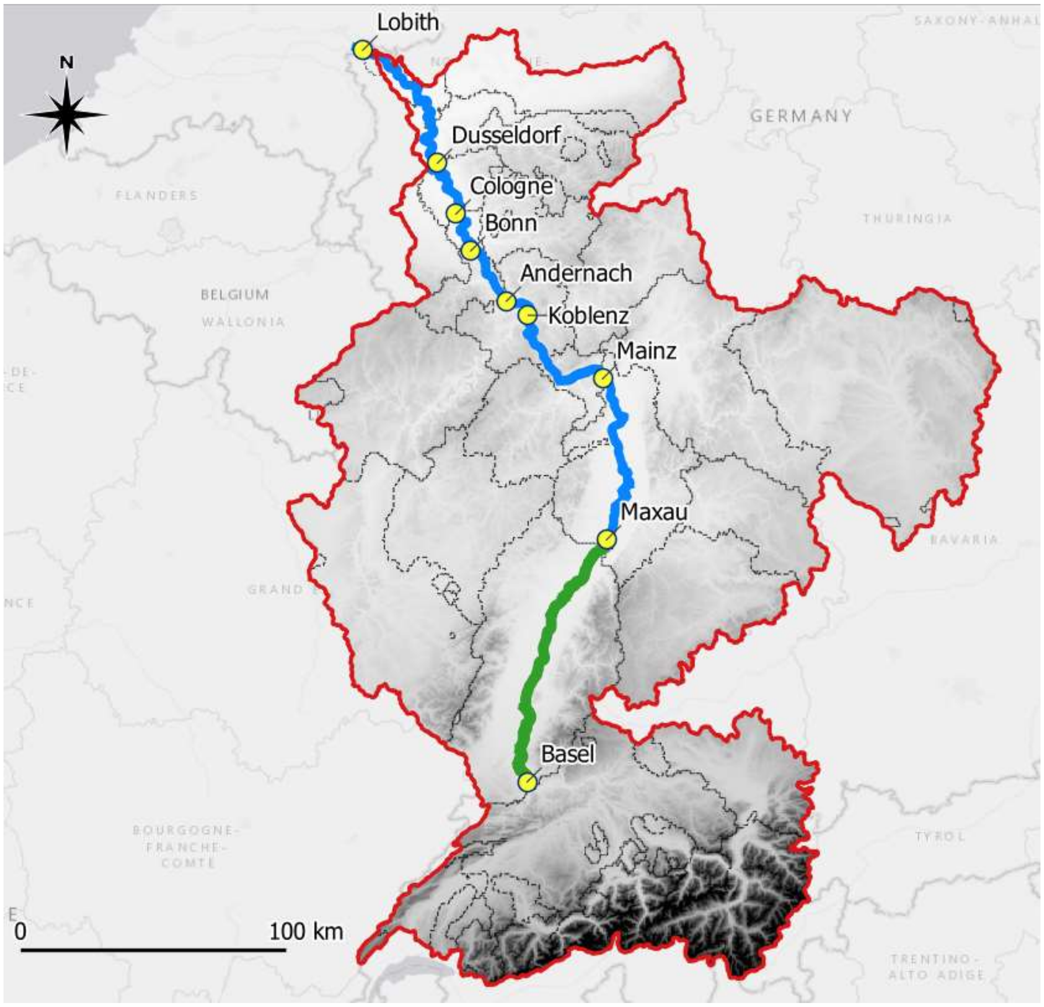

Figure 4-2 Overview of the main Rhine River, starting from Basel and ending at Lobith, with in green the stretch of the river covered by the Muskingum model.

The Muskingum model was not changed compared to the GRADE 2.0 version. More details are provided in the GRADE 2.0 report (Hegnauer, et al. 2014).

4.1.2 SOBEK-RE model for Maxau – Andernach – Lobith

For the section between Maxau and Lobith (as illustrated in Figure 4-3) a 1D SOBEK-RE model is available. This model includes effects of retention measures and flooding behind dikes. In this model the effect of flooding on the discharges in the river is calculated using retention-basins.

The SOBEK-RE model was not changed compared to the GRADE 2.0 version. More details on the SOBEK-RE model are provided in the GRADE 2.0 report (Hegnauer, et al. 2014).

The SOBEK-RE model is either used for calculating the yearly peak discharges at Andernach respectively Lobith or results of discharge waves are used as input for the SOBEK3-1D2D model as further described in chapter 4.2.

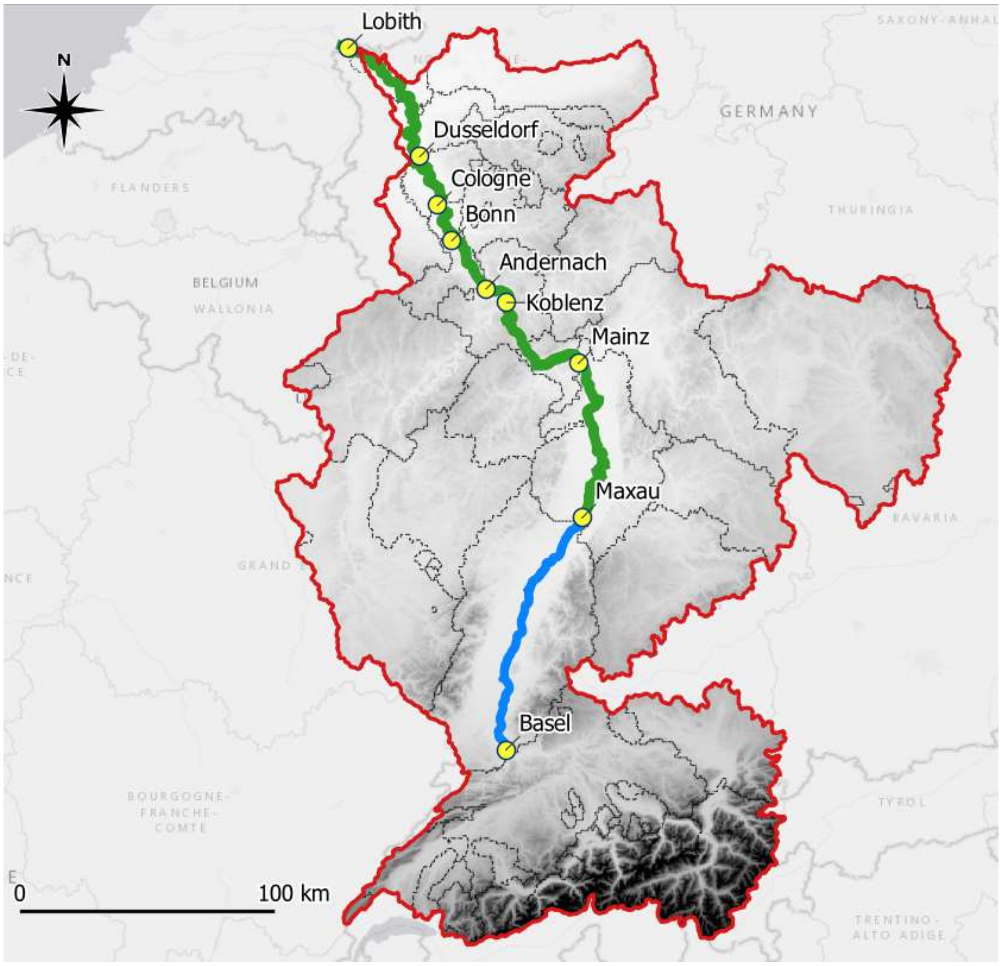

Figure 4-3 Overview of the main Rhine River, starting from Basel and ending at Lobith, with in green the stretch of the river covered by the SOBEK-RE model.

4.1.3 Additional SOBEK3-1D2D model for Andernach – Lobith

For the section between Andernach and Lobith (as illustrated in Figure 4-4) a SOBEK3-1D2D (in short SOBEK3) model is available. This model includes a high(er) level of detail of the effects of retention and flooding, including the potential flood areas just upstream of Lobith in dikerings 42 and 48 (see Figure 4-5).

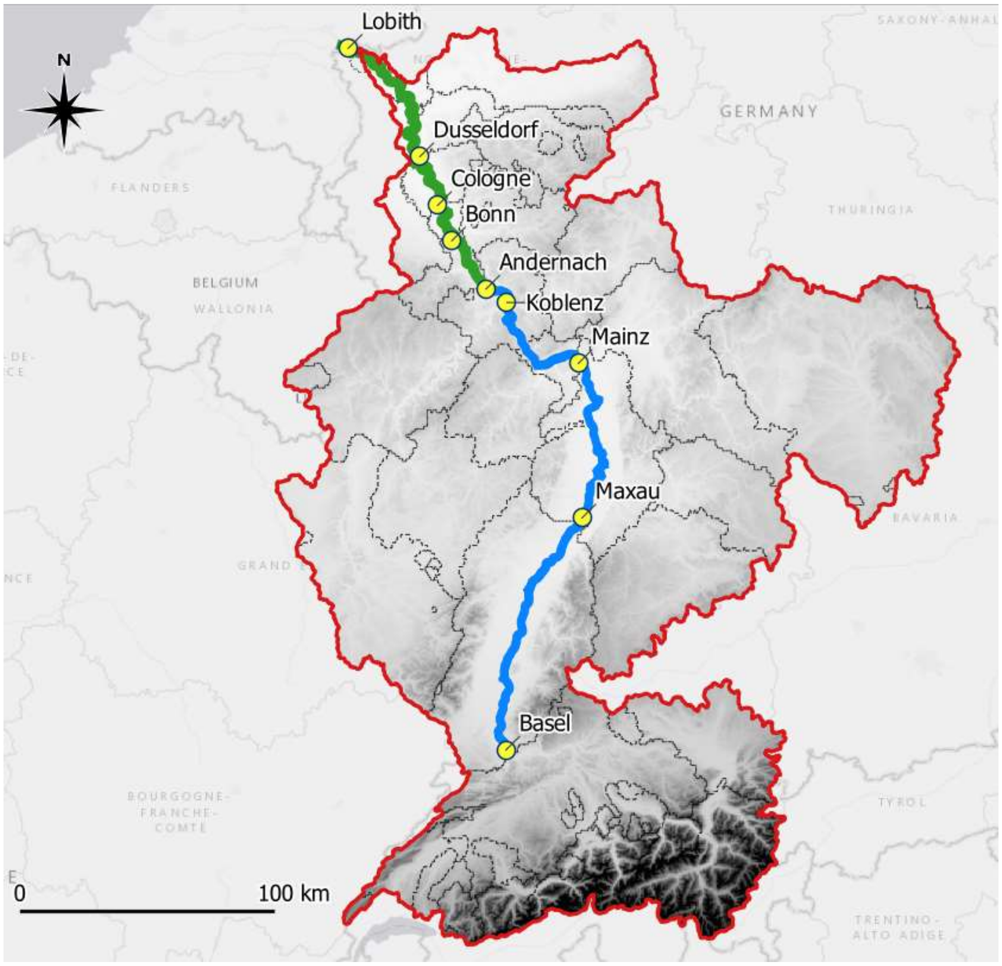

Figure 4-4 Overview of the main Rhine River, starting from lake Constance and ending at Lobith, with in green the stretch of the river covered by the SOBEK3-1D2D model.

The SOBEK3-1D2D model is described in detail in the model report (Becker, 2020).
The SOBEK3 model is used to simulate all flood waves with a flood peak above 14,000 m^3/s at Andernach. For more details see chapter 4.2.

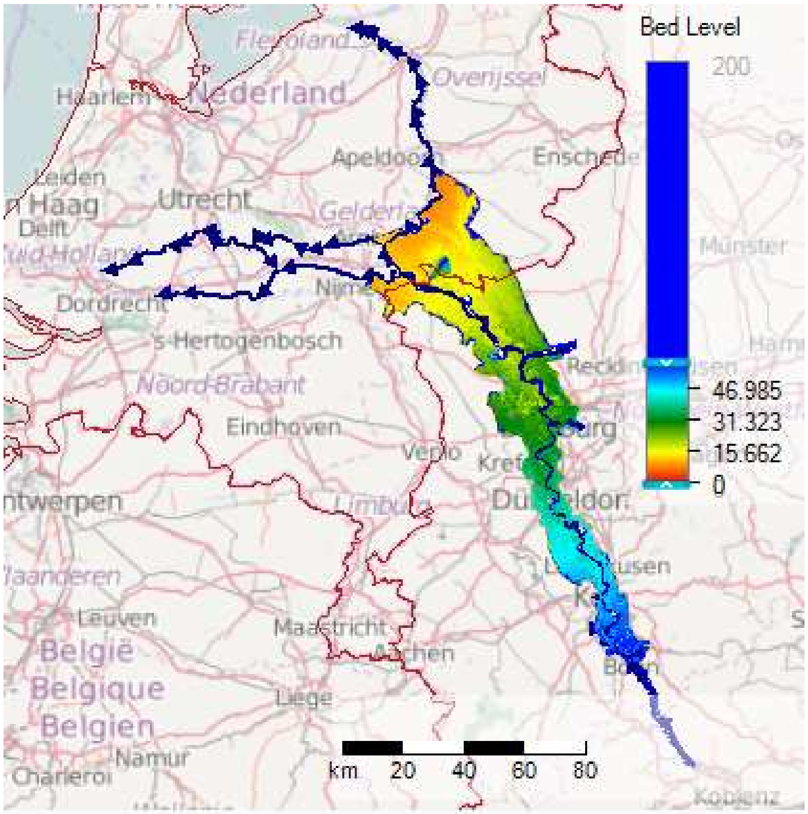

Figure 4-5 Overview of the SOBEK3-1D2D model domain, including the 2D areas.

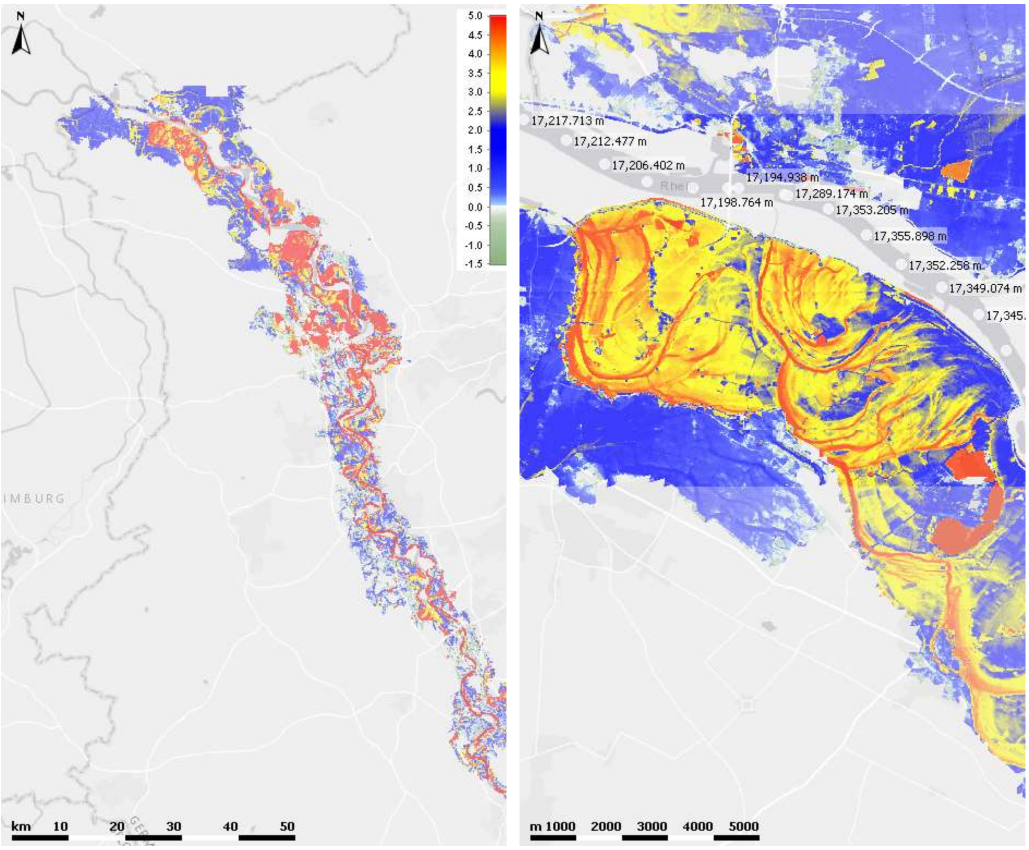

Figure 4-6 Water depth as calculated by the SOBEK3 model for an example discharge peak.

