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GRADE 2012

Procedure to derive the design hydrograph

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Title
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Rijkswaterstaat Waterdienst	1205966-003	1205966-003-ZWS-0009	27

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Summary
GRADE (Generator of Rainfall and Discharge Extremes) is a new methodology to provide a better physical basis for the estimation of the design discharge of the main Dutch rivers compared to the present method based on frequency analysis of extreme discharge values. GRADE can also be used for the determination of the shape of the design hydrograph, important for the duration of the stress on the river dikes, for the assessment of the downstream flood defences. The advantage of using GRADE-discharge-series is that the present method of upscaling of historical flood waves is superfluous, which prevents volume errors.

This report proposes a procedure to derive the shape of the design discharge hydrograph and the accompanying uncertainty width using the synthetic GRADE discharge series for the river Meuse at Borgharen. The focus is placed on the derivation of a design hydrograph for the failure mechanisms overflow and overtopping. The new proposed method will be evaluated by the project WTI2017, where the hydrograph is used as input for the assessment of the Dutch primary flood defences. Next year, the procedure will be improved, tested for the Rhine, and possibly extended for extra failure mechanisms.

Version	Date	Author	Initials	Review	Initials	Approval	Initials
	nov 2012	N. Kramer		R. Passchier		G. Blom	

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Contents

1 Introduction

1.1 Context of this report

This report in part of the 'GRADE'-project, which is carried out for RWS Waterdienst. GRADE (Generator of Rainfall and Discharge Extremes) is a new methodology to provide a better physical basis for the estimation of the design discharge of the main Dutch rivers compared to the present method based on frequency analysis of extreme discharge values.

GRADE is based on re-sampling of historical weather conditions of limited length, long series of precipitation and temperature are generated with a rainfall generator. These series are input to semi-distributed, conceptual HBV rainfall-runoff models to create long discharge series, further physically modelled by hydrodynamic routing of the largest floods using Sobek, to end up with a realistic series of 20,000-50,000 years of discharge at the point of interest in the basin. The long generated discharge series can be used for the determination of the design discharges.

A second purpose of the long discharges series is the determination of the shape of the design hydrograph. A design discharge hydrograph is a discharge wave that characterizes a typical discharge event with a certain return period. The current procedure for the derivation of the hydrograph was based on upscaling of observed hydrographs. A disadvantage of this method is the applied upscaling and sensitivity of the results for the applied choices (Ogink, 2012). With GRADE much longer discharge series are available, which expands the possibilities for the deviation of the design hydrograph. And longer series asks also for a new procedure. In this report different procedures were tested for the deviation of the design hydrograph and a new method is proposed. These tests focus on the failure mechanisms overflow and wave overtopping and uses the GRADE discharge series for the river Meuse.

The new proposed method will be evaluated by the project WTI2017[1], whereas WTI uses the hydrograph as input for the assessment of the Dutch primary flood defences. Next year, the procedure will be improved, tested for the Rhine, and possibly expand with extra failure mechanisms.

1.2 Background design discharge hydrograph

The 5-yearly safety assessment of flood defences of 2006 (HR2006) used a design discharge hydrograph for three goals:

- as upstream boundary condition in the hydraulic SOBEK/WAQUA models of the Rhine and Meuse. The output of the hydraulic calculations gives maximum water levels for the downstream output locations. These maximum water levels are used to fill the Hydra-database. Hydra is a probabilistic instrument to calculate the normative load levels.
- as trapezium in the Hydra-calculations to take into account the time-aspect in the probabilistic calculations. A trapezium is a schematized hydrograph.
- as upstream boundary condition in the hydraulic SOBEK/WAQUA models of the Rhine and Meuse for the determination of the standard water level hydrographs for the downstream output locations (in Dutch: waterstandsverloop). These standard water level hydrographs were introduced to take into account the duration of the stress on the river

[1] The project WTI-2017 is responsible for the deviation of the Hydraulic Boundary Conditions (HBC) and the Safety Assessment Regulation (VTV: Voorschrift op Toetsen op Veiligheid) for the next safety assessment of the Dutch primary sea and flood defences

dikes in the assessment of the failure mechanisms macro- and micro-stability of the inner slope and piping. For macro-stability (resistance against sliding) of the outer slope, revetments and forelands no matching design discharge hydrographs were available to derive the accompanying hydraulic load conditions for the downstream output locations. The normative discharge hydrograph for these latter failure mechanisms is more complex. For example: for the failure mechanism of revetments a long lasting, low discharge wave could be normative instead of a high and relatively short lasting discharge peak.

For the determination of the hydraulic boundary conditions of 2006 (HR2006), the probabilistic calculations were done with the probabilistic Hydra-instrument. For the next safety assessment (WTI2017), a new model (Hydra-Ring), will be developed. Since Hydra-Ring will be able to determine the normative conditions for (almost) all failure mechanism, extra information about the upstream design discharge hydrograph is needed. For typical discharge events, the following information is required:

- Shape of the upstream discharge hydrograph;
- Uncertainty width of the discharge hydrograph.

The current (HR2006) procedure to derive the upstream design discharge hydrograph is based on scaling of observed hydrographs. In Ogink (2012) this procedure was reviewed. The outcomes of this review are given in the text box below. The present procedures are straight forward and easy to apply, however, it has a number of shortcomings:

1 Arbitrarily chosen base levels are applied to observed hydrographs prior to scaling with linear extrapolations backward and forward from the base level. After upscaling, this creates an artificial front and tail of the hydrographs used to determine the design hydrograph.
2 The size of the peak selection window is arbitrary and leads to allowance of secondary peaks. These features widen the design hydrograph and lead to an unrealistic shape, which underestimates the rates of rise and of fall.
3 Up-scaling of observed hydrographs to the design level creates a scaling effect, which widens the design hydrograph, particularly on the falling limb, and affects the size of the confidence interval considerably.
4 Averaging time wise around the peak leads to sharper peaked and more realistic hydrographs then with the current procedure (horizontal averaging), and also preserves the flood volume around the peak.

The shortcomings can largely be eliminated by generating long representative discharge series derived from precipitation and climatic series from a rainfall generator, reliable rainfall-runoff models with their output routed by a physically based routing model, representing the physical characteristics of the hydraulic infrastructure for the full range of flows. Of course, this shifts part of the problem to the precipitation and climatic series used in the rainfall generator, with its own generation problems but at least all limitations in the hydraulic infrastructure can be taken into consideration and assumptions on and extrapolation of distributions and up-scaling of hydrographs is not required.

The main recommendations of Ogink (2012) are:
1) use vertical averaging instead of horizontal averaging, and
2) use long synthetic discharge series generated by GRADE.

In this study both recommendations will be examined in order to derive a procedure for determining the design hydrograph.

1.3 Goal

The goal of this study is to determine a procedure to derive the design hydrograph for different peak levels and the accompanying uncertainty. The procedure will use the synthetic-GRADE discharge series (20.000 – 50.000 yr).

This analysis will focus on the failure mechanisms overflow and wave overtopping, In the GRADE 2013 study also other failure mechanisms are considered.

In this study, the application of the new method is only shown for the river Meuse at Borgharen. No data were yet available for the Rhine at Lobith to allow a similar hydrograph derivation at this location.

2 Traditional method[2]

2.1 Design hydrograph

The design hydrograph procedure is based on scaling of observed hydrographs as schematically presented in Figure 2-1 (developed by Klopstra et al., 1999 and updated by Wijbenga and Stijnen, 2004). In short, the method includes the following.