4.2 Usage of the routing models

All three flood routing models are used for calculating the discharge waves belonging to the annual peak discharges of the long (50,0000-year) timeseries calculated by the HBV model using the results from the weather generator.

The scheme in Figure 4-7 demonstrates the calculation steps. Basically, it comes down to the following:

1. The complete 50,000-year series is simulated with the HBV model, including a simple routing module which is included in the HBV model. The result of this step is a continuous 50,000-year discharge timeseries at Andernach and Lobith (and all other tributaries of the Rhine).
2. The complete 50,000-year series is also simulated with the Muskingum model for the stretch between Basel and Maxau. The result of this step is a continuous 50,000-year discharge timeseries at Maxau. Input is the discharge at Basel and the tributaries of the Rhine between Basel and Maxau calculated by the HBV model.
3. From the 50,000-year continuous HBV-timeseries at Andernach and Lobith from step 1, the annual maximum discharges are selected for the hydrological year, starting on the 1st of October till the 30th of September.

4 For each annual maximum above 10,000 m^3/s at Andernach, a simulation is done with the SOBEK-RE model. For this, a period around the annual maximum is selected to run the model for a period of around 40 days (25 days before the peak and 15 days after the peak). The input comes from the Muskingum model (at Maxau) and HBV (for all tributaries between Maxau and Lobith). The purpose of this model run is to get a good boundary condition at Andernach in which the effect of retention and flooding between Maxau and Andernach is taken into account.

5 For each annual maximum above 14,000 m^3/s at Andernach (based on the input from the HBV and SOBEK-RE model results), a simulation is done with the SOBEK3-1D2D model. For this, a period around the annual maximum is selected to run the model for a period of around 40 days (25 days before the peak and 15 days after the peak). The input comes from the SOBEK-RE model (at Andernach) and HBV (for all tributaries between Andernach and Lobith).

6 All annual maxima that were not calculated using the SOBEK3-1D2D model (i.e., for all discharge below 14,000 m^3/s at Lobith) still need to be translated to a pseudo SOBEK3-1D2D discharge[3]. For this, a regression formula has been derived between the HBV and SOBEK3-1D2D model results. The regression formula is presented in Appendix C.

Alternatively, based on the regression, all HBV discharges can be translated into Pseudo SOBEK3-1D2D results using the regression. This is done for all Jackknife and HBV combinations in the uncertainty analysis.

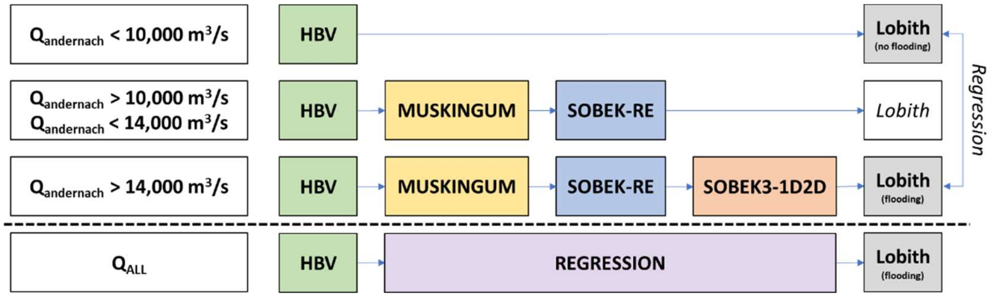

Figure 4-7 Scheme for the flood routing simulations.

After having the results of the routing models, the SOBEK3-1D2D model results need to be corrected for the missing river-groundwater interaction. In the SOBEK-RE model river-groundwater interaction is included. This interaction is not (yet) included in the SOBEK3-1D2D model. To correct for this, a simple additional regression formula was derived, which is also presented in Appendix C.

The result of this calculation scheme is a set of 50,000 calculated or pseudo SOBEK3-1D2D discharges. This set of annual maxima is the input of the statistical analysis to generate the (empirical) discharge statistics.

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[3] These pseudo discharges calculated via a regression, rather than via a model simulation. This is done to save computation time, especially with the SOBEK3-1D2D model. These regression formulas are also used in the uncertainty analysis of the weather generator (Jackknife series) and HBV model, to create pseudo values for the discharges for Jackknife and HBV parameter combinations.

4.3 Uncertainty analysis

For considering the uncertainties of hydraulic modelling an uncertainty analysis is done for the new developed SOBEK3-1D2D model. The methodology of the uncertainty analysis follows largely the same approach as in Prinsen et al. (2015), with the main difference that model uncertainties (Section 4.3.1) and uncertainties related to emergency measures (Section 4.3.2) are separated in the analysis. Another important difference is the way of processing of the data to get the uncertainty band to account for skewness caused by the process of flooding in Germany. The skewness originates from the fact that uncertainties in the weather generator or the hydrological model, which are assumed to follow a Gaussian distribution, could potentially lead to discharges that are higher than the discharge capacity of the river, in particular near the German-Dutch border. This means, that at the upper end of the uncertainties, the resulting discharges are equal to the discharge capacity itself. The resulting uncertainty band will then become skew by definition.

The uncertainty in the other routing models is not considered in GRADE 3.0. The method for the uncertainty analysis, as presented in Prinsen et al. (2015) is replaced by the current uncertainty analysis for the SOBEK3-1D2D model. More details can be found in Geertsema et al., 2021.

4.3.1 Model uncertainties hydrodynamic model

To assess the model uncertainties in the SOBEK3-1D2D model, a Monte Carlo experiment was setup. Details of this analysis is described in Geertsema et al. (2021). The model uncertainties are translated into an uncertainty band using a statistical distribution function. This is illustrated in Figure 4-8.

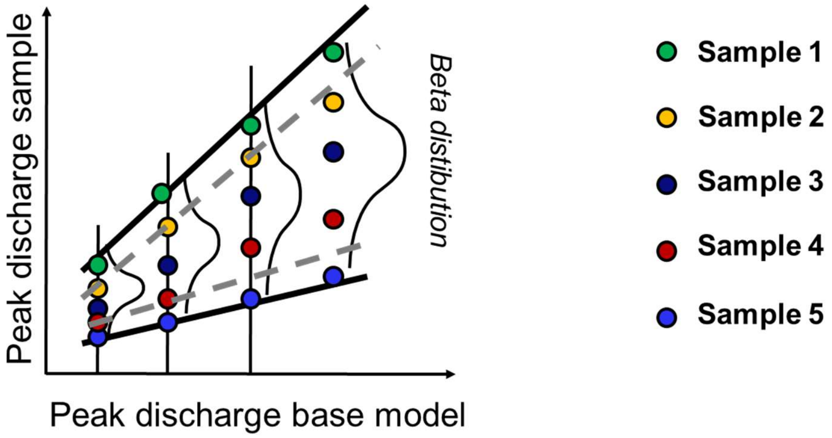

Figure 4-8 Schematic of the Monte Carlo experiment and expected outcome.

Three sources of uncertainty were included in the analysis:

- The roughness of the riverbed (both main channel and floodplains).
- The embankment heights.
- The dike breach process (yes/no and trigger level).

In total, 11 stochastics were defined in the Monte Carlo experiment. These are:

- The roughness
- Embankment height for 4 groups dependent on embankment type and source of embankment height (see Table 4-2).
- Dike breach trigger yes/no for 3 groups dependent on the location (locations 1-7, location 8 and location 9, see Figure 4-9)
- Dike breach level below the top of the levee for 3 groups dependent on the location (locations 1-7, location 8 and location 9, see Figure 4-9)

The selection of the stochastics was based on the previous work by Prinsen et al. (2015) en discussed by an expert session and verified by a sensitivity analysis. The grouping of certain stochastics (e.g., the grouping of the 9 dike breach locations into 3 groups) was based on the results of a sensitivity analysis, with the purpose to limit the number of stochastics and with that, the number of required simulations.

Table 4-1 Overview of the different embankment types/heights, which are treated differently in the uncertainty analysis (see Geertsema et al., 2022).

Group	Embankment type	Source of embankment height	Uncertainty range
A	Dike, not reinforced after 2010	• Uncertainty in the height in the DEM	• ± 0.2 m
B	Elevated area	• Uncertainty in the height in the DEM • Location from where the elevation is taken from the DEM • Total	• ± 0.2 m • ± 0.3 m • ± 0.5 m
C1	Wall or mobile barrier	• Calculated from high normative water levels (MHW in Dutch, BHW in German) and translated to the embankment	• ± 0.5 m
C2	Dike, reinforced after 2010	• Calculated from high normative water levels (MHW in Dutch, BHW in German) and translated to the embankment	• ± 0.5 m

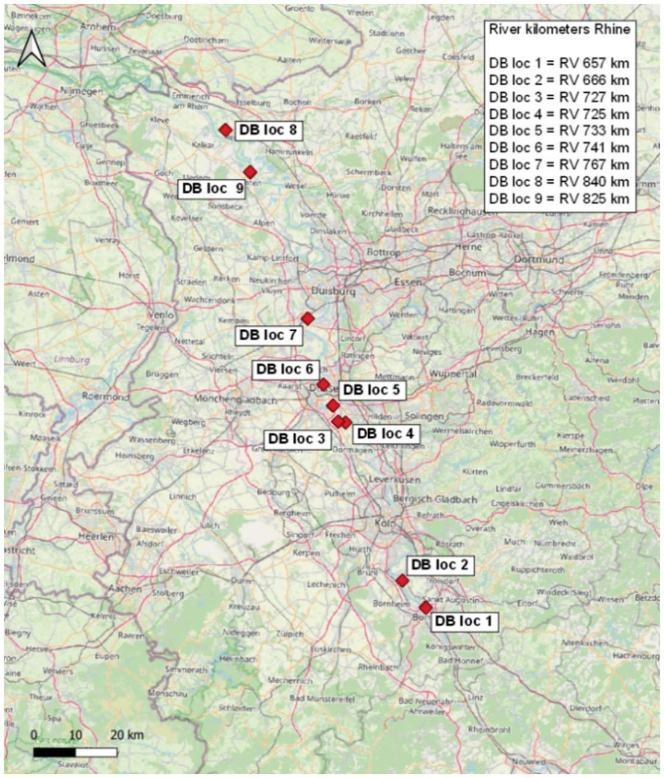

Figure 4-9 Location of the nine dike breach locations. The legend indicates the corresponding river kilometers. Note that dike breach location 9 is located upstream of dike breach location 8 and dike breach location 4 is located upstream of dike breach location 3. It must be indicated here that this are only the locations where dike breaches can be modelled. However, over the whole river stretch the embankment can been overflown (for details see Becker, 2021)

From the Monte Carlo analysis, a sample of 101 parameter-combinations is selected. The number of 101 parameter combinations was chosen as an optimum between the number of simulations and runtime on the one hand and the coverage of the parameter space on the other hand.

To have an optimal coverage of the parameter space, meaning an optimal spread of the parameter values, a Latin Hypercube Sampling technique was used. This LHS experiment consisted of 10,001 random samples of 101 sets of parameter values for the 11 stochastics. The characteristics of each sample were analyzed on two indicators: The maximum correlation coefficient between the stochastics (which should be as low as possible) in the sample and the minimum L2 distance (which should be as large as possible). The 10,001 parameter combinations are summarized in Figure 4-10, where the axes are representing the two characteristics: the maximum correlation coefficient (y-axis) and the minimum L2 distance (x-axis). In this figure, the optimum sample is in the right-bottom corner. In this figure, the top 10 (blue and green points) are high-lighted. The optimal sample (green point) was selected and contains of 101 parameter values.

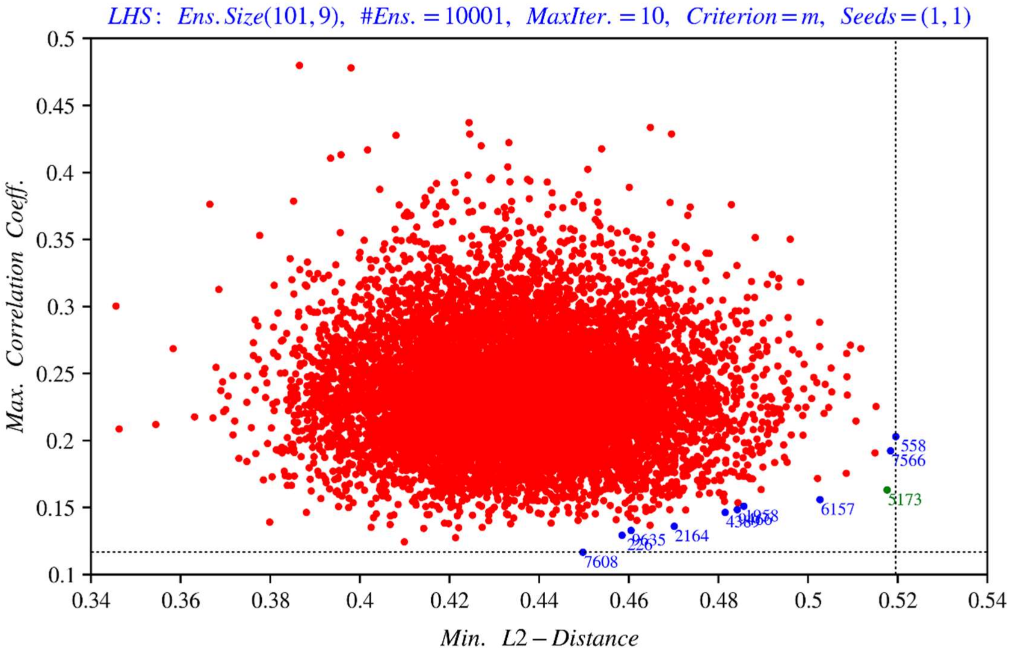

Figure 4-10 Results of the LHS ensemble analysis, showing the Pareto optimum solution (green dot).

The set of 101 combinations of the (11) model parameters was combined with a set of 50 discharge hydrographs that were selected to span a wide range of peak discharges and hydrograph shapes. Together, this gives a total set of simulations of around 5,050. Given the fact that on average each simulation takes approximately 3 hours to run, this would imply already 625 days of continuous simulations. By splitting up the runs over multiple computers, this was reduced to ~100 days. Given the long runtime, a larger sample set was decided to be not feasible within the available time to perform the simulations.

The result of the Monte Carlo experiment was a set of 5,050 flood hydrographs and corresponding flood peaks at Lobith. Due to the change in the parameter values, the peak discharge is different for each of the parameter sets.

4.3.2 Other uncertainties

During the analysis and after consulting a group of experts also other sources of uncertainties were identified. Two sources were mentioned explicitly, ice dams and the position of the riverbed. It was concluded that these processes could not be easily included in the uncertainty analysis and thus, are not explicitly considered for BOI2023.

4.3.3 Combining all uncertainties

Finally, the uncertainties resulting from the hydrodynamic model need to be combined with the uncertainties from the weather generator and the hydrological model. The latter uncertainties are not derived again but are reused from the previous GRADE2.0 results. To combine these uncertainties, a two-step approach is used.

The first step is that for the complete dataset from the Jackknife analysis (11 realizations) combined with the results of the HBV model uncertainty analysis (5 realizations), 55 realizations of a discharge statistics are derived. These HBV results are extrapolated using a Weisman extrapolation. The HBV model results are translated into a pseudo-SOBEK (SOBEK-RE respectively SOBEK3-1D2D) result using the regression introduced in appendix C after the extrapolation.

In the second step the uncertainties from the hydrodynamic model are added to the other uncertainties. The result of the uncertainty analysis presented in section 4.3.1 en in more detail in Geertsema et al. 2021 is basically a relation between a reference discharge and the resulting parameters of a statistical distribution describing the uncertainties in the hydrodynamic model. To combine the uncertainties, a reference discharge is randomly sampled from the results of step 1 and many times a representative discharge is sampled from the parameters of the hydrodynamic model uncertainties. This is done numerically many times for the complete range of discharges in the GRADE results.

Finally, from the new set of discharge, the uncertainty band can be constructed by fitting a distribution for each return period.

4.4 Scenarios of emergency measures

Next to the parameter uncertainties of the SOBEK3 1D2D model, the effects of emergency measures is an additional source of uncertainty. In GRADE 2.0, the emergency measures were mixed in with the model uncertainties. In GRADE 3.0 it was decided to make the impact of emergency measures more explicit and provide a choice to the user (i.e., BOI2023) about for which level of emergency measures in Germany they want to be prepared.

This means in practice that for each scenario of emergency measures separate discharge-statistics are constructed. In Figure 4-11 the relation between peak discharge without (i.e., the base model) and with emergency measures (i.e., a scenario) for different scenarios is presented in a conceptual way.

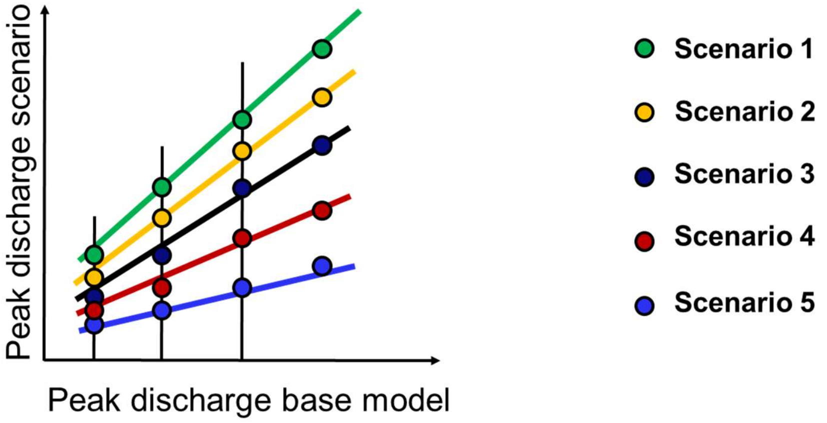

Figure 4-11 Schematic of the approach for the emergency scenarios and expected outcome.

The impact of emergency measures is assessed in different scenarios. These scenarios include 4 geographical areas in which the emergency measures are applied and 3 different levels, or heights, of the emergency measures, corresponding to different type of emergency measures (see Figure 4-12). An overview of all scenarios is given in Table 4-2.

Figure 4-12 Overview of the types of emergency measures included in the scenarios, with the assumed height.

Table 4-2 Overview of the scenarios of emergency measures.

Name	Description
SC1a	All dikes and walls between Andernach and the Dutch border + 50cm
SC1b	All dikes and walls between Andernach and the Dutch border + 70cm
SC1c	All dikes and walls between Andernach and the Dutch border + 100cm
SC2a	All dikes and walls between Wesel and the Dutch border + 50cm
SC2b	All dikes and walls between Wesel and the Dutch border + 70cm
SC2c	All dikes and walls between Wesel and the Dutch border + 100cm
SC3a	All dikes and walls in the cities Rees and Emmerich+50cm
SC3b	All dikes and walls in the cities Rees and Emmerich+70cm
SC3c	All dikes and walls in the cities Rees and Emmerich+100cm
SC4a	All dikes and walls between Andernach and Wesel + 50cm
SC4b	All dikes and walls between Andernach and Wesel + 70cm
SC4c	All dikes and walls between Andernach and Wesel + 100cm

The result of the scenarios is a set of 600 (12 scenarios times 50 flood waves) flood hydrographs and corresponding flood peaks at Lobith. Because of the emergency measures implemented in the model, the peak discharge is different for each of the simulations.

5 Results of the GRADE simulations

In this Chapter, the new GRADE results are presented mentioned as GRADE’21. The results are also compared to results of earlier versions of GRADE. In Table 5-1 an overview of the different runs is given together with a short description to help explaining the results presented in the following sections.

Table 5-1 GRADE versions and GRADE results.

Name in figures	GRADE version	Applications	Description
WTI2011	-	WTI2011	These results are based on extreme value statistics of the observed discharge at Lobith. They were used for assessing the primary flood defense system in the Netherlands in the period 2011 - 2016
GRADE’17-HBV	2.0		These results are based on calculations using the Weather generator and the HBV model of GRADE 2.0 not considering the uncertainties of these components (Hegnauer et al., 2014).
WBI2017	2.0		These results are based on calculations using all components of GRADE 2.0 not considering the uncertainties of these components (Hegnauer et al., 2014).
WBI2017 incl. uncertainties	2.0	WBI2017	These results are based on calculations using all components of GRADE 2.0 while considering the uncertainties of these components. They were used for assessing the primary flood defense system in the Netherlands in the period since 2017 (Hegnauer et al., 2014).
GRADE’21-HBV	3.0		These results are based on calculations using the Weather generator and the HBV model of GRADE 3.0 not considering the uncertainties of these components
GRADE’21	3.0		These results are based on calculations using all components of GRADE 3.0 not considering the uncertainties of these components
GRADE’21 incl. uncertainties	3.0	Probably BOI2023	These results are based on calculations using all components of GRADE 2.0 while considering the uncertainties of these components. They probably will be used for assessing the primary flood defense system in the Netherlands in the period from 2023 on (BOI 2023)

5.1 Frequency-discharge curves

To come to the final discharge statistics, the following steps are taken:

1 Continuous 50,000-year simulation using the HBV model and input from the weather generator.
2 For all periods with discharge peaks above 10,000 m^3/s at Andernach, SOBEK-RE simulations are done to account for the effect of flooding.
3 For all periods with discharge peaks above 14,000 m^3/s at Andernach, SOBEK3-1D2D simulations are done to account for the effect of flooding.
4 Calculation of the annual maxima of the merged timeseries (HBV + SOBEK-RE + SOBEK3-1D2D with HBV results at Lobith for peak discharges at Andernach < 10,000 m^3/s, SOBEK-RE results at Lobith for peak discharges at Andernach between 10,000 and 14,000 m^3/s and SOBEK3-1D2D results at Lobith for peak discharges at Andernach > 14,000 m^3/s).
5 Calculation of the return periods for the sorted annual maxima.

6 Extrapolation of the discharge statistics above 1/50,000-year return periods using a log-normal fit (Weissman).
7 Applying the Langbein correction to correct the Annual Maxima for Peak over Threshold method (Appendix F).

The results of these steps are presented in the following sections, for HBV first and after that for SOBEK3-1D2D. In Section 5.2, the steps to calculate and add the uncertainties are presented.

5.1.1 50,000-year simulations with HBV

The GRADE’21 HBV model results are presented in Figure 5-1. The results are compared to the observations and to the previous GRADE’17 HBV results. It can be seen in the figure that the new results correspond very well to the old results. The differences are caused by the differences in the weather generator primarily as described in the chapter 2.

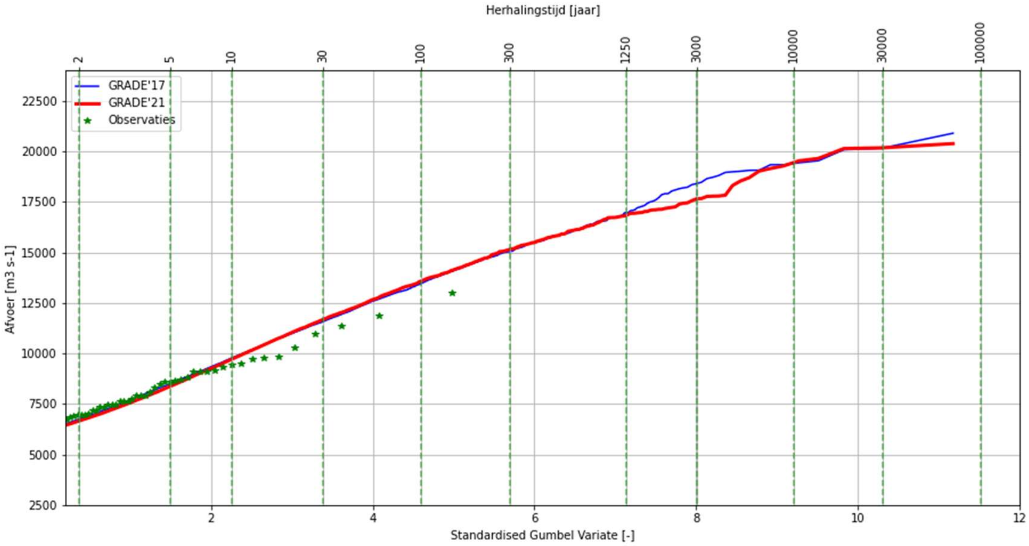

Figure 5-1 Discharge statistics for the Rhine at Lobith, based on HBV simulations for GRADE’21 (red line) and GRADE’17 (blue line), compared to the observations.

5.1.2 50,000-year simulations with SOBEK3-1D2D

In Figure 5-2 the GRADE’21 results are shown. Both the results of the HBV model (black dotted line) as the results based on the SOBEK3-1D2D model and the SOBEK-RE model are shown (for the details of the whole process see chapter 4.2). The difference between the two lines is caused by hydraulic effects and upstream flooding. The model results based on the combination of both SOBEK-models fit very well with the observations too.

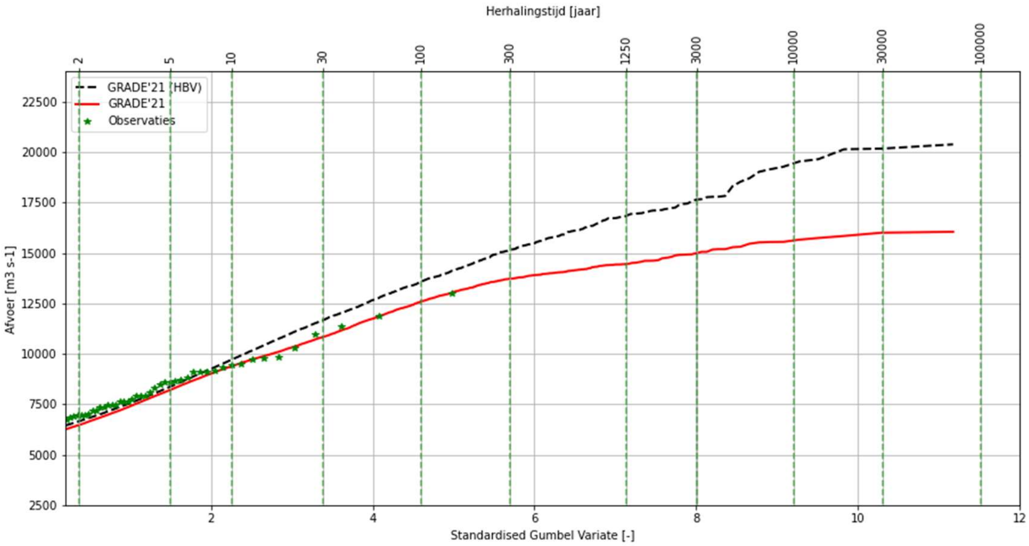

Figure 5-2 Discharge statistics for the Rhine at Lobith, based on SOBEK3-1D2D simulation (red line), compared to the observations. In black, the HBV results are also shown.

In Figure 5-3 the GRADE’21 results are compared to the GRADE’17 results. For short return periods, both results are very comparable, whereas for longer return periods (> 300 year), the results start to deviate more. The main reason for this deviation is that for WBI2017, implicitly a part of the uncertainties was added to the discharge statistics. This effect was already demonstrated in Figure 5.2 in Prinsen et al. (2015) (a copy of this figure is added to this report in Figure 5-4). As can be seen, the difference between GRADE’21 and GRADE’17 is very comparable and can thus be contributed to this aspect.

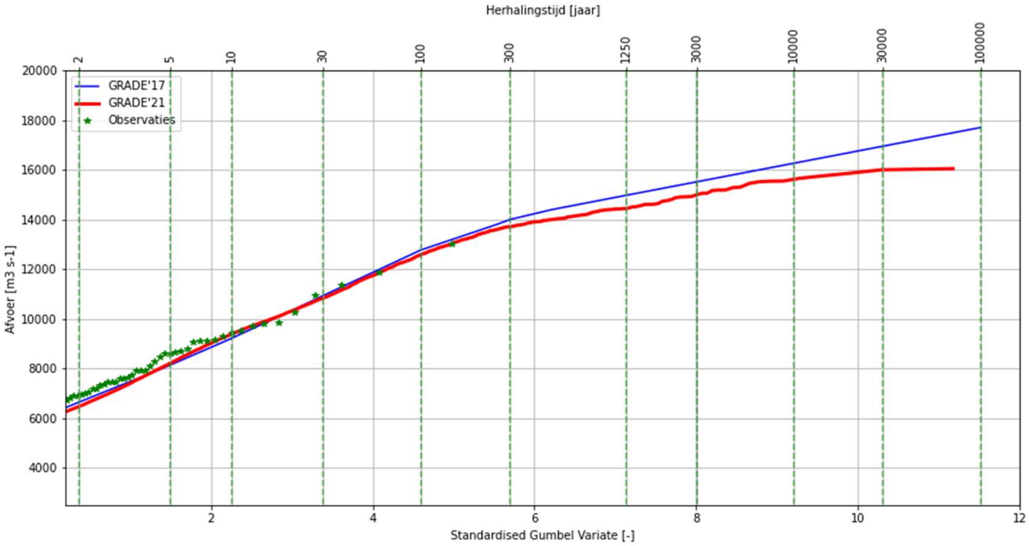

Figure 5-3 Discharge statistics for the Rhine at Lobith, based on SOBEK3-1D2D simulation (red line), compared to the observations and to the GRADE’17 (i.e., the WBI2017) results (blue line).

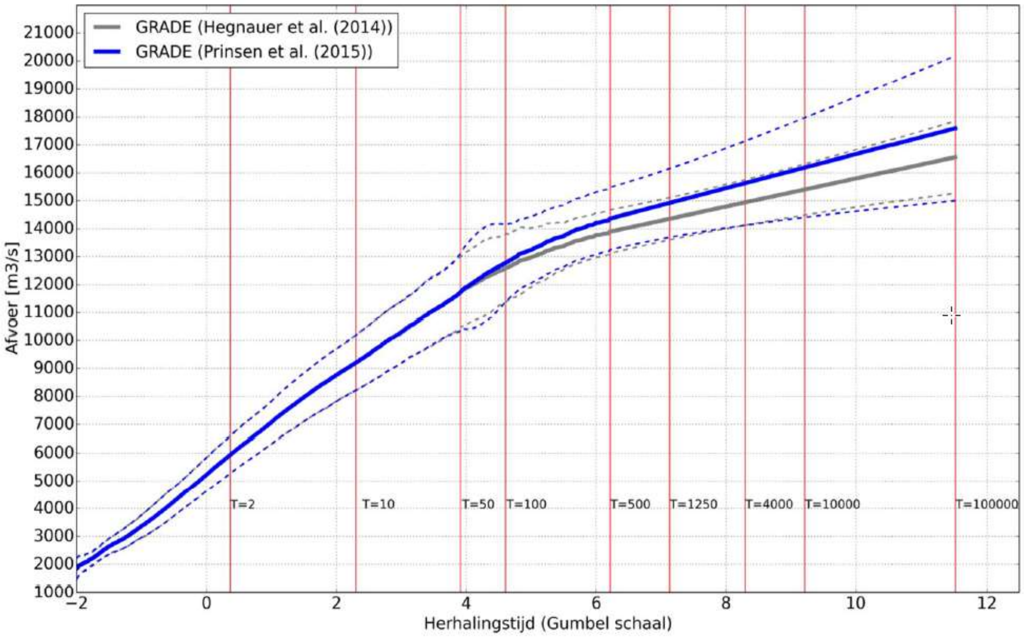

Figure 5-4 This is a copy of Figure 5.2 from the report of Prinsen et al. (2015), which shows the difference between the discharge statics before and after adding the hydraulic uncertainties.

Finally, the discharge statistics also need to be available for longer return periods than can be extracted from the empirical distribution. Therefore, a log-linear fit (Weissman) is done on the empirical distribution. The fit does both smoothing of the results for long return periods and can be used for extrapolation. The fitted and extrapolated discharge statistics are shown in Figure 5-5.