Observed discharge hydrographs with peak values exceeding a peak threshold value are selected. If the distance between the peaks of two flood waves is larger than a specified time window, or if the discharge drops below a specified base level, the discharge waves are treated as separate events. Below the base level the hydrographs are extended linearly backward/forward dependent on the observed discharge gradient. The selected flood waves are subsequently scaled up to the design discharge by multiplying each ordinate of the hydrograph with the ratio of the design discharge / observed peak value. The duration of the top is adjusted by raising the discharge at 1 cm under the top to the peak value and correcting the rising and falling limbs accordingly. At selected water levels under the peak of the scaled hydrograph, the discharge is determined at which the duration of rise (a+b), total exceedance duration (a+b+c) and flood volume are calculated, and their mean and standard deviation determined from the selected hydrographs. The rising limb of the design hydrograph is then constructed by connecting the average rise at each selected level. The shape of the falling limb follows from the difference between the total wave duration and the corresponding rise at each selected level. The 95% confidence interval for the rising limb is derived from the duration statistics at each threshold level assuming a log-normal distribution. The interval for the falling limb is derived from the total exceedance and rise statistics including their correlation, assuming also a log-normal distribution.

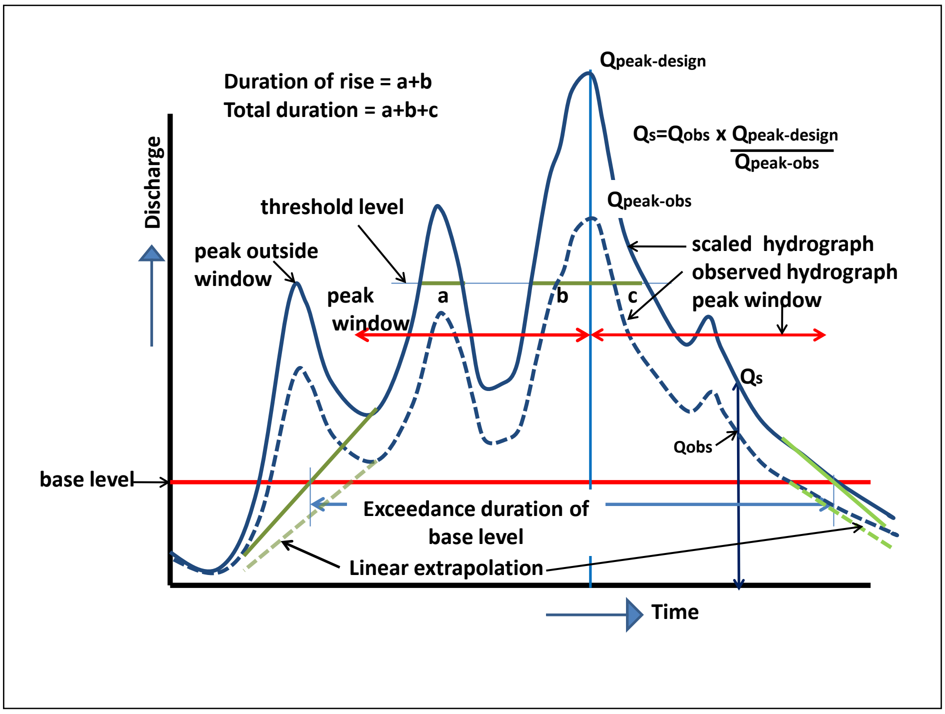

Figure 2-1 Illustration of procedure of flood wave selection, scaling and exceedance duration computation

[2] *The text is mainly from Ogink (2012).*

The resulting design hydrographs for the Meuse and the Rhine are shown in Figure 2-2 and Figure 2-3. The design hydrographs labelled 2001 have been published in Parmet et al., (2002). The design hydrographs labelled 2006 (dashed red lines) have not been published yet, but follow from application of the wave generator to the available hydrographs (Heijnis, 2004). It is observed that particularly for the Meuse the latest design hydrograph is much leaner than the previous one. This is due to the cut off procedure of the wave at the base level with linear extrapolations backward and forward, introduced in 2004 (Wijbenga et al., 2004). The design hydrograph-2006 for the Meuse is now seen to approximate the standard hydrograph used for the 5-yearly assessment of the flood defences developed in the 1970's. For the Rhine the design hydrograph-2006 is still wider than the standard hydrograph, but leaner that the 2001-design hydrograph on the front side.

2.2 Standard hydrograph

For HR2006, besides the design discharge hydrograph, also a standard discharge hydrograph is available. The standard hydrographs were taken up in the instructions for testing of safety of flood defences VTV 2001-2006 (Voorschrift Toetsen op Veiligheid, MVW, 2004) and HR2006 (MVW, 2007), with clear expression that the standard discharge hydrographs are not suitable for design; they are only used for the by law requested recurrent assessment of the test levels of the primary flood defences outside the tidal zone (Bovenrivierengebied).

Where the design hydrograph is much wider than the standard hydrograph, this is a dangerous policy as with the standard hydrograph a stronger attenuation will be determined and the test will lead to too low water levels. The confusion in HR2006 is even aggravated as the applied (standard) hydrographs are described as based on a reconstruction of observed flood waves with multiple peaks scaled to waves with a single peak at the design discharge, which are subsequently averaged: exactly the procedure also used for the design hydrograph.

The standard hydrograph for the Rhine at Lobith originates from the late '60's and is based on single discharge hydrographs of the period 1901-1965 with maximum values > 5,000 m^3/s (RWS, 1968). Single discharge hydrographs are constructed by elimination of secondary and lower peaks on to a level of 4,000 m^3/s. For threshold levels between 4,000 and 9,000 m^3/s at intervals of 1,000 m^3/s, the durations of rise and fall are determined separately. Per threshold level, relations have been developed for rise and fall durations as a function of the maximum discharge. These relations are used for estimation of the durations at the design discharge. Between 9,000 m^3/s and the design discharge, the hydrograph has been constructed based on statistically established discharge-discharge exceedance durations, ignoring differences between durations of rise and fall. The discharge exceedance durations have been estimated for the assumed exponentially distributed peak discharges.
The standard hydrograph for the Meuse at Borgharen is derived on a likewise method.