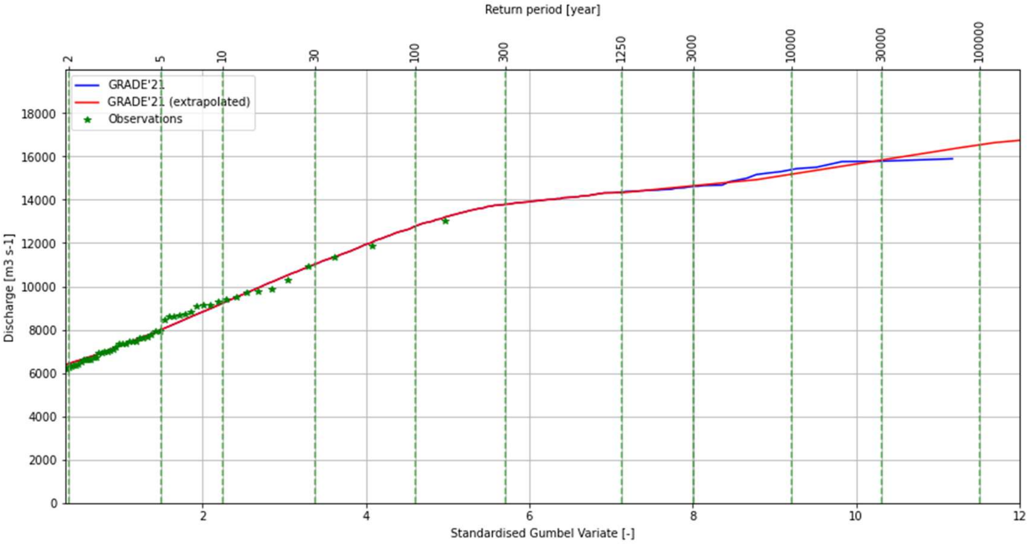

Figure 5-5 GRADE’21 results, with (red) and without (blue) extrapolation.

5.2 Uncertainty analysis and results

In Figure 5-6 the GRADE’21 results are shown, including the uncertainties originating from the weather generator and hydrological model. The uncertainties are assumed to be symmetrical around the central line and can be given as a sigma from which the 95% uncertainty band is constructed ($\mp 1.96\sigma$).

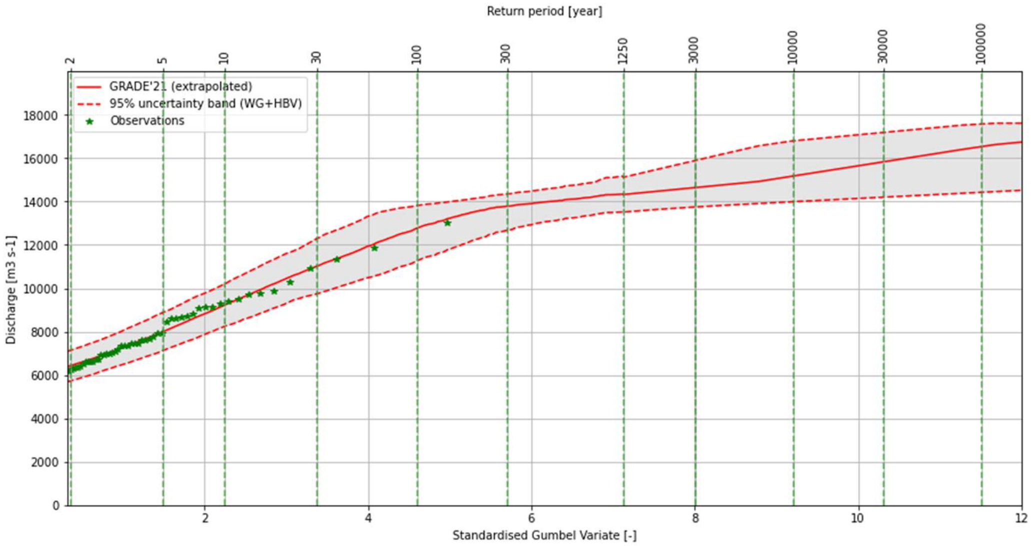

Figure 5-6 GRADE'21 results, including the uncertainties from just HBV and the weather generator.

In addition to the uncertainties in the weather generator and the HBV model, there are also uncertainties in the SOBEK3-1D2D model. These uncertainties are, in comparison to the other uncertainties, not symmetrical. This skewness is caused by the process of flooding. This can be seen in Figure 5-7 where it's visible that the distance between the reference statistics and the upper bound is smaller compared to the distance between the refence statistics and the lower bound, for longer return periods.

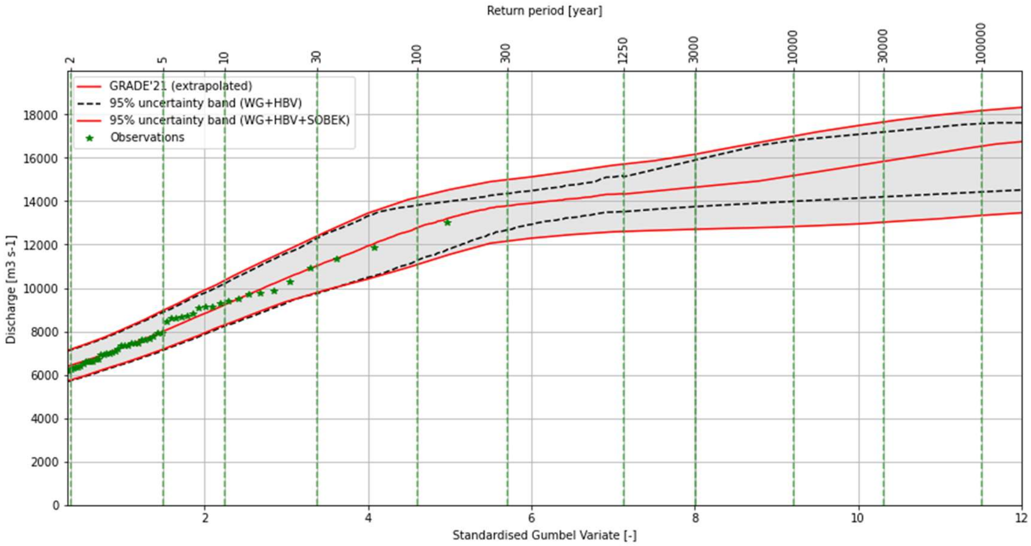

Figure 5-7 GRADE'21 results, including the 95% uncertainty band now also including the effect of the uncertainty in the hydrodynamic model. In black, the uncertainty band when only considering the uncertainty in the weather generator and the HBV model.

In Figure 5-8 the magenta line represents the discharge statistics including uncertainties from the weather generator, the HBV model and the hydrodynamic model. The method for processing of the uncertainties (in Dutch: "uitïntegreren") is described in Appendix D.

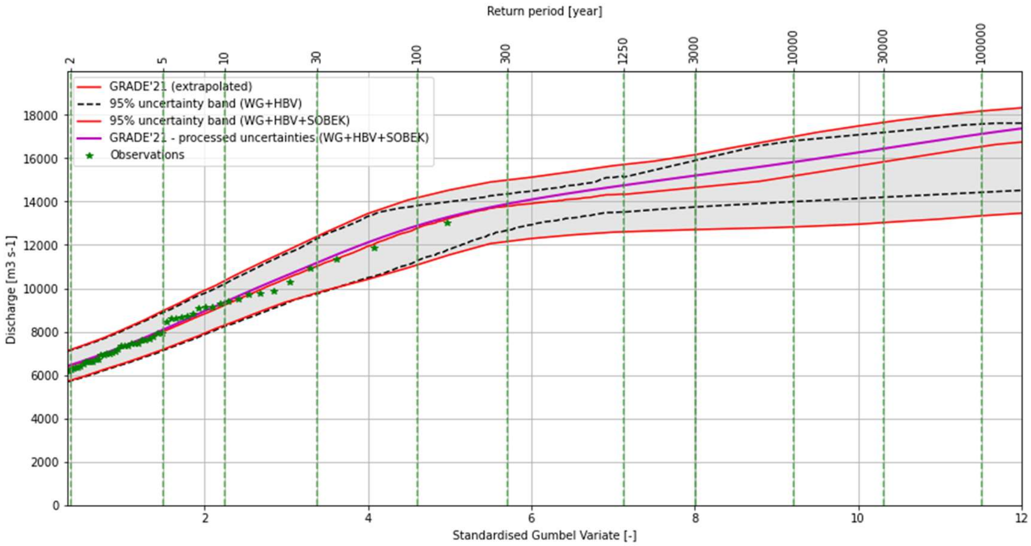

Figure 5-8 GRADE'21 results, including the 95% uncertainty band now also including the effect of the uncertainty in the hydrodynamic model. In black, the uncertainty band when only considering the uncertainty in the weather generator and the HBV model. In magenta the discharge statistics including the uncertainties.

In Figure 5-9 the discharge statistics including uncertainties for WBI2017 (GRADE'17) and GRADE'21 are shown. The results are very much in line with each other for shorter return periods. For longer return periods, the two lines begin to deviate, resulting in lower results for the GRADE'21 statistics.

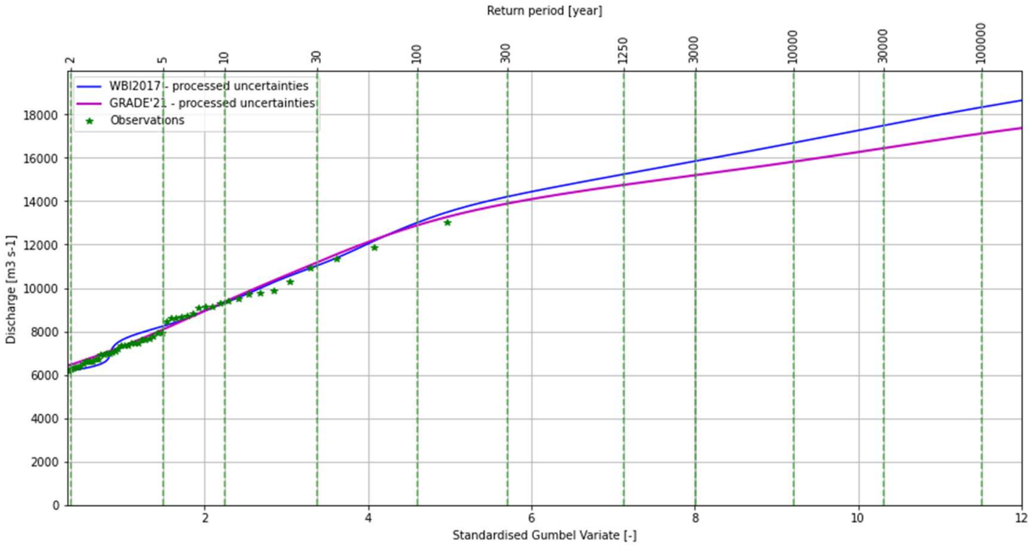

Figure 5-9 Comparison of the discharge statistics including uncertainties for the GRADE'17 and GRADE'21 results.

The final results (discharge statistics including uncertainties) are presented in Figure 5-10. The corresponding discharges for specific return periods can be found in Table 5-2 and 6.2E.

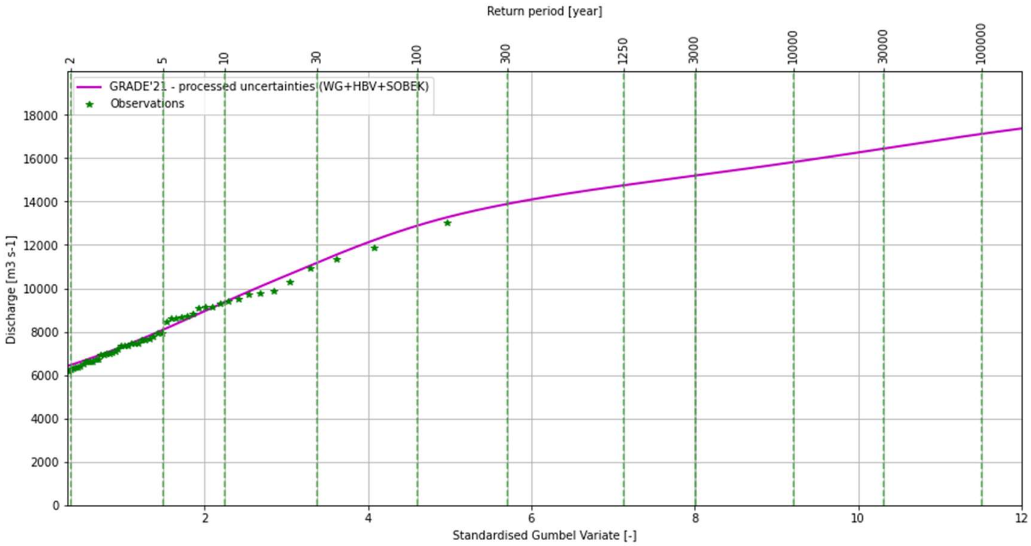

Figure 5-10 Final result with the discharge statistics including uncertainties for the Rhine at Lobith.

Table 5-2 Discharge statistics for the Rhine at Lobith, based on SOBEK-RE/SOBEK3-1D2D, including the description of the 95% uncertainty band. The table with values used in HydraRing is presented in Appendix 6.2E

Return period (year)	**Discharge without uncertainties (m^3/s)**	**Sigma (m^3/s)**	**Lower bound (m^3/s)**	**Upper bound (m^3/s)**	**Discharge with uncertainties (m^3/s)**
2	6387	310	5779	6994	6387
5	8055	400	7271	8839	8262
10	9315	470	8394	10236	9442
25	10838	610	9643	12034	11102
30	11098	640	9844	12353	11335
100	12657	760	11167	14146	13080
250	13531	660	12237	14824	13839
300	13611	660	12317	14904	13957
500	13840	660	12547	15134	14200
1000	14140	700	12768	15512	14590
1250	14210	710	12819	15602	14700
2500	14450	780	12921	15979	15050
3000	14520	800	12952	16088	15140
5000	14740	880	13015	16465	15400
10000	15060	970	13159	16961	15760
20000	15380	1050	13322	17438	16150
25000	15480	1070	13383	17577	16280
30000	15560	1080	13443	17677	16390
50000	15770	1110	13594	17946	16690
100000	16030	1130	13815	18245	17090

5.3 Scenarios of emergency measures

The previous sections presented the results of GRADE’21, assuming no emergency measures are taken in Germany. In this section, the results of different scenarios for emergency measures are presented.

In Figure 5-11 the calculated discharges with and without emergency measures are presented along with the constructed polynomial fit (5th order). As can be seen that the difference between the base model and the scenarios is small. The scenarios presented in this figure are corresponding to scenarios SC1-3 in Table 4-2, of which the top is repeated in table 5.4 below. It must be noted that the effect is largest for these three scenarios, given their geographic extend (all dikes and walls).

From the figure, it can also be concluded that, to make an optimal fit, more data points are needed. It seems there is a jump between 17,000 m^3/s and 18,000 m^3/s. To improve the fit, more simulations need to be done.

Table 5-3 Overview of 3 scenarios of emergency measures; Subset of Table 4-2

Name	Description
S101	All dikes and walls between Andernach and the Dutch border + 50cm
S102	All dikes and walls between Andernach and the Dutch border + 70cm
S103	All dikes and walls between Andernach and the Dutch border + 100cm

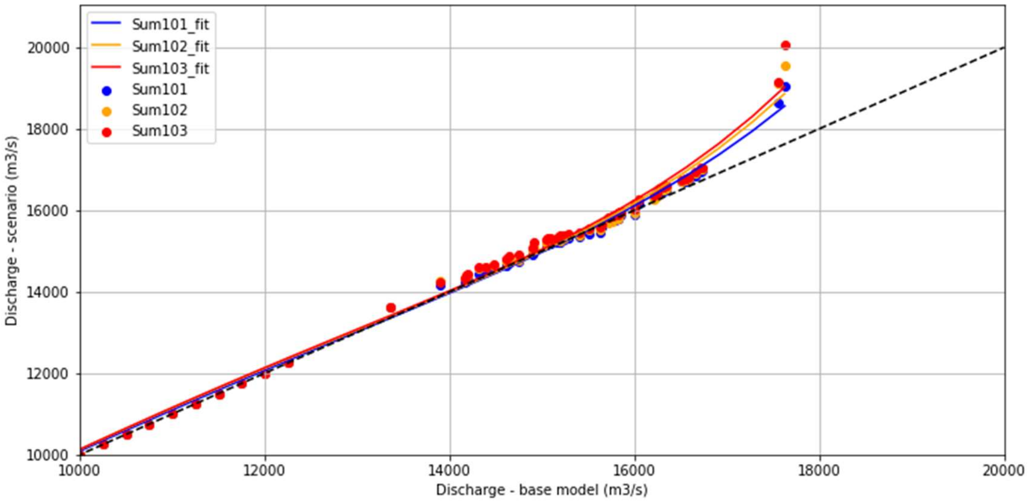

Figure 5-11 calculated discharges with and without emergency measures and fit of the three most extreme (i.e., the emergency measures applied along the complete lower Rhine) scenarios.

In Figure 5-12 the resulting discharge statistics for the different emergency scenarios are presented.

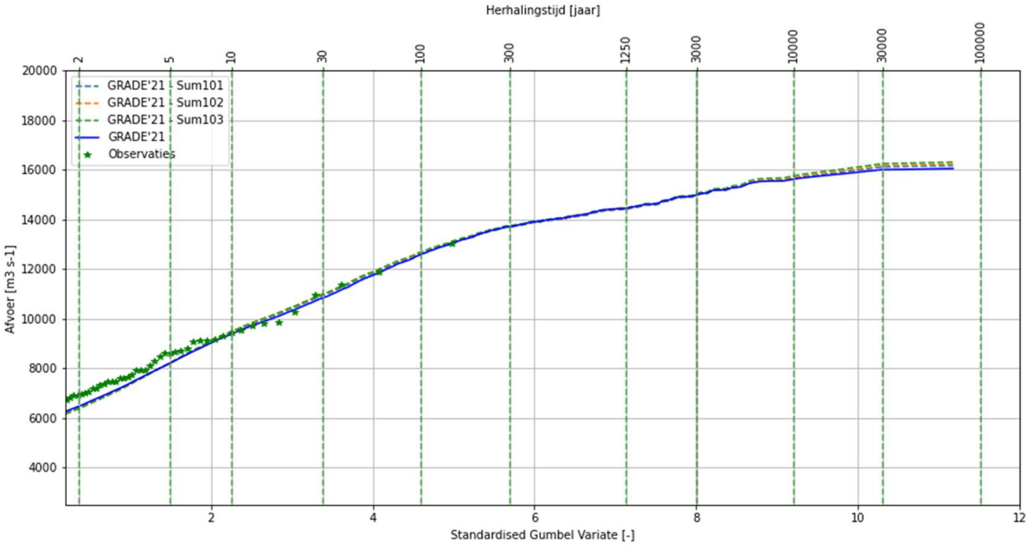

Figure 5-12 Discharge statistics for the three most extreme (i.e., the emergency measures applied along the complete lower Rhine) scenarios, using the polynomial fit as presented in Figure 5-11.

It can be concluded that the impact of the emergency measures on the discharge statistics for the current climate at Lobith are small. A larger effect is to be expected for discharges above 17,000 m^3/s, which is the discharge above which the dikes between Wesel and Lobith start overtopping. Taking emergency measures there would most probably have a large effect on the discharges reaching Lobith. For dike assessment in BOI2023, the scenarios can probably be ignored, for dike design, when larger discharges are account for it may not.

5.4 Flood hydrographs

Next to the discharge statistics, GRADE also provides information on the average hydrograph shape. The GRADE database consists of 50,000 yearly peak discharges along with corresponding flood waves, from which the average hydrograph can be determined. The shape of the hydrograph is important input for the safety assessment and design of the Dutch dikes. A narrow hydrograph will result in more damping of the peak compared to a broad hydrograph, due to hydrodynamic effects such as retention of water in retention areas along the Rhine in the Netherlands.

The method for the determination of the average hydrograph shape is described in detail in Kramer (2012). For this discharge classes are defined for discharge waves with a peak discharge of for example 14,000-17,500 m^3/s. For all waves in this class an average hydrograph shape is calculated. The method of vertical averaging of the hydrographs is used in GRADE 3.0. For the determination of the pointwise 95% band around the average hydrograph shape a beta-distribution is used.

In Figure 5-13 the mean hydrograph shape and the 33% and 95% ranges are shown for the class of discharges between 14,000 and 17,500 m^3/s. In Figure 5-14 the mean hydrograph shape is shown for all discharge classes.

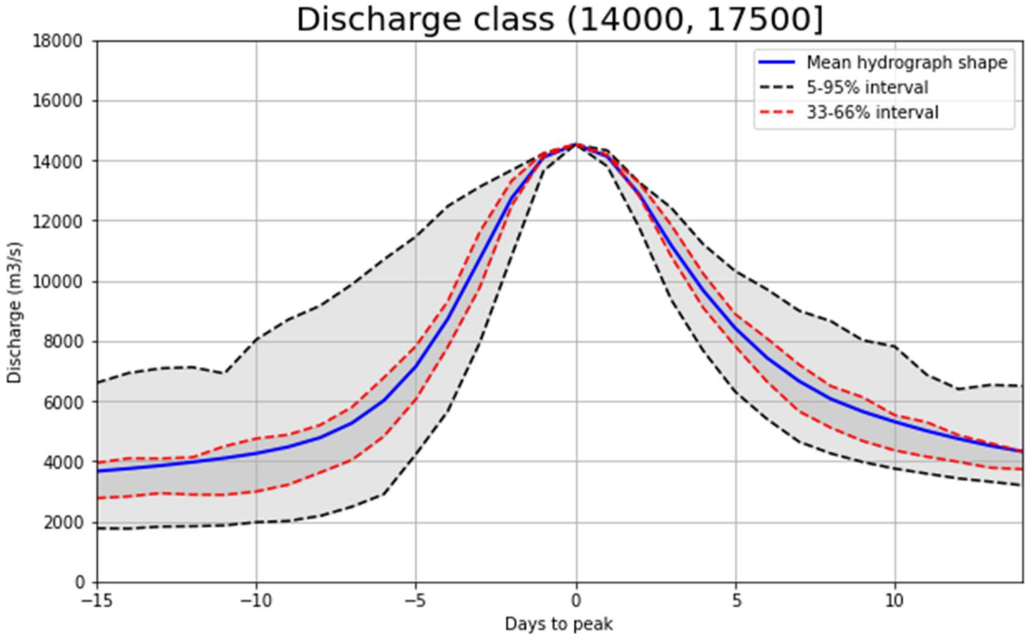

Figure 5-13 Mean shape of the flood hydrograph for the Rhine at Lobith and corresponding (pointwise) 32-68% [or 33%] and 5-95% [or 90%] ranges for all events between 14,000 and 17,500 m^3/s peak discharge.

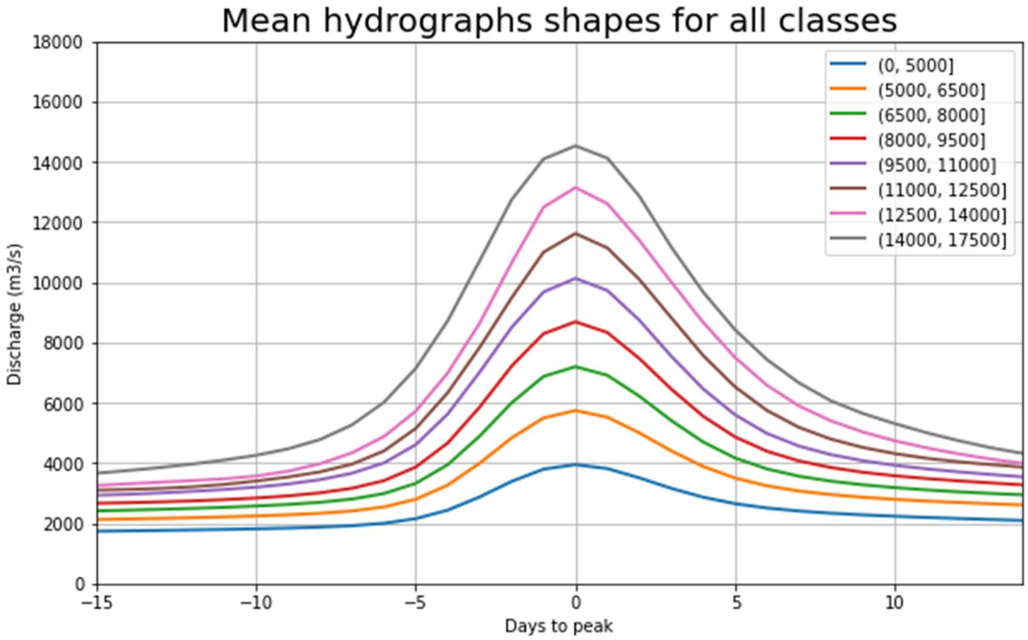

Figure 5-14 Mean shape of the flood hydrograph for all events in each class.

In Figure 5-15 the mean hydrographs shape of the GRADE’21 results Is compared to the WBI2017 hydrographs shape both for the class 14.000 – 17.800 m^3/s. The GRADE’21 result leads to a slightly narrower hydrograph shape compared to the WBI2017 results. The reasons for the small difference could be:

1 The different number of flood hydrographs considered in one class because of the different magnitude of the peaks in the GRADE’21 results compared to WBI2017. As the GRADE’21 results are slightly lower, using the same discharge classes for both WBI2017 and GRADE’21, by default less discharge peaks fall in the highest classes in GRADE’21. This will affect the average shape of the hydrograph.
2 The use of a new hydrodynamic model (SOBEK3-1D2D) to simulate the flood peaks in the river, could lead to a slightly different behavior. This could cause differences in the flood hydrographs shape.

As a reference, also the hydrograph shape for a lower discharge class is given in Figure 5-16. Here it shows that the mean hydrograph shapes for WBI2017 and GRADE’21 are very similar around the peak, but the GRADE’21 hydrograph shape is slightly higher around for the range of more than 5 days before or after the peak.

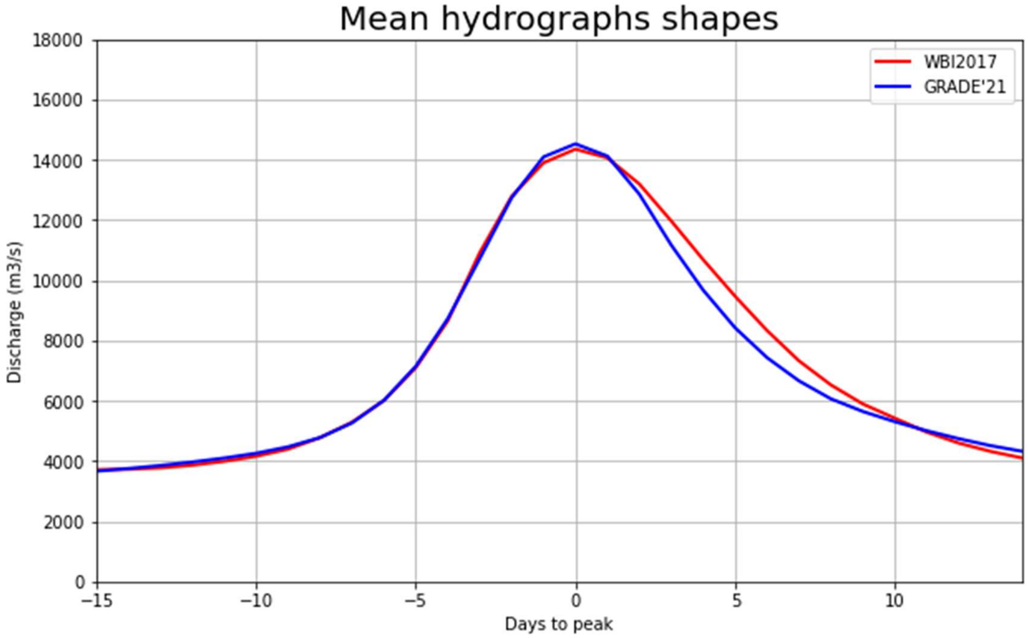

Figure 5-15 Mean shape of the flood hydrograph for the WBI2017 and GRADE'21 results for the discharges between 14,000 and 17,500 m³/s (left).

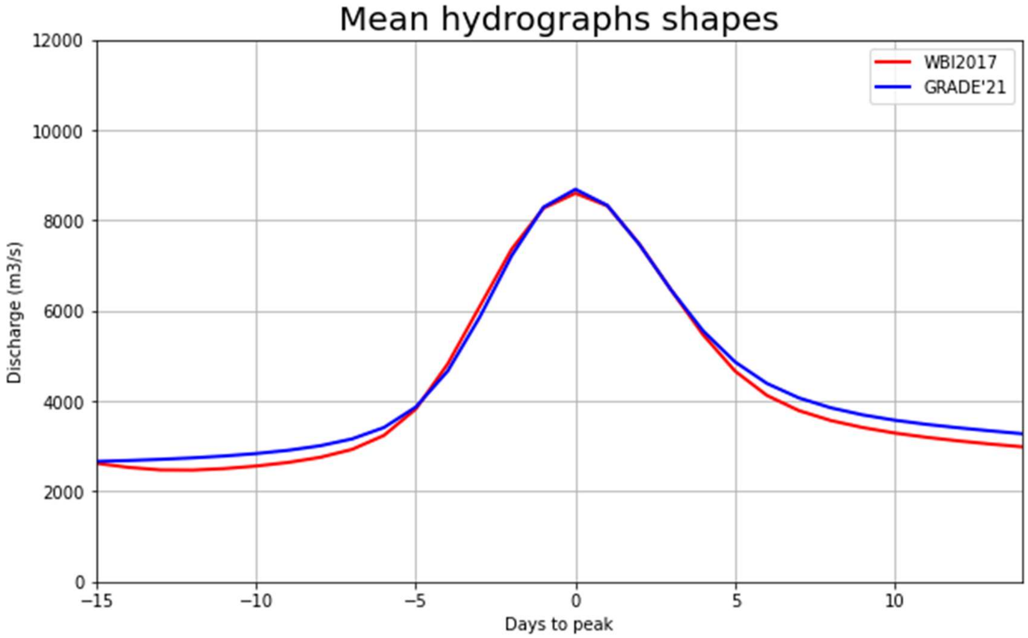

Figure 5-16 Mean shape of the flood hydrograph for the WBI2017 and GRADE'21 results for the discharges between 8,000 and 9,500 m³/s (left).

Table 5-4 Hydrograph shape, scaled to the peak of the average hydrograph shape.

Day to the peak	-2 sigma	-1 sigma	average	+1 sigma	+2 sigma
-15	1768	2770	3664	3943	6603
-14	1758	2829	3751	4094	6928
-13	1825	2936	3852	4088	7084
-12	1837	2888	3967	4126	7121
-11	1863	2879	4099	4493	6913
-10	1970	2991	4257	4749	8039
-9	2012	3217	4472	4878	8701
-8	2178	3621	4780	5198	9163
-7	2486	4041	5266	5795	9875
-6	2904	4829	6015	6777	10702
-5	4229	6056	7146	7821	11462
-4	5661	7798	8725	9312	12473
-3	7933	9771	10716	11614	13116
-2	10821	12493	12738	13316	13668
-1	13647	14122	14093	14237	14221
0	14526	14526	14526	14526	14526
1	13792	14177	14120	14164	14322
2	11753	12804	12858	13248	13261
3	9361	10803	11170	11843	12418
4	7671	9097	9673	10229	11208
5	6308	7823	8423	8888	10318
6	5398	6642	7432	8077	9709
7	4645	5656	6661	7211	9000
8	4253	5109	6065	6494	8652
9	3970	4667	5646	6124	8015
10	3750	4357	5307	5527	7811
11	3585	4148	5005	5294	6871
12	3424	3974	4743	4863	6394
13	3315	3781	4510	4597	6534
14	3197	3733	4321	4318	6501

*Table 5-5 Hydrograph shape, **not** scaled to the peak of the average hydrograph shape.*

Day to the peak	-2 sigma	-1 sigma	average	+1 sigma	+2 sigma
-15	1259	2459	3664	4011	7723
-14	1249	2518	3751	4163	8048
-13	1316	2626	3852	4157	8203
-12	1328	2578	3967	4195	8241
-11	1354	2569	4099	4562	8033
-10	1461	2680	4257	4818	9158
-9	1503	2907	4472	4947	9821
-8	1669	3310	4780	5267	10283
-7	1978	3730	5266	5864	10994
-6	2395	4518	6015	6846	11822
-5	3720	5746	7146	7890	12581
-4	5152	7488	8725	9381	13593
-3	7424	9460	10716	11683	14235
-2	10313	12182	12738	13385	14788
-1	13138	13811	14093	14305	15341
0	14017	14215	14526	14595	15646
1	13284	13867	14120	14232	15442
2	11244	12494	12858	13317	14381
3	8852	10492	11170	11911	13538
4	7162	8786	9673	10297	12328
5	5800	7512	8423	8957	11438
6	4889	6331	7432	8146	10828
7	4136	5346	6661	7280	10119
8	3745	4798	6065	6563	9772
9	3461	4357	5646	6192	9135
10	3241	4046	5307	5596	8931
11	3076	3838	5005	5363	7991
12	2915	3664	4743	4932	7513
13	2807	3470	4510	4666	7653
14	2688	3422	4321	4387	7621

6 Conclusions & recommendation

6.1 Conclusions

GRADE Rhine 3.0 was successfully applied to derive new discharge statistics that can be used in the BOI2023 project.