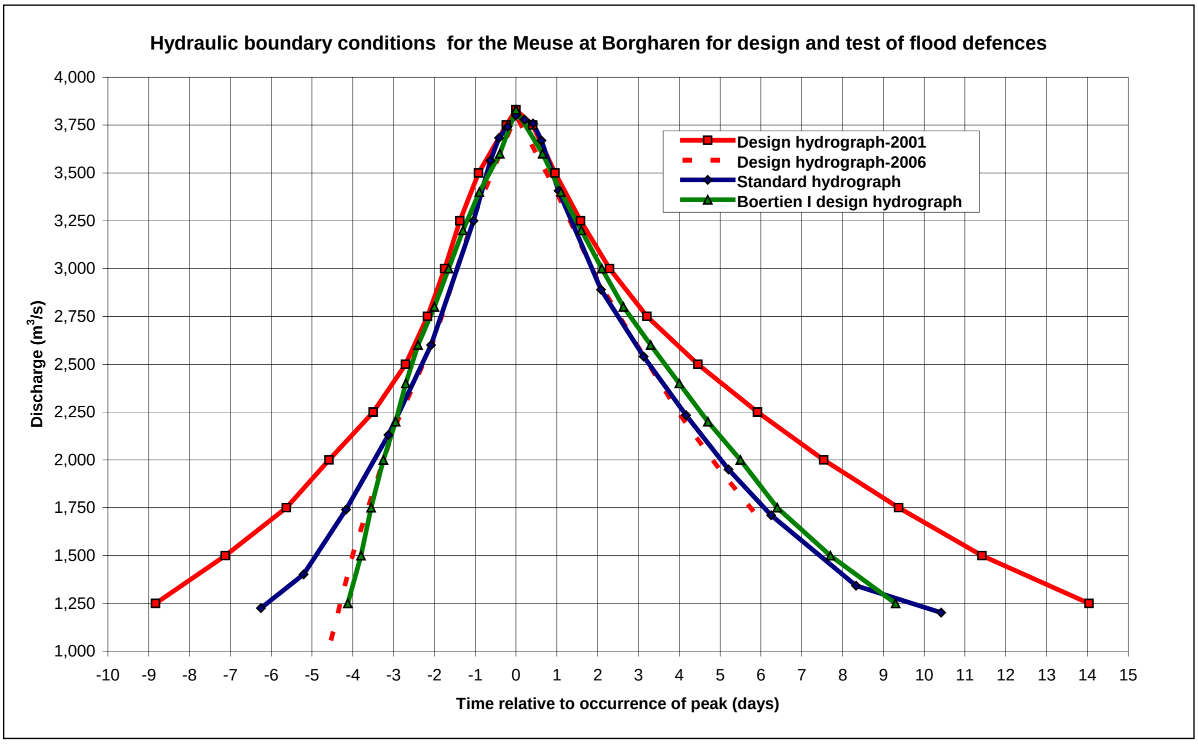

Figure 2-2 Standard and design discharge hydrographs for the Meuse at Borgharen

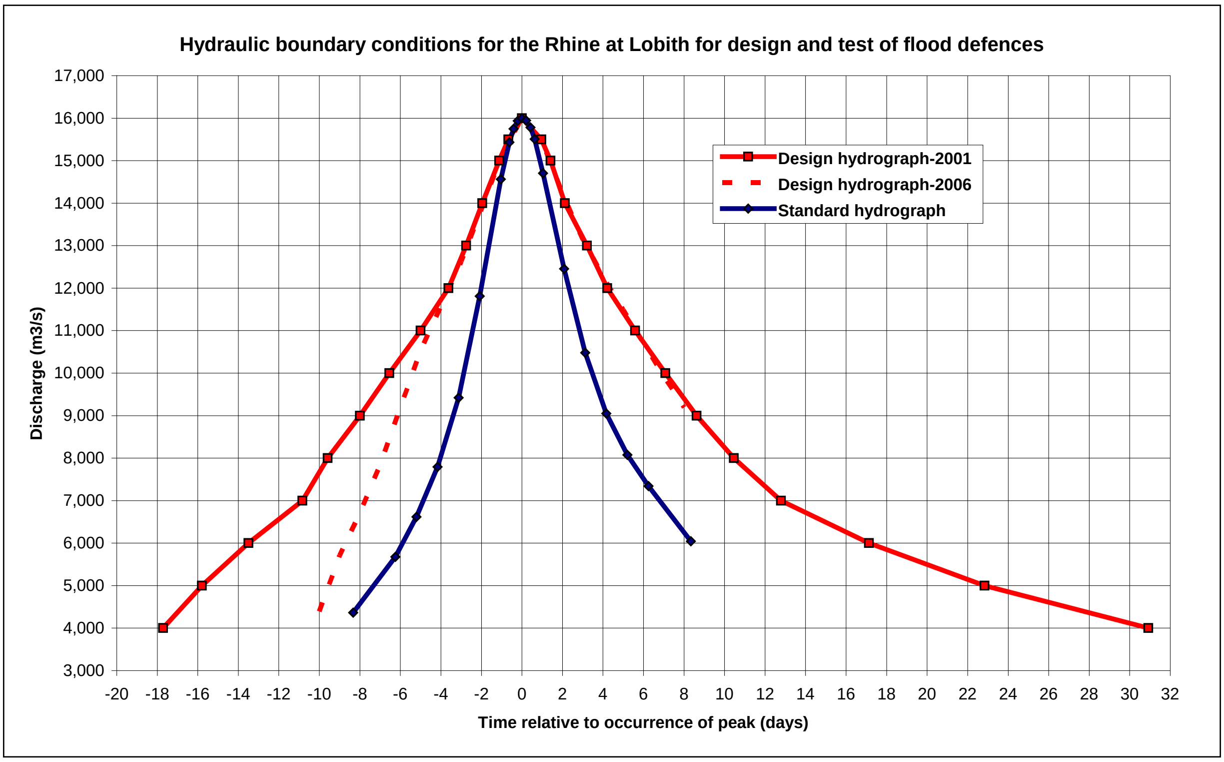

Figure 2-3 Standard and design discharge hydrographs for the Rhine at Lobith

3 Proposed method for the determination of the design hydrograph

The determination of the design hydrograph can be done in several ways. In this chapter all important steps in the procedure of the determination of the design hydrograph are verified. The main decisions are:

1. historical versus synthetic discharge series (section 3.1);
2. selection of the peaks (section 3.2);
3. cut off criteria (section 3.3);
4. horizontal versus vertical averaging (section 3.4);
5. distribution of the confidence interval (section 3.5);
6. average discharge hydrograph (section 3.6)
7. correction of the peak value (section 3.7);

As mentioned earlier, for the proposed method, only results for the Meuse at Borgharen are available. No data are yet available for the Rhine at Lobith, but the same procedure as outlined here for the Meuse river will be used to derive the design hydrograph and all its characteristics.

3.1 Historical versus synthetic discharge series

Ogink (2012) showed that up-scaling of observed hydrographs to the design level creates a scaling effect, which widens the design hydrograph particularly on the falling limb and affects the size of the confidence interval considerably. An alternative is to use the long synthetic discharges series created by the GRADE instrument.

The Generator of Rainfall and Discharge Extremes (GRADE) is an instrument that generates synthetic discharge series for the river Rhine at Lobtih and the river Meuse at Borgharen. It includes a rainfall generator, rainfall-runoff models with their output routed by a physically based routing model, representing the physical characteristics of the hydraulic infrastructure for the full range of flows. All effects of the hydraulic infrastructure on the genesis and shaping of the hydrograph can be taken into consideration and up-scaling of hydrographs is not required.

For the new method for derivation of flood hydrographs, use is made of the GRADE generated synthetic discharge series.

3.2 Selection of the peaks

For the failure mechanism, overflow and wave overtopping the peak-value, and also the volume of the wave, are the normative factors. Since we mainly focus on overflow and wave overtopping, we are interested in the highest peaks of the discharge series. For other failure mechanisms, other hydrograph characteristics could be normative.

In the traditional method, the highest peaks in the series are selected using a peaks-over-threshold (POT) method. An alternative is the selection of annual maxima. Since in the GRADE analysis, extreme long series (order 20.000 – 50.000 years) of synthetic discharges are available, the difference between POT and annual maxima will be small. The choice between the peak selection methods is mainly relevant when small datasets are available.

Since the disadvantage of POT is its sensitivity for the arbitrarily chosen threshold and peak selection window, in the next analyses in this report annual maxima are used.

For the determination of the hydraulic boundary conditions for the next safety assessment (WTI2017), design hydrographs and their accompanying uncertainty for different peak discharges are required. To derive these standard hydrographs, the annual maximum GRADE waves, taken from a 20.000 year synthetic series, were divided in classes based on their peak discharge. Every class includes at least 100 waves (Table 3-1). Finally the discharge waves are scaled, which makes that all waves have the same peak value. In this case the scaling effects are limited, because only the waves in the class of interests are taken into account.

Table 3-1 Peak discharge classes for the Meuse at Borgharen.

Class	Min (m^3/s)	Max (m^3/s)	(Round) average (m^3/s)	Number of waves
1	3250	4300	3800	113
2	3000	3250	3100	154
3	2750	3000	2900	272
4	2500	2750	2600	516
5	2250	2500	2400	853
6	2000	2250	2100	1371
7	1750	2000	1900	2076

3.3 Cut off criteria

As explained in Chapter 1, in 2004 a cut off procedure was introduced in the traditional design discharge hydrograph method by Wijbenga et al. (2004). This cut off procedure includes linear extrapolations backward and forward under a defined base level in order to eliminate side peaks. Figure 3-1 shows 10 randomly chosen GRADE waves for Borgharen, where the cut off criteria are applied. If the discharge exceeds the base level of 1000 m^3/s, extrapolation is applied. The use of the cut off procedure leads to a smaller base of the hydrograph.

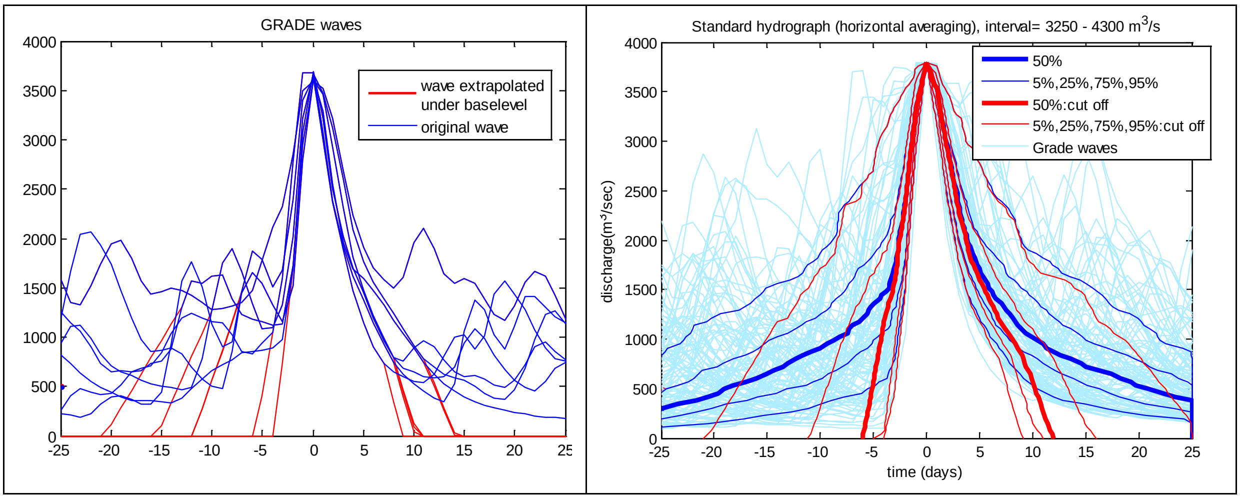

Figure 3-1: cut off procedure: linear extrapolations backward and forward of the hydrographs at the base level. The blue and red lines give respectively the original and corrected waves. The left figure gives the cut off procedure for single GRADE hydrographs. The right figure gives the effect on the average hydrograph.

However, as shown in Figure 3-1, this extrapolation leads to an arbitrary and unrealistic lower part of the rising and of the falling limb of the scaled hydrograph. Secondly, the volumes of the hydrograph are underestimated. And thirdly, the selected base levels are generally chosen as the discharge where the river starts flowing overbank and as such make sense when a flood plain lies in front of the flood defence. At locations where conditions are different another base level may be critical. Furthermore, the non-exceedance of the base level for a very short period of time would cut off the hydrograph, but these parts - either at the beginning or the end of the hydrograph - may still be of importance for stability aspects of the flood defence. Hydraulic loads should not exhibit such arbitrary cut offs.

In further analyses, the extrapolation is not taken into account.

3.4 Horizontal versus vertical averaging

Instead of determining the durations of rise and of total exceedance at given water level / discharge levels within a given peak window (horizontal averaging), as in the wave generator procedure, one can also create an alternative design wave by sorting the discharge at discrete times (e.g. hourly, daily) prior to and after the peak (vertical averaging, see Figure 3-2). For each time step, a frequency distribution is made. By connecting the discharges for a particular frequency at the discrete times prior to and after the peak, a hydrograph is obtained. It represents for each time the observed discharge frequency, though successive entries may not be related. It results, however, in hydrograph shapes that have a more realistic appearance with steeper rates of rise and of fall than those created by the wave generator. By taking the mean values for each step, the volume represented by such a flood wave represents the correct average flood volume around the peak, which cannot be said of the present procedure. This is tested in more detail in the subsequent part of this Chapter..

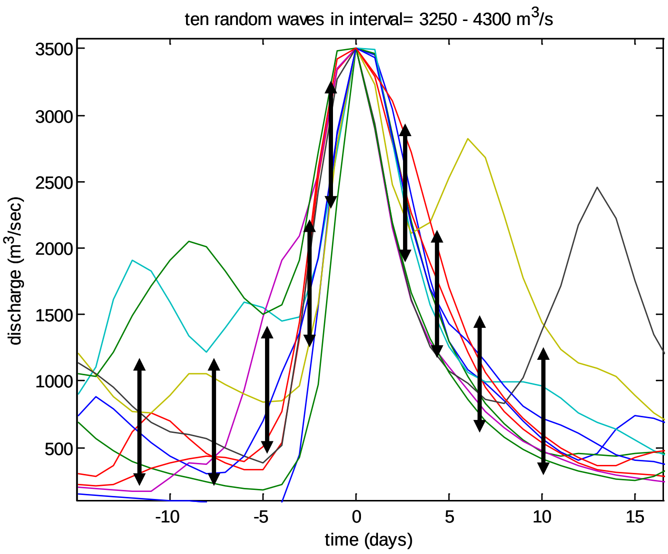

Figure 3-2 determine standard hydrograph by averaging the discharge per time step (vertical averaging).

In this analysis, the two methods (vertical versus horizontal) for averaging are considered to determine the average hydrograph. The results for both methods are given in Figure 3-3 to Figure 3-5. For both methods the selected GRADE waves are used. Figure 3-6 shows the average hydrographs for all peak-intervals.

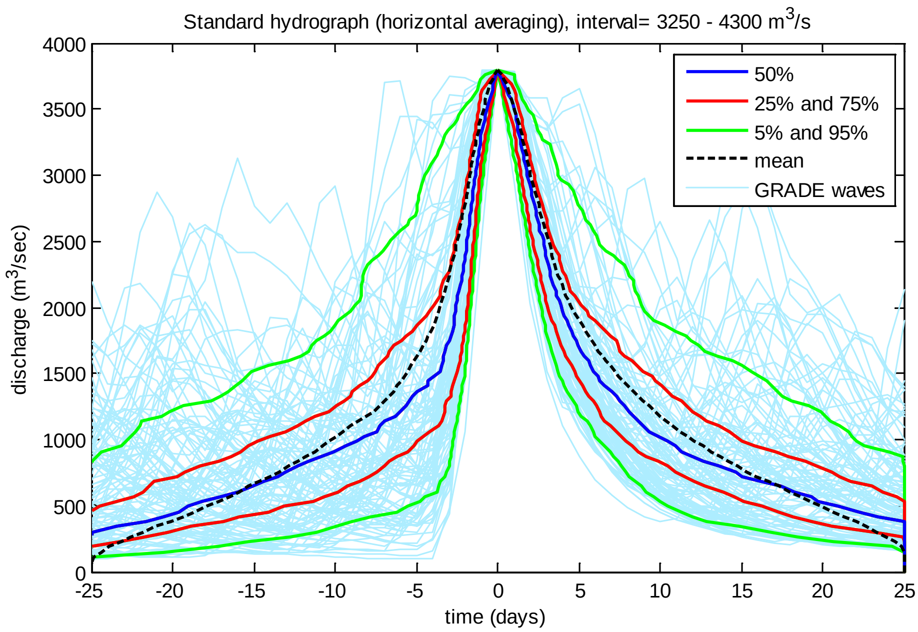

*Figure 3-3 Hydrograph for discharge interval 3250-4300 m^3/s using **horizontal averaging**.*