The main differences of GRADE Rhine 3.0 compared to the previous version are:

- **The base period for the weather generator**
  In the new weather generator, the base period has been extended to also include the period 2007-2015.
- **A new hydrodynamic model of the Rhine between Andernach and Lobith based on the SOBEK3-1D2D model**
  To include in more detail the effect of upstream flooding in Germany, a new hydrodynamic model was developed. This model, a SOBEK3-1D2D model, covers the Rhine between Andernach and Lobith and into the Rhine branches in the Netherlands. The effect is that discharges above 17,000 m^3/s at Wesel are dampened more, resulting in a physically maximum peak discharge at Lobith of around 17,800 m^3/s under current conditions of the riverbed and dikes.
- **A new method to derive the high-frequency statistics (return period between 2 and 25 years)**
  In the previous version of GRADE that was used for WBI2017 the discharge statistics for the high-frequency domain of the discharge statistics between return period of 2 and 25 years the statistics were purely based on annual maxima. It was concluded that a better method would be based on peak over threshold. Therefore, in GRADE’21, the results were corrected using a Langbein correction.
- **An improved uncertainty analysis for the hydrodynamic model**
  As already done for GRADE 2.0 an uncertainty analysis was also done for GRADE 3.0 to estimate the uncertainties in the discharge statistics. The uncertainties in the first two components, the weather generator and the HBV model, were copied from the GRADE’17 results. For the hydraulic model, a new uncertainty analysis was done. New in the approach is the split between model uncertainties, that were assessed using a Monte Carlo simulation, and the emergency scenarios, which were assessed as individual scenarios. The effect of the scenarios, in the range of discharges relevant for the safety assessment (in Dutch: “beoordelen”), is small.

With the updated weather generator, the existing HBV model and the updated SOBEK3-1D2D model new discharge statistics for the Rhine at Lobith were constructed.

The reference statistics for GRADE’21 is comparable to the WBI2017 results for return periods up to 100 years. For longer return periods, the GRADE’21 results are lower, ranging from 5-15% difference for return period above 1000 years. The 95% uncertainty band of the GRADE’21 results is slightly larger for short return periods but is smaller for longer return periods (> 10,000 year) when compared to the WBI2017 uncertainty band. This is the result of the improved uncertainty analysis that was done for GRADE’21. The uncertainty of the discharge statistics, and more precisely the 95% uncertainty band around the discharge frequency curve, can be ‘integrated’ yielding to a so-called ‘discharge frequency curve including uncertainty’.

When comparing these frequency curves including uncertainty for WBI2017 and GRADE’21, the resulting curves for GRADE’21 are comparable for return periods up to 100 years and around 5-10% lower compared to WBI2017.

The GRADE’21 hydrographs shape shows strong similarities with the hydrograph shape derived for WBI2017. For the same discharge classes for higher discharges (14,000 – 17,500 m^3/s), the GRADE’21 hydrograph shape is slightly narrower. This could be caused by a different number of hydrographs in this class, or by the fact that a different hydrodynamic model was used.

6.2 Recommendations

General improvements
Updates have been made in the methodology for the weather generator. For example, the optimal slice selection. For the Rhine the uncertainty analysis for the weather generator, however, was not repeated for GRADE’21, as was done for the Meuse. It is recommended in the next update, to also include an updated uncertainty analysis for this part of GRADE.

Currently, the HBV model still uses the ETF method for calculation of potential evaporation. If it is decided to keep working with the HBV model, it is advised to update the HBV model. Even better would be to move to a new / better hydrological model, to be able to include potential evaporation from e.g., Makkink method. This will make GRADE better suited for application in climate change impact analysis and allows for more consistency in the GRADE approach for the Rhine, Meuse and Vecht rivers respectively.

For the hydrodynamic model several recommendations are made. First, it is recommended to implement in a better way the interaction between surface water and groundwater for the trajectory of the Rhine between Andernach and Lobith. Next to that, an update of the model between Maxau and Andernach is needed to better reflect hydraulic effect at extreme high discharges. Finally, GRADE now does not consider effect of retention measures and potential flooding for the reach between Basel and Maxau. It is therefore recommended to further investigate and invest in the development of a model that can better simulate these effects for the stretch between Basel and Andernach.

From a modelling perspective, the modelling chain in GRADE is gradually getting more complex. More models are added and if also new model will be added for the stretches Maxau-Andernach and Basel-Maxau, it is advised to carefully review the full modelling chain in GRADE. Typically, it is needed to reflect on model software complexity and suitability for GRADE (long simulations), run-time and fit-for-purpose. Hybrid solutions (pseudo 1D2D, meta-models and Machine Learning / Artificial Intelligence models) could be considered.

As stated, the effect of the emergency scenarios is small in the range of discharge interesting for the safety assessment. However, for the design of the levees (OI), when working with more extreme climate change scenarios, the impact of the emergency scenarios could become larger. Therefore, it is recommended to update the fits for the emergency scenarios based on a larger set of simulations, specifically for high discharges (above 17,000 m^3/s).

Finally, during the consultation of external experts, other sources of uncertainties were mentioned, such as the development of the riverbed and the forming of ice dams. These sources were not included in the uncertainty analysis. However, it is recommended to (qualitatively) assess the uncertainties related to these processes in relation to the safety assessment and design of the dikes.

The flood event of 2021

In 2021 an extreme flood event happened in the basin of the Meuse and tributaries of the Rhine, which produced an unprecedented summer discharge at the Meuse. The result was a record high discharge in the Meuse and extreme high discharges in the tributaries of the Meuse, both in Belgium (amongst others the Lesse, Ourthe and Vesdre) and in the Netherlands (the Geul and Roer), as well as in tributaries of the Rhine (mainly the Ahr basin). A quick analysis of the GRADE results has shown that especially the very high discharges in Belgium could not be simulated in GRADE (both the weather generator as the resulting discharges from the HBV model). It has not been evaluated how this event would affect GRADE Rhine.

Based on the 2021 event, several recommendations can be made:

- Assess in detail how GRADE can be improved further to also quantify events like the event in the summer of 2021. This analysis should focus on all components of GRADE.
- Analyze whether specific focus on the winter maxima in GRADE is still a valid approach.

Acknowledgements

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A Determination of a representative 50,000-year resampling set

A.1 Summary

From a 500Kyr record of resampled daily precipitation and temperature, the slice of 50Kyr subsequent years is selected that represents the 500Kyr run as good as possible - also for the most extreme values. The representation is simultaneously optimized for the different seasons (winter and summer) as well as for the different summation periods (7, 10 and 20 days.).

The selected slices for two simulations (i.e., with and without memory term included in the feature vector) will be used for calculating the hydrological and hydraulic results.

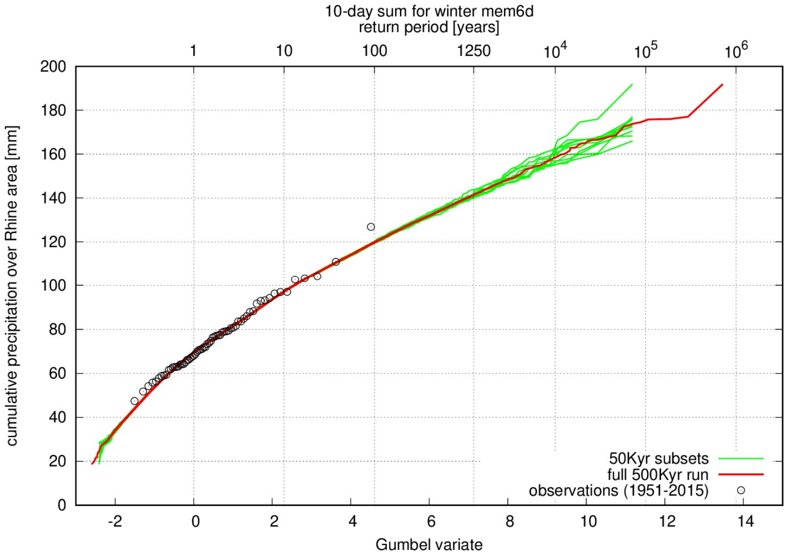
A.2 Introduction

In December 2019, several 50Kyr resampling runs were generated from the same historical data, with the only difference the start seed for the random generator. However, for large return periods (>1000 years), considerable differences in the return values were observed. This complicates a clean comparison of different simulation settings (e.g., resampling with or without a memory term added).

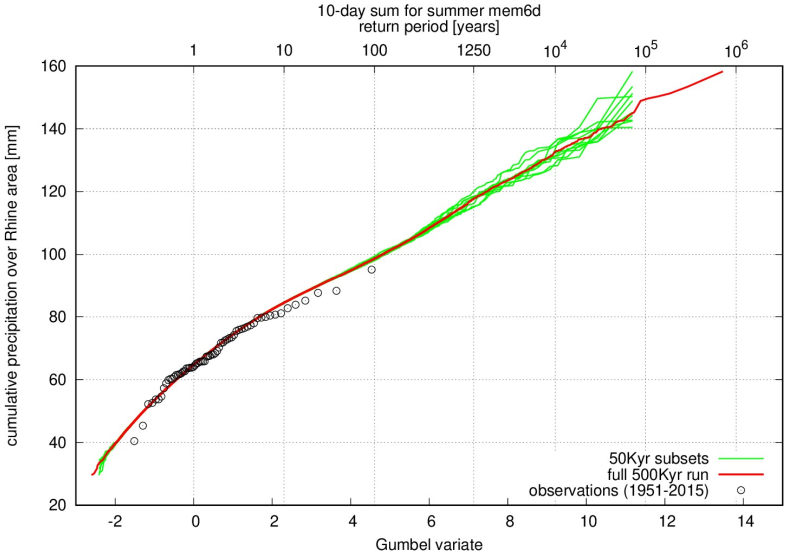
As it is too expensive to use a full 500Kyr run for further processing it through the hydrological and hydraulic simulations, we are looking for the 50Kyr subset that best represents the whole 500Kyr run, also for its most extreme cases. In this memo we explain how we select this optimal slice. We present the results for 2 simulations, one without a memory term (the nomem simulation), and with a 6-day memory term (the mem6d simulation).

A.3 Methodology

We have made a long run of 500Kyr, i.e., 10 times longer than the required length, both for the situation with and without a 6-day memory term included in the resample criterion. Figure 6.1 shows the annual 10-day maxima of the precipitation - averaged over the whole Rhine catchment - for the winter (Oct-Mar) and summer (Apr-Sep) period, respectively, for the case that a 6-day memory term is incorporated in the feature vector. The lines are the Gumbel plots for the 10 subsets of successive 50Kyrs from the whole 500Kyr simulation. The figure shows that from return periods of about 1000 years on, the subsets start to deviate.



(a) winter



(b) summer

Figure 6-1 Gumbel plots for 10-day winter (a) and summer (b) cumulative precipitation over the Rhine catchment for a 500Kyr resampled record (red), which is divided into 10 subsets of 50Kyr each (green). The black circles indicate the observed (HYRAS3.0) maxima for 1951-2015.

From a 500Kyr run, 10 non-overlapping 50Kyr subsets can be taken, but also 450,000 subsequent overlapping slices of 50Kyr. The determination of the optimal 50Kyr slice - out of these 450,000 - that best resembles the 500Kyr run is illustrated in Figure 6.2 and explained below.

First a Gumbel distribution is fitted to the 50 10,000-year maxima from the 500Kyr run (long dash) .

Next, the distance between the plotting position of the 3 highest maxima in the subset and the Gumbel fit are calculated (blue arrows in inset). Note that in this example all these 3 distances are positive, but they can be negative as well if the maxima are lower than the fit.

Third, the squared distances are summed over the 3 highest values, over the summer and winter plots, and over the 7, 10 and 20-day sums, i.e., we calculate:

$$\Delta_y = \sum_{7,10,20} \sum_{W,S} \sum_{i=n-2,n} (x_i - \overline{x_i})^2$$

in which W and S are the winter- and summer- half year seasons, it is the ranking of the n=50,000 maxima, the plotting position of the maximum, and the abscissa of the Gumbel fit for which the ordinate is equal the two maximum. Again, we refer to Figure6. 2 for a visual representation. The subscript y in Δ_y refers to the year number in which the subset starts, so y varies from 1 to 450,001.

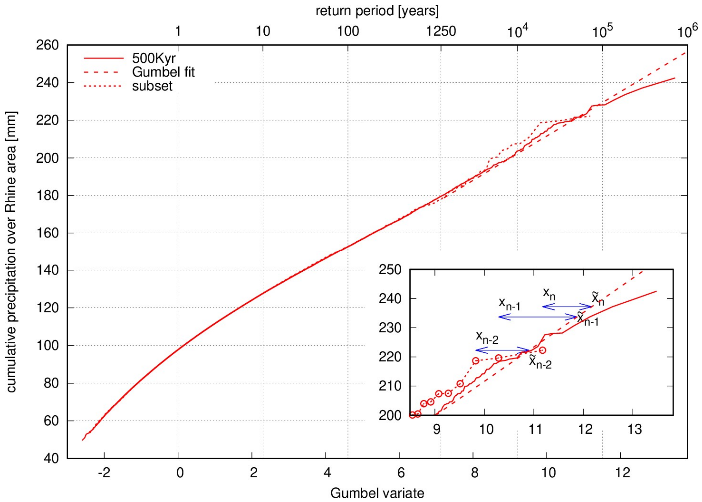
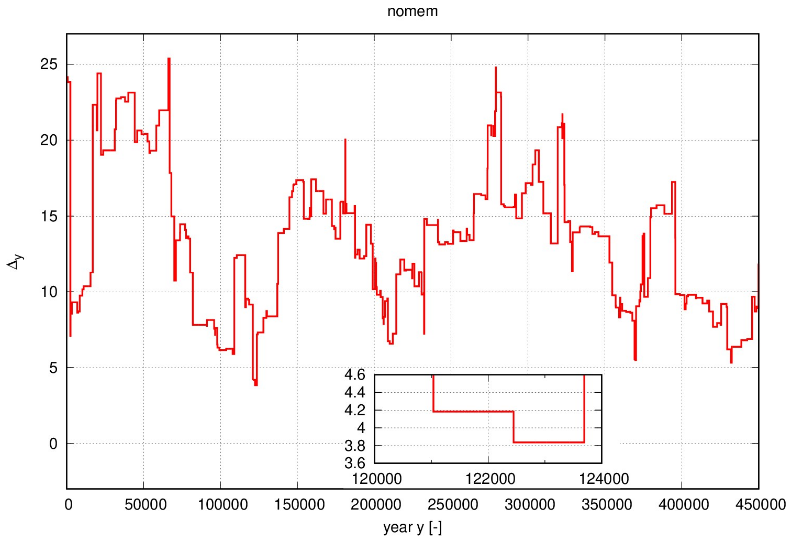
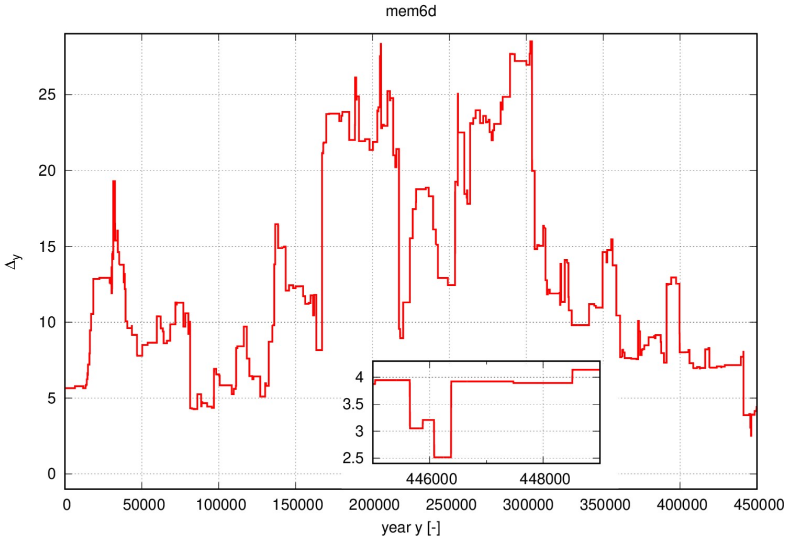


Figure 6-2 Explanation of the procedure to determine the optimal slice. For the 3 highest values of the 50Kyr slice, the difference between the plotting position and the corresponding abscissa of the Gumbel fit is calculated. These differences are indicated with the blue arrows in the inset.