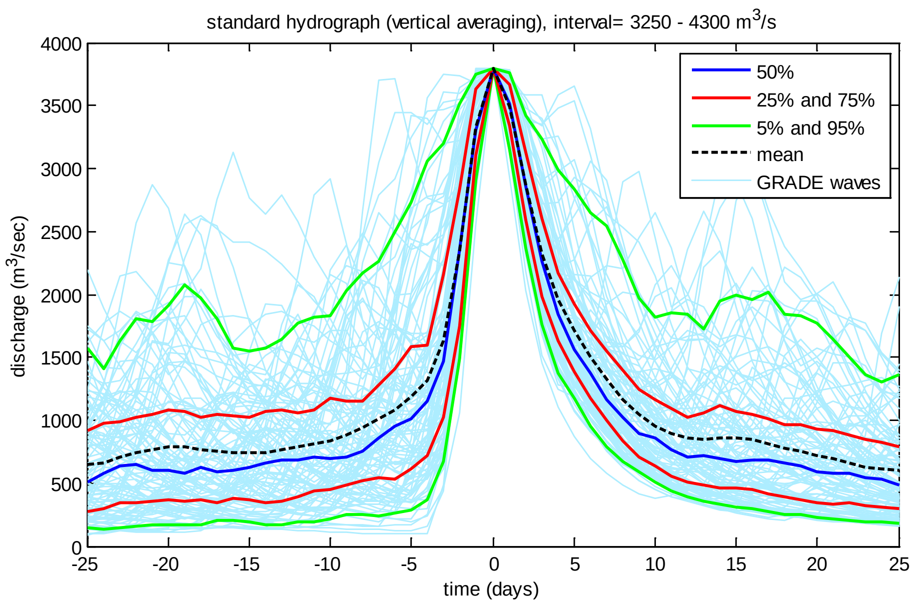

*Figure 3-4 Hydrograph for discharge interval 3250-4300 m^3/s using **vertical averaging**.*

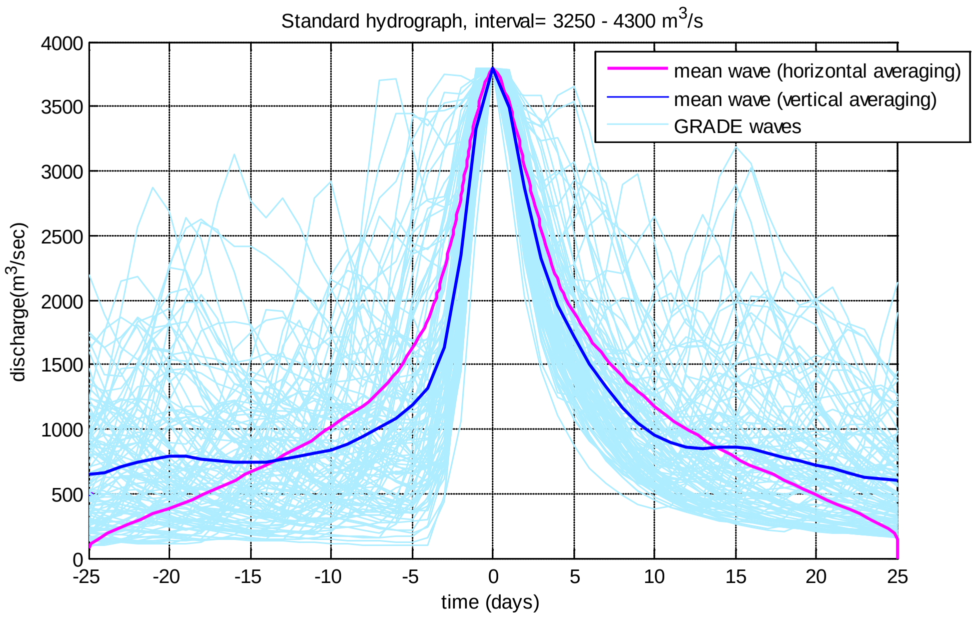

Figure 3-5: Mean hydrograph for discharge interval 3250-4300 m^3/s for horizontal and vertical averaging

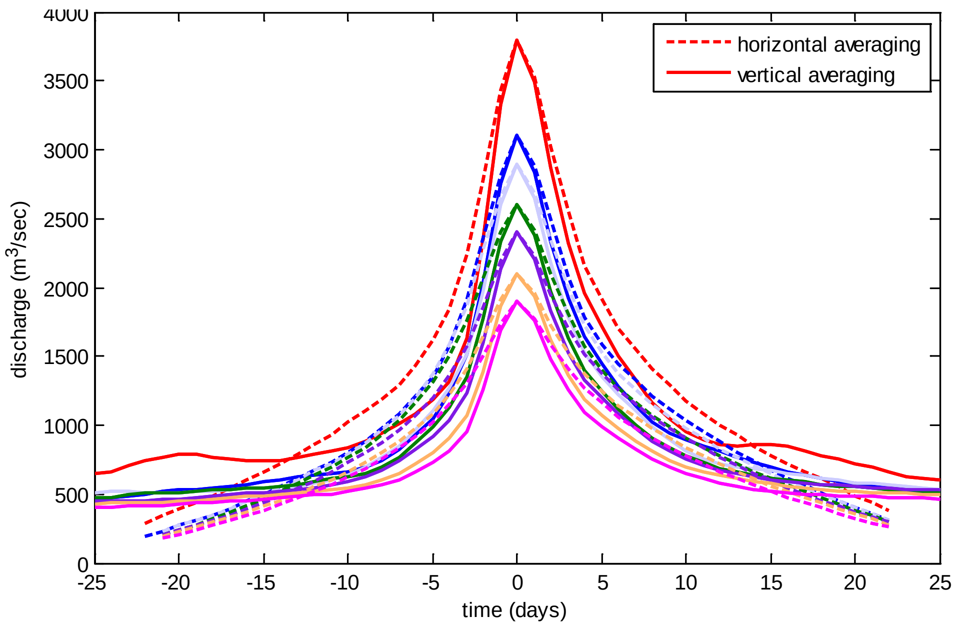

Figure 3-6: Mean hydrograph for all discharge classes and for horizontal and vertical averaging.

Disadvantages of horizontal averaging are:

- the rate of rise and fall is underestimated. An example is given in Figure 3-7. When a hydrograph has multiple peaks, the total time to the peak is defined as $dt_{rise1}+dt_{rise2}$ (see left panel). After horizontal averaging, this results in a different shape of the hydrograph (red line in right panel).
- the volumes appear to be incorrect. The change in rise and fallen of the hydrographs lead to overestimation of the volumes. The effect of the overestimation is shown in Figure 3-9 and Figure 3-10.

- sensitivity for choices of the peak selection window. The wider the section window is chosen, the more side peaks are taken into account, and the wider the design hydrograph.

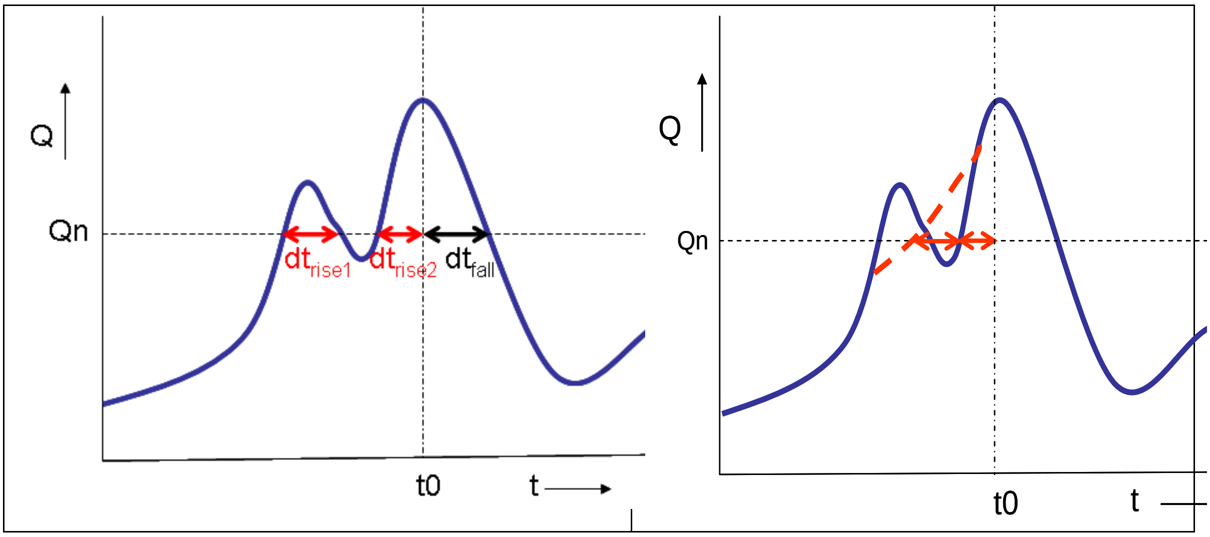

Figure 3-7: Left: schematized flood wave. Right: resulting hydrograph when using horizontal averaging.

When one is interested in the total exceedance of a certain discharge level, there is also a disadvantage with the vertical averaging method. When using horizontal averaging, all hours of exceedance of a certain discharge level are maintained, while this is not the case using vertical averaging. Geerse (2009) applied both methods on two storms. Figure 3-8 shows that the methods give different results if for example the level of v=0.7 is considered. In both storms together, the storm has 24 hours of exceedance, 18 hours in storm 1 and 6 hours in storm 2.

- When applying the horizontal averaging method, this means two times 12 hours of exceedance. This equals the 24 hours as mentioned before.
- When applying the vertical average method, the average exceedance duration is 9 hours. Two times this storm hydrograph means a total duration of 18 hours. The total amount of hours of exceedance is not equal to the total of 24 hours.

Generally the vertical averaging method will give a smaller hydrograph at the higher part of the storm when compared with horizontal averaging. In the lower part, the vertical averaging is broader.

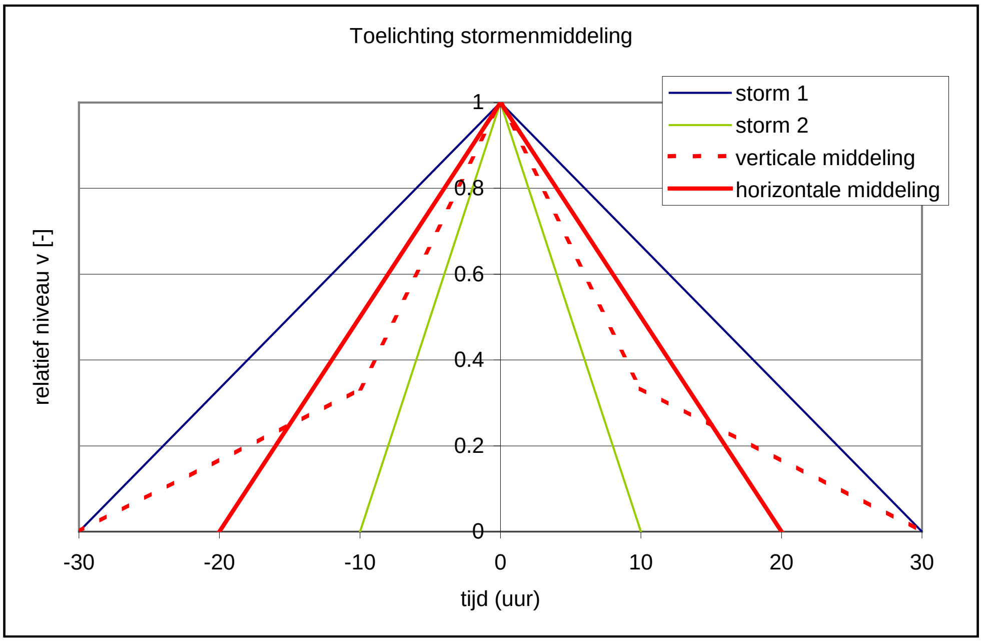

Figure 3-8 The two storms and the result of vertical and horizontal averaging (source: Geerse, 2009).

In this section it is shown that both methods have advantages and disadvantages. Since in this study the focus is on the failure mechanisms overflow and wave overtopping, the important factor is the height of the peak and the associated volume of the wave as this influences the height of the peak: a steep wave (small volume) has a large attenuation, this results in lower hydraulic loads downstream (e.g. for a sinusoidal wave the wave damping is proportional to the wave amplitude and inversely proportional to the square of the wave period). In order to check the volume of both methods, in Figure 3-9 and Figure 3-10 the volumes of the scaled hydrographs of Class 1 are calculated. We distinguish:

- median in combination with horizontal averaging (dark green bar and •);
- mean in combination with horizontal averaging (green bar and ○);
- median in combination with vertical averaging (light green bar and +);
- median in combination with vertical averaging (yellow bar and x).

The box-plot in Figure 3-9 gives information about the volume of the individual synthetic GRADE waves. The distributions of the volume of the individual synthetic GRADE waves are also shown in Figure 3-10 (blue line).

Both figures show that the median in combination with horizontal averaging overestimates the volume. The use of the mean and vertical averaging seems to give the best estimate of the average flood volume.

Since the vertical averaging method best preserves the flood volume, we recommend to use vertical averaging method in further analysis.

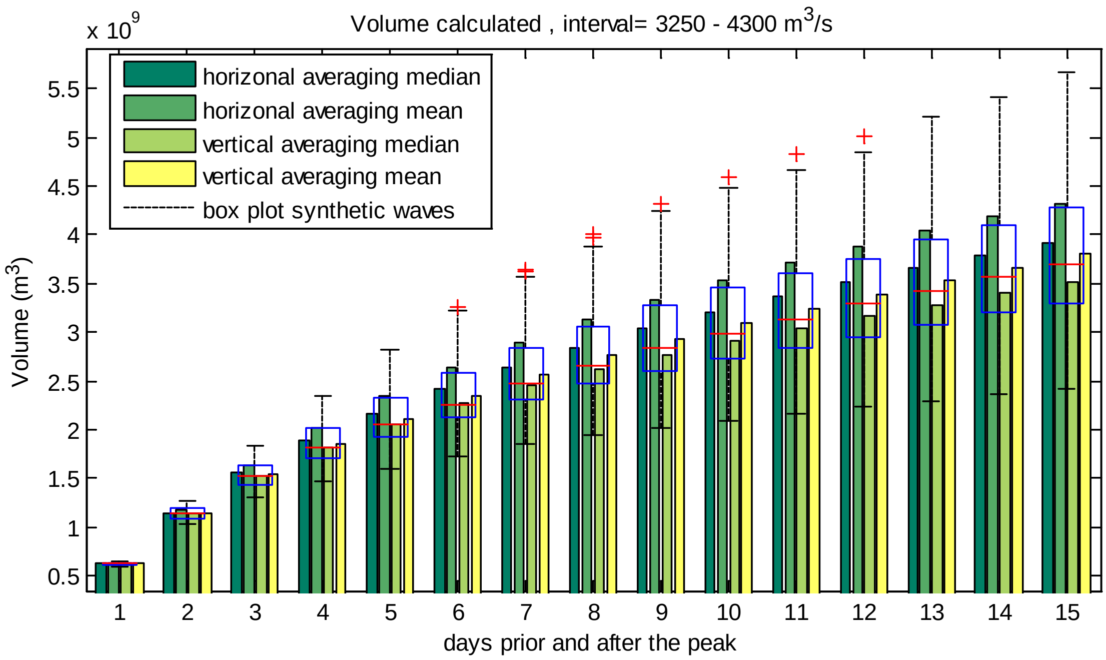

Figure 3-9 Volume of the hydrograph using different methods (horizontal vs vertical averaging and median vs mean) and discharges-waves in Class 1 (3250-4300 m³/s).