Figure 6-3 shows Δ_y as a function of the starting year y of the 50Kyr slice from the 500Kyr nomem run.



(a) nomem



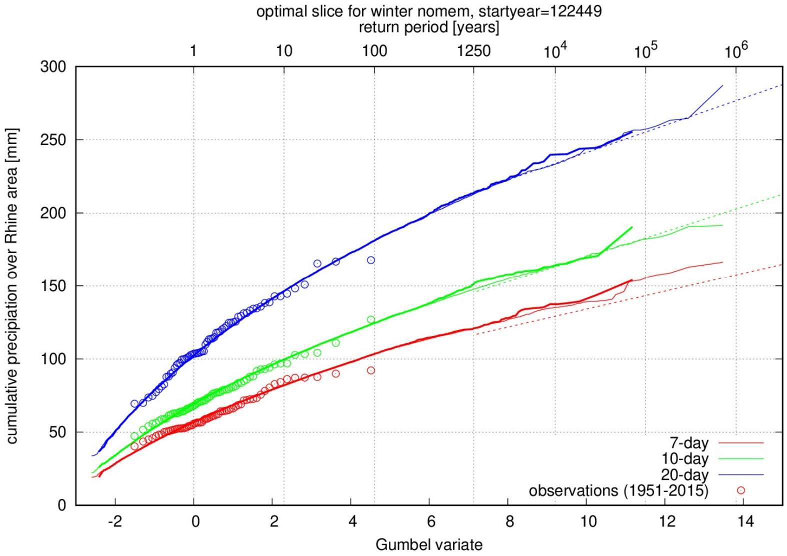
(b) mem6d

Figure 6-3 Value of Δ_y as a function of starting year y of the 50Kyr-slice from the 500Kyr nomem (a) and mem6d (b) simulation. The inset in (a) zooms in on the years 120,000 to 124,000 and shows the minimum values of =3.84 for the years 122,449 to 123,695. The inset in (b) shows the years 445,000-449,000, with a minimum value =2.51 for the years 446,081-446,377.

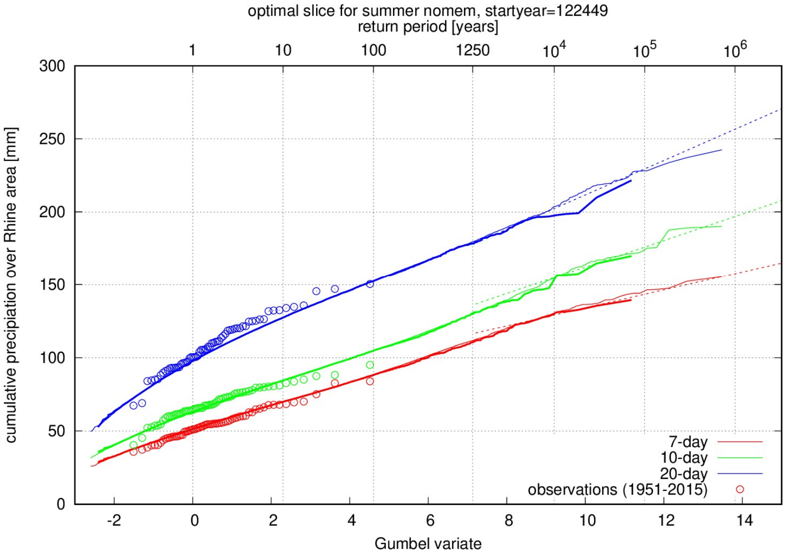
The lowest value of 3.84 is obtained for the years 122,449 to 123,695. For the final optimal slice, the first year for which the fourth year is a leap year (in order to be consistent with a run that starts in 2001) is selected, i.e., y=122,449. Similarly, for the mem6d simulation, the optimal slice starts at year 446,081.

A.4 Results

Figure 6-4 shows the Gumbel plots for the optimal slice (years 122449-172448) from the nomem run for the winter- (a) and the summer maxima (b).
It shows that the Gumbel plots of the optimal slice are close to the 500Kyr plots except for the 20-day summer maxima, where especially the 3rd highest value is lower than the 500Kyr run.



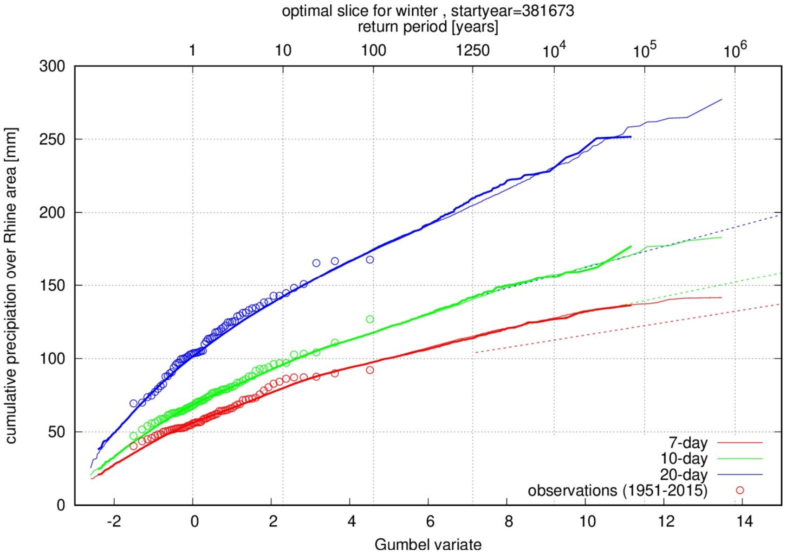
(a) calender year



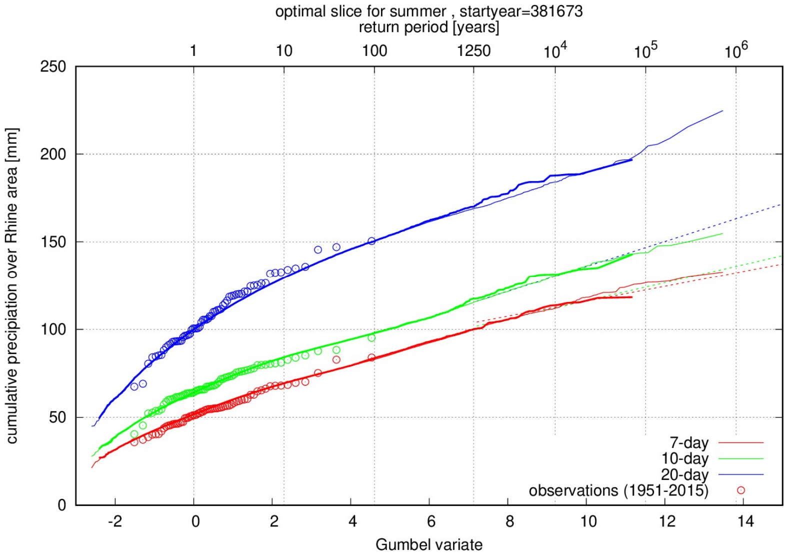
(b) summer

Figure 6-4 Gumbel plots for the optimal 7, 10 and 20-day slices for the nomem run. This slice contains the years 122449-172448 from the 500Kyr run. The plots for the winter- and the summer maxima are shown in (a) and (b) respectively. The circles indicate the observed (HYRAS3.0) maxima for 1951-2015.

Figure 6-5 shows the same plots as Figure 6.4 for the mem6d run. Here the optimal slice contains the years 446081-496080. The minimum value of =2.51, i.e., slightly lower than for the nomem run. This is also visible in the Gumbel plots, as none of the highest values of the optimal slice deviates from the 500Kyr run fit.



(a) winter



(b) summer

Figure 6-5 Gumbel plots for the optimal 7, 10 and 20-day slices for the mem6d run. This slice contains the years 446081-496080 from the 500Kyr run. The plots for the winter- and the summer maxima are shown in (a) and (b) respectively. The circles indicate the observed (HYRAS3.0) maxima for 1951-2015.

A.5 Conclusion

An optimal slice of 50Kyr from a 500Kyr run can be selected by minimizing the differences in return periods between the 3 highest values of the slice and their ’theoretical’ return values. In this way, the slice is representative for the 500Kyr run, also for the highest events in the slice.

By minimizing the different seasons (winter and summer) and the different summation periods (7, 10 and 20 days) simultaneously, the optimal slice is representative for all relevant seasons and summation periods.

For the nomem, the optimal slice contains the years 122449-172448, and the mem6d run the years 446081-496080.

B Potential evaporation: Comparison of Makkink and ETF-based PET

There is a strong preference to replace the ETF-based evaporation calculation with a more sophisticated method based on Makkink. Since global radiation data became available in the E-OBS dataset, it is possible to calculate evaporation based on the Makkink formula. This can be done externally and can potentially replace the complex way it is now implemented in the HBV model via the ETF method. To test if just changing to this Makkink evaporation estimates without re-calibrating the hydrological model, would give good enough results, a few test simulations were done. The results are presented in this appendix.

Discharge results based on the original HBV model (using the internally calculated ETF evaporation) and of the HBV model using the externally provided E-OBS (Makkink) evaporation are shown in Figure 6.6 (timeseries for 1993-1995), Figure 6.7 (discharge regime) and Figure 6.8 (statistics).

Based on this results it was concluded not to use the E-OBS v21.0e potential evaporation data set (external provided to HBV-Rhine like precipitation and temperature) but still using the (internal) HBV-Rhine ETF method which calculates the potential evaporation from temperature.

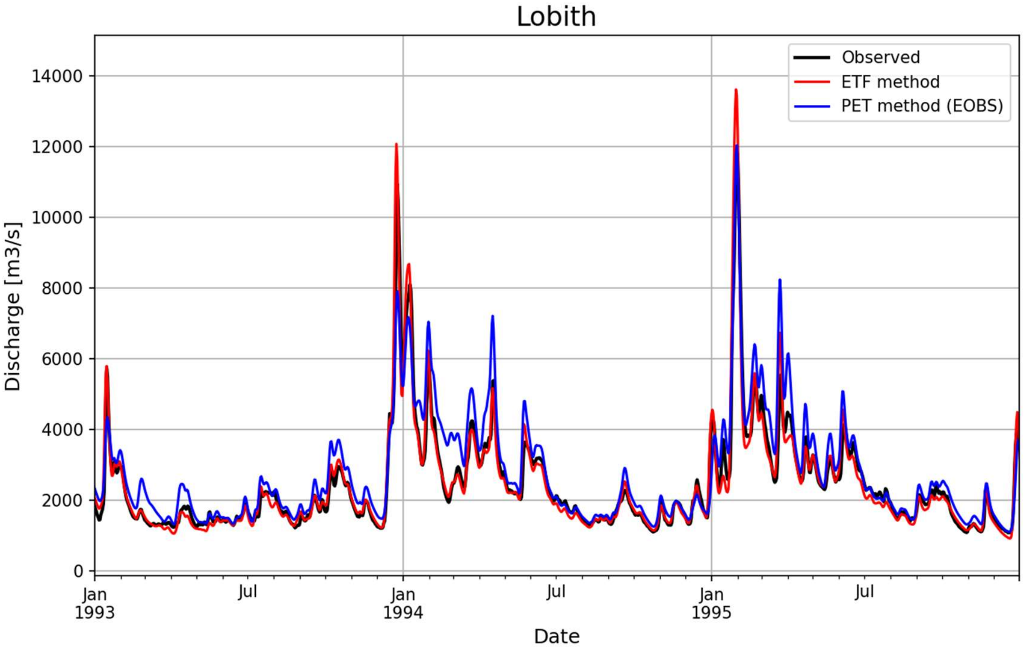


Figure 6-6 Hydrographs for the ETF (red line) and the PET (blue line) methods, compared to the observations (black line).

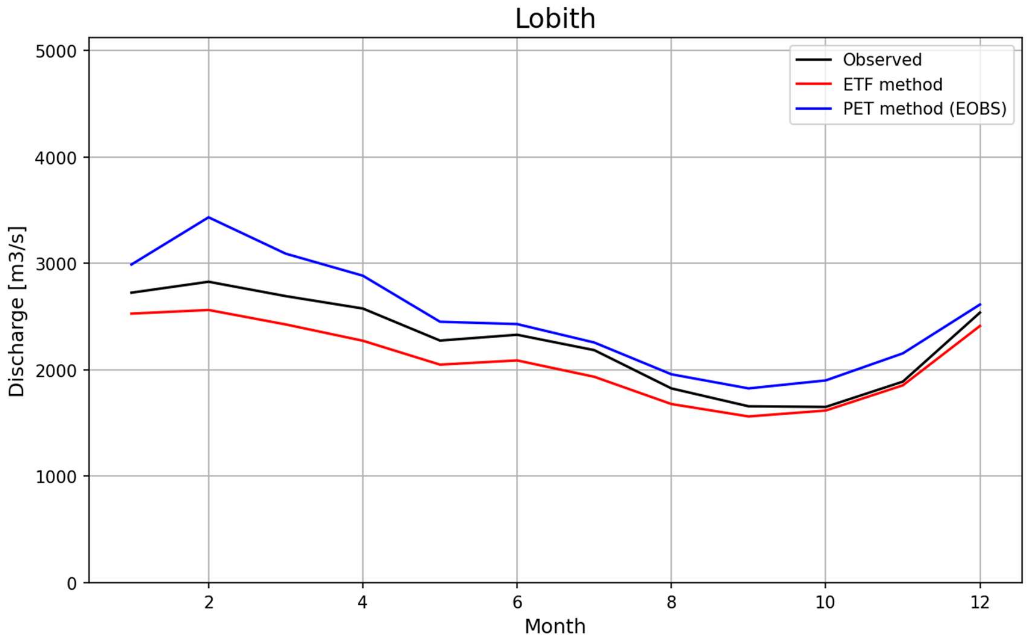


Figure 6-7 Discharge regime for the ETF (red line) and the PET (blue line) methods, compared to the observations (black line).

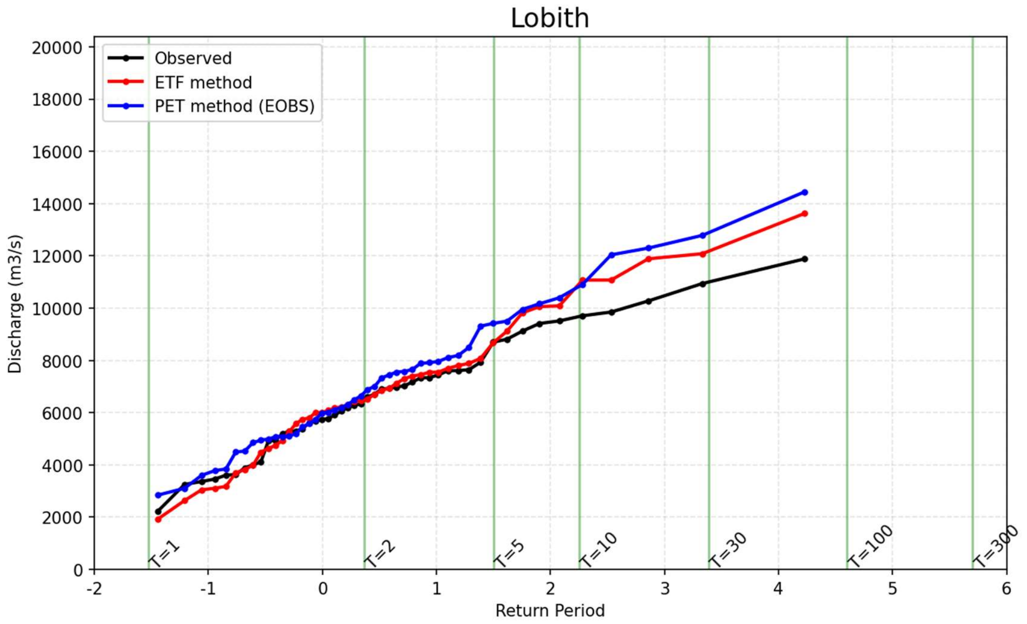


Figure 6-8 Discharge statistics for the ETF (red line) and the PET (blue line) methods, compared to the observations (black line).