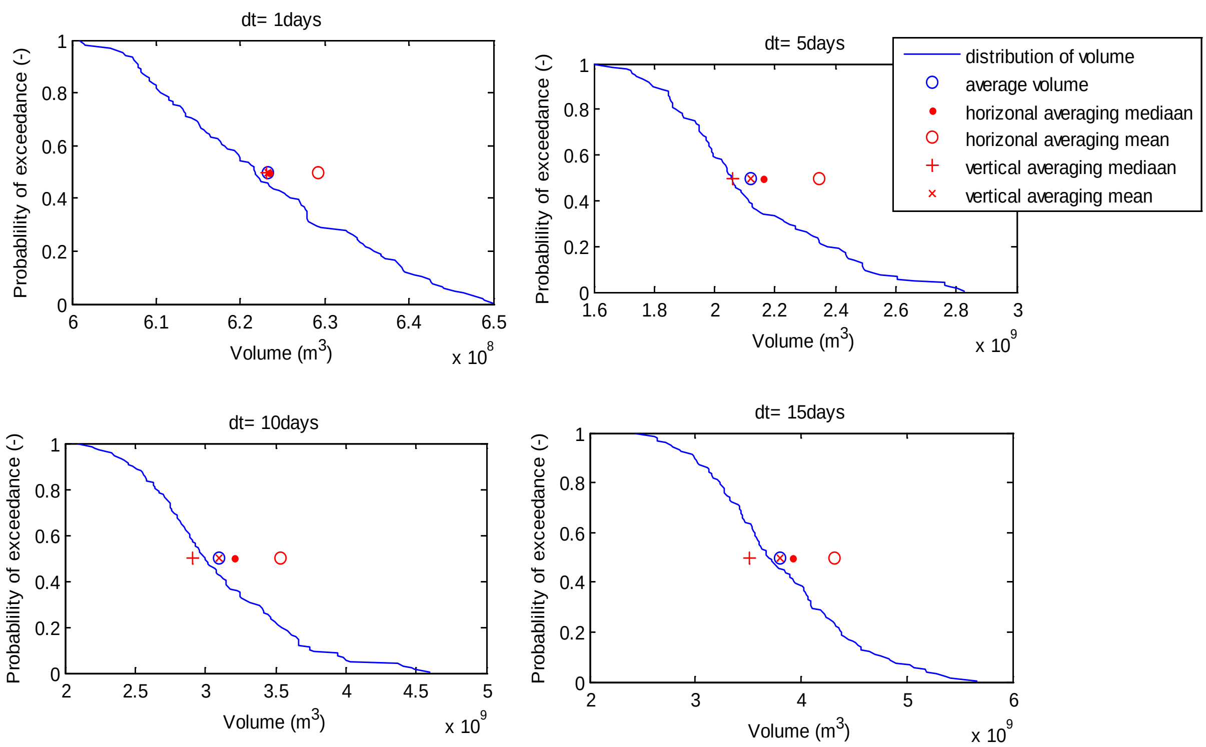

Figure 3-10 Flood volumes. The blue line gives the distribution of the volume for different days prior and after the peak (dt). For the analysis discharges-waves in Class 1 (3250-4300 m³/s) were used.

3.5 Distribution of the confidence interval

In the traditional method (horizontal averaging), the 95% confidence interval for the rising and falling limb is derived from the duration statistics at each threshold level assuming a log-normal distribution. In this section it is checked whether the confidence interval of the “vertical averaging method” is also log-normal distributed.

A first indication of a log-normal distribution is the skewness. Figure 3-11 shows the percentiles using vertical averaging. Since the distance between the 5 and 50%-line is much smaller than the distance between 50 and 95%-line, this indicates that the distribution of the discharge per time step is positively skewed.

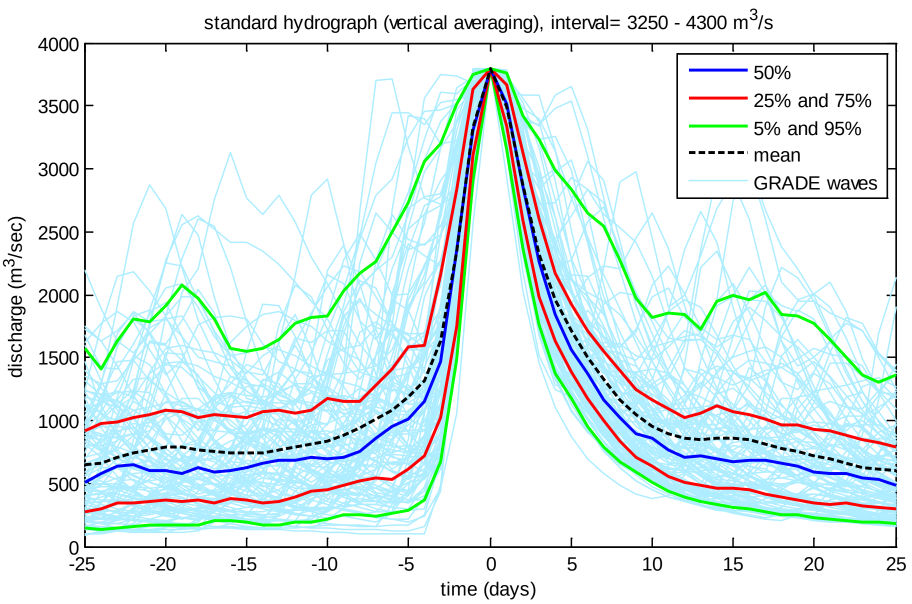

Figure 3-11 Hydrograph for discharge interval 3250-4300 m^3/s using ***vertical averaging***..

Figure 3-12 shows a log normality test. A distribution is log-normal when a logarithm of the discharge plotted on a linear scale of the reduced normal variate (Ambramowitz et al,1964) gives a straight line (Hydrology Project Operation Manual, 2003). The figures show that for all time steps, the plotted line is straight, so the 95% confidence values are log-normal distributed. In Figure 3-13 it can also be seen that the log-normal distribution gives a good approximation. For several time steps a log-fit is plotted over the distribution of the discharge.