C Regression formulas for GRADE Rhine

Computation time of the hydrodynamic models is heavy manly for the SOBEK-RE model and even more for the SOBEK3-1D2D model. To reduce computation time two regression formulas were derived to translate the discharge from the HBV model into pseudo values for SOBEK-RE and SOBEK3-1D2D respectively. This was possible after the SOBEK3-1D2D model was developed and already was used for calculating discharge extremes for climate change KNMI'06 W^+ and KNMI'14 WH scenarios. For more details see Hegnauer, 2018.
As can be seen in the schematic in Figure 4-7,

C.1 HBV to SOBEK-RE

To translate the HBV discharges to pseudo SOBEK-RE values at Lobith, a regression formula was derived. This formula was used for the WBI2017 calculations but is replaced by the newly derived formula between the HBV model and the SOBEK3-1D2D model (see C.2). For completeness, the formula is given below.

$$Q_{SOBEK-RE} = a_1 + a_2 \cdot \left(Q_{HBV} - a_3\right) + a_4 \cdot ln(1 + EXP(Q_{HBV} - a_3)$$

Where: $a_1 = 12958, a_2 = 0.90927, a_3 = 13828, a_4 = 3.02247 \cdot 10^{-3}$

C.2 HBV to SOBEK3-1D2D

To speed up the process of generating statistics for different scenarios and for use in the construction of the uncertainty bands, a regression formula is derived to translate HBV results to corresponding SOBEK3-1D2D results, without the need to do time consuming hydrodynamic calculations self. In Figure 6-9 the workflow for generating discharge statistics by using the regression is demonstrated.

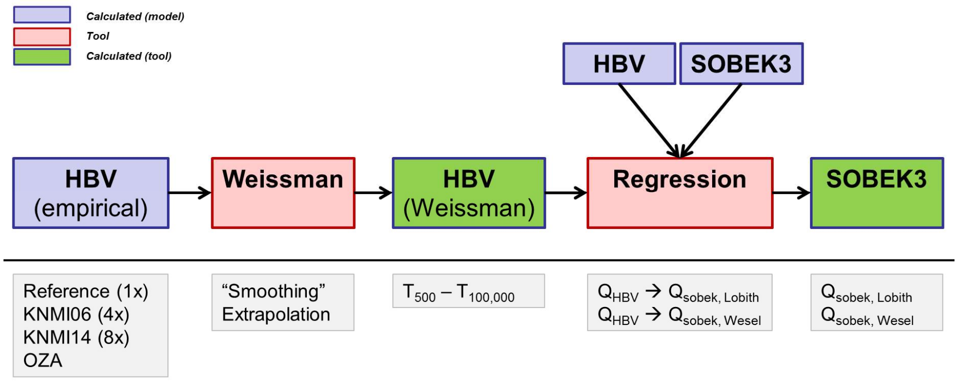


Figure 6-9 Workflow for generating discharge statistics by using the regression formula.

To find a regression between HBV and SOBEK3, the following steps are followed:

1 Calculate discharges for many cases using HBV and SOBEK3.
2 Plot the HBV and SOBEK3 results (top panel in Figure 6-10).
3 Fit a LOESS (Locally Estimated Scatterplot Smoothing) function (middle panel in Figure 6-10). This function is later used to determine the so-called "super" points to fit the regression formula.
4 Fit a regression formula, based on the LOESS function (bottom panel in Figure 6-10).

The regression is derived based on all currently available combinations of HBV and SOBEK3 model results. Since the number of points in the tail of the distribution (i.e. for very large discharges) is still very limited, fitting the regression is still challenging.
Therefore, a choice still has to be made manually on the real maximum discharge at Lobith for even higher extremes. For now the choice was made to select the highest calculated discharge by the SOBEK3 model to be used as limit value in the regression formula. The effect can be seen in the bottom panel in Figure 6-10, where the regression becomes a horizontal line at the right side of the plot.

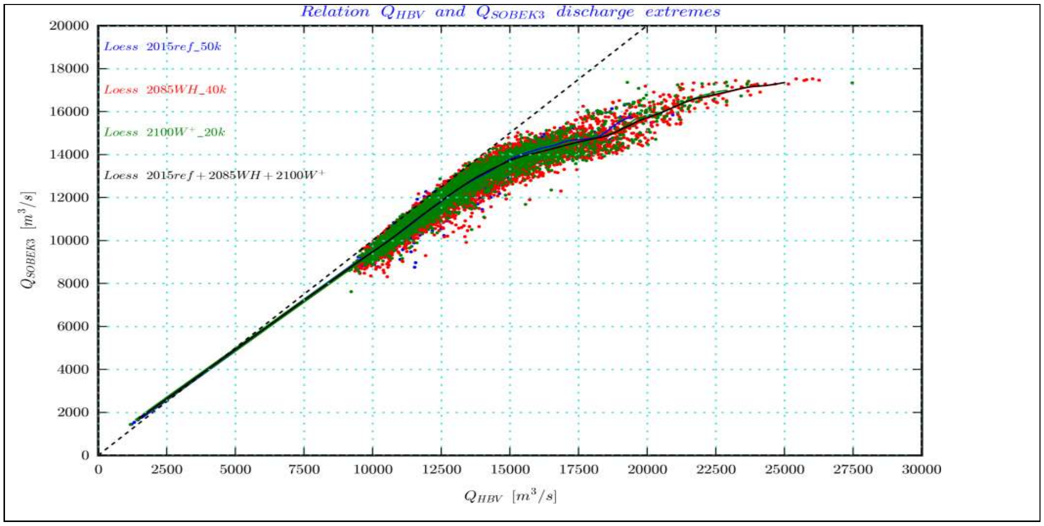
The form of the regression is basically a set of connected linear regressions:

$$Q_{SOBEK3} = c + a_1 + a_2 + a_3 + a_4 + a_5$$

Where:
$a_1 = r_1 * Q_{HBV}$
$a_2 = ((r_2 - r_1) * \sigma_1 * log(1 + e^{Z_1})$
$a_3 = ((r_3 - r_2) * \sigma_2 * \log(1 + e^{Z_2}))$
$a_4 = ((r_4 - r_3) * \sigma_3 * log(1 + e^{Z_3})$
$a_5 = ((r_5 - r_4) * \sigma_4 * log(1 + e^{Z_4})$

$z_1 = (Q_{HBV} - \mu_1)/\sigma_1$
$z_2 = (Q_{HBV} - \mu_2)/\sigma_2$
$z_3 = (Q_{HBV} - \mu_3)/\sigma_3$
$z_4 = (Q_{HBV} - \mu_4)/\sigma_4$

Where:
$c = 340.25$
$r_1 = 0.9158, r_2 = 0.3275, r_3 = 0.5363, r_4 = 0.2130, r_5 = 0.0000$
$\sigma_1 = 307.12, \sigma_2 = 2.72E - 14, \sigma_3 = 136.81, \sigma_4 = 79.55$
$\mu_1 = 14442.3, \mu_2 = 18573.2, \mu_3 = 21904.1, \mu_4 = 26177.7$



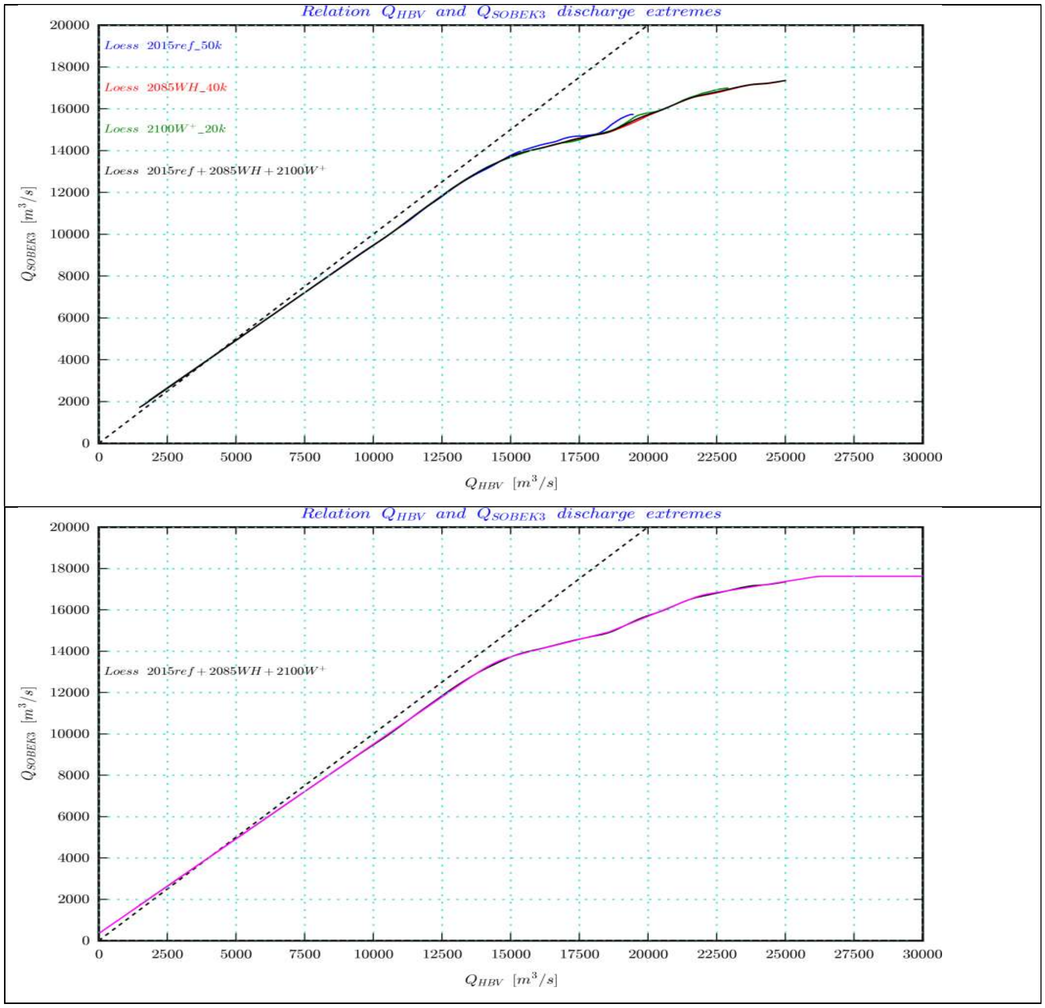


Figure 6-10 Scatter plot between HBV and SOBEK3 discharges including a LOESS fit (top), the LOESS fits for the different datasets (middle) and the regression based on the Loess fit (bottom).

C.3 Correction for river and groundwater interaction

Along the Rhine between Andernach and Lobith interaction between river and groundwater influences peak discharges. These interactions are included in the SOBEK-RE model. In the SOBEK3-1D2D model, this interaction is not included in the simulations.

To continue with the SOBEK3-1D2D simulations, a pragmatic correction factor is used. The correction factor is based on expert judgement and a visual interpretation of the data from a comparison between SOBEK-RE and SOBEK3-1D2D model results. The proposed correction factor is constant for discharges above 7,500 m³/s and follows a linear function ($y = ax$) for the range between 0 and 7,500 m³/s. The correction factor is shown below. The resulting formula for the correction is given below:

$$Q_{GW} = Q_{noGW} - \left(0.04 * Q_{noGW}\right) \qquad \text{for } Q_{noGW} \leq 7500 \text{ m}^3/\text{s}$$

$$Q_{GW} = Q_{noGW} - 300 \qquad \text{for } Q_{noGW} > 7500 \text{ m}^3/\text{s}$$

Where:

Q_{GW} is the discharge considering groundwater interaction.

Q_{noGW} is the discharge not considering groundwater interaction.

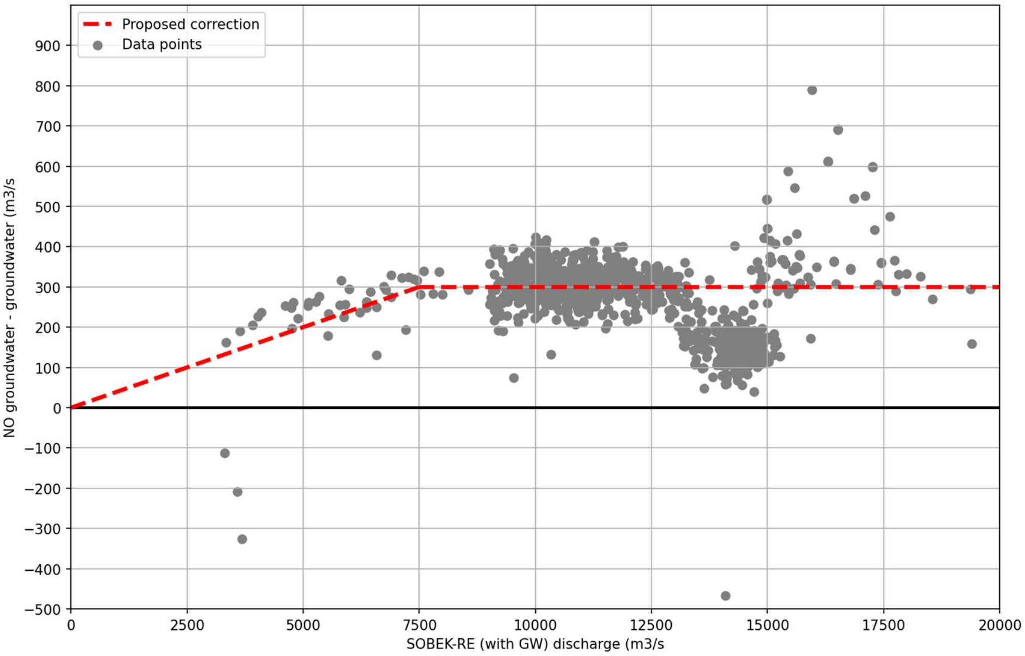


Figure 6-11 Difference between the model results with and without groundwater interaction (grey points) and the proposed correction factor (red line).

D Processing of uncertainties

See separate PDF “**Appendix D - Voorbeeld_uitintegreren.pdf**”.

E Tables for BOI2023

The discharge statistics presented in this report are shown for specific return periods. In HydraRing it is however important to choose the breakpoints very carefully, since in between the breakpoints HydraRing will do a linear interpolation. Therefore, the derived discharge statistics were tested, and the optimal breakpoints were selected to best fit with the simulated discharge statistics. The tables, as used in HydraRing are presented below.

Table 6-1 Discharge statistics for HydraRing.

Return period [1/year]	**Discharge (without uncertainties) [m3/s]**	**Uncertainties (sigma) [m3/s]**
1.5596	5999	310
1.5606	6000	310
2.1886	6553	329
2.9877	7105	349
4.0143	7658	386
5.4337	8211	419
7.3706	8763	451
10.0031	9316	476
13.9713	9868	521
19.4468	10421	563
27.4247	10974	634
41.7317	11526	702
64.0391	12079	750
98.1283	12632	760
173.8717	13184	706
397.2591	13737	654
1574.4013	14290	732
6235.7471	14842	907
20680.2601	15395	1058
80149.2114	15947	1124
350081.3598	16500	1121

F Langbein correction

The GRADE statistics are based on annual maxima (AM). The statistics of the observations are based on the peak over threshold (POT) method. This method considers more information, especially for the high frequency part of the statistics. As a result, the discharges in the high frequency domain are higher when using POT compared to AM. To correct the GRADE statistics for this, the so-called Langbein correction was done. This correction is used to correct the return period based on AM to match the return periods found via POT. The Langbein formula is shown below.

Langbein correction: $T_{POT} = \frac{1}{-\ln\left(1-\frac{1}{T_{AM}}\right)}$

The correction is, for reasons of simplicity, done for the complete range of annual maxima. The difference become very small (or even negligible) for return periods above 1/25 years. This is illustrated in the following table.

Effect of Langbein correction

T_{AM}	$T_{Langbein}$
2	1.4
5	4.5
10	9.5
25	24.5
100	99.5

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