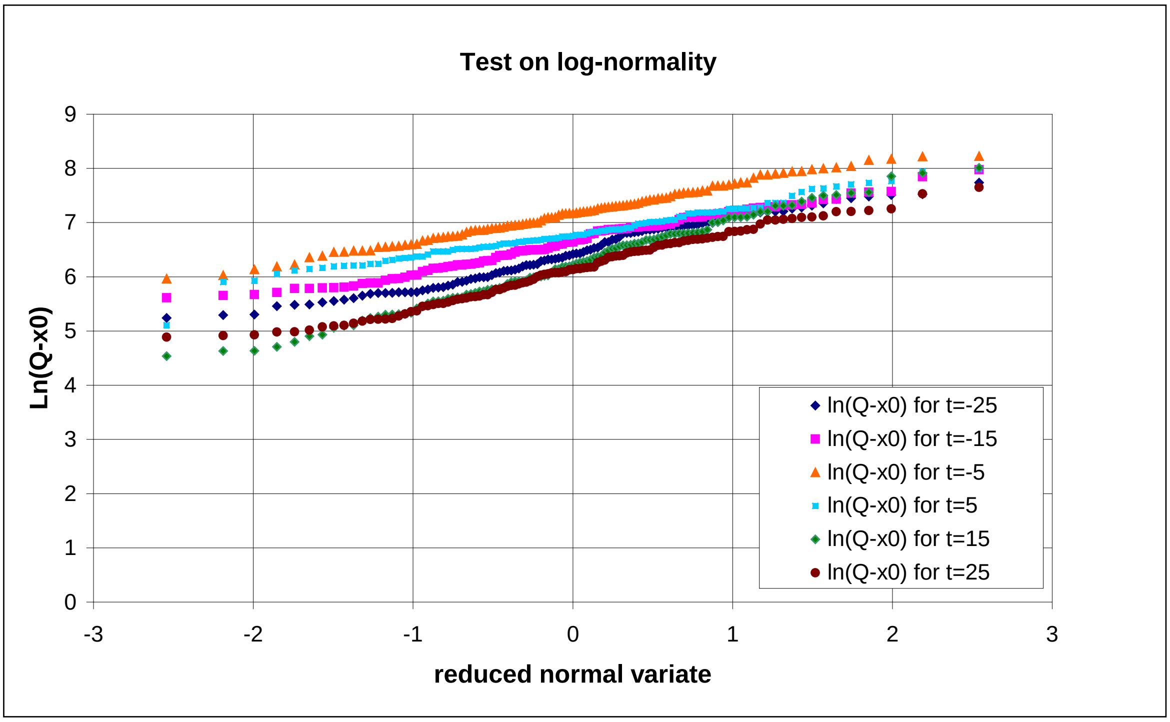

Figure 3-12 Test on log-normality of the discharge for different time steps and waves in class 1 (3250-4300 m^3/s).

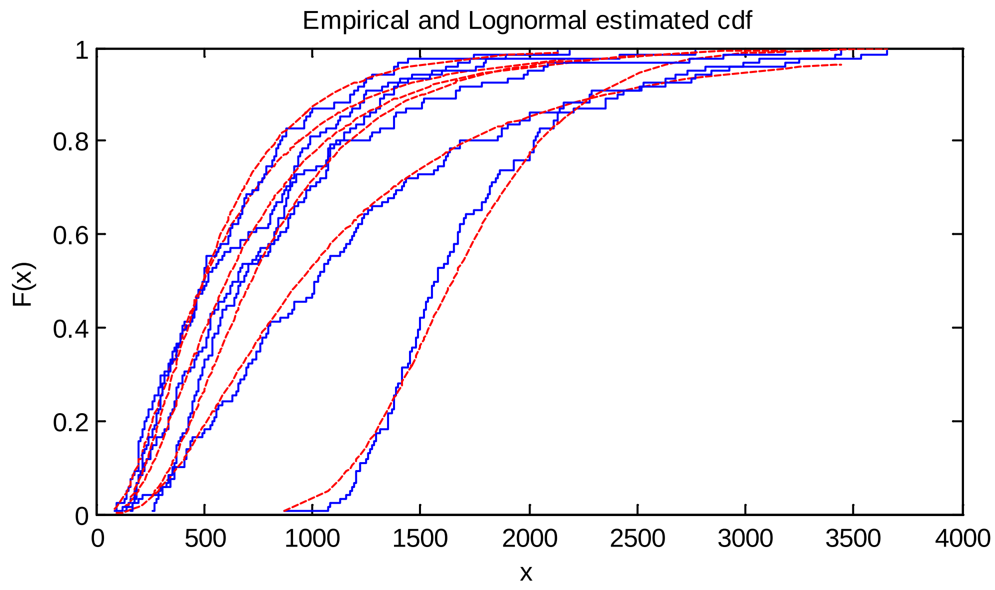

Figure 3-13 Log-normal distribution fit (red dashed lines) over the discharge for the time steps -25, -15,-5,+5,+15 and +25 days.

The results in this section show that when using “vertical averaging”, the 95% confidence interval can be approached by a log-normal distribution. In Figure 3-14 the confidence interval is compared to the interval when using percentiles. The difference is small. The advantage of the use of the log-normal distribution is that the interval is smoother. For further analysis we recommended to use a log-normal distribution to define confidence intervals.

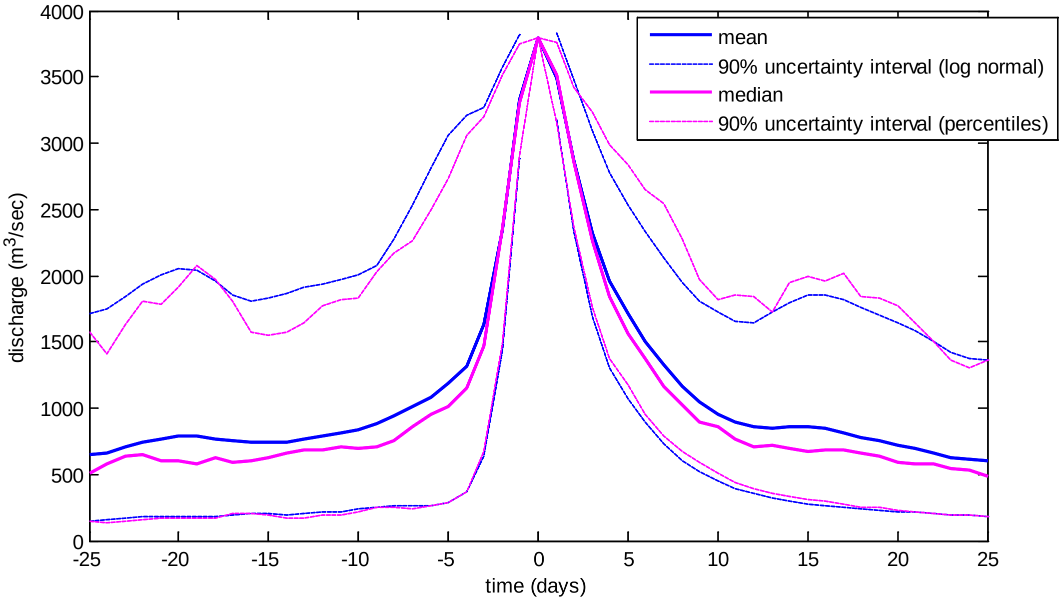

Figure 3-14 90-uncertainty interval of the hydrograph, the hydrograph is calculated by vertical averaging of discharges-waves in Class 1 (3250-4300 m^3/s).

3.6 Mean discharge hydrograph

In section 3.4 it was shown that the distribution of the confidence interval for the different time steps is mostly positively skewed. Because of the non-zero skewness, the median will not be equal to the mean (see also Figure 3-4). Section 3.4 also shows that the average volumes of the hydrograph are approached best by using the mean. Secondly, the median gives a smaller hydrograph than the mean. For the failure mechanisms overflow and wave overtopping the load of a wider hydrograph is heavier than the load of a small hydrograph due to peak redundancy. In order to be on the safe side in further analysis, it is recommended to use the mean to determine the design hydrograph. For the stability failure mechanisms further research has to be carried out to determine which hydrograph will be normative.

3.7 Daily to hourly data

In the currently used wave generator based procedure (Wijbenga, et al.,2004), a majority of the hydrographs is based on daily average discharges, which are disaggregated to hourly values by linear interpolation. This leads to an unrealistically sharp peak. In order to compensate for this, the duration of the top is adjusted by raising the discharge for water levels ≤1 cm under the top to the peak value and correcting the rising and falling limbs accordingly.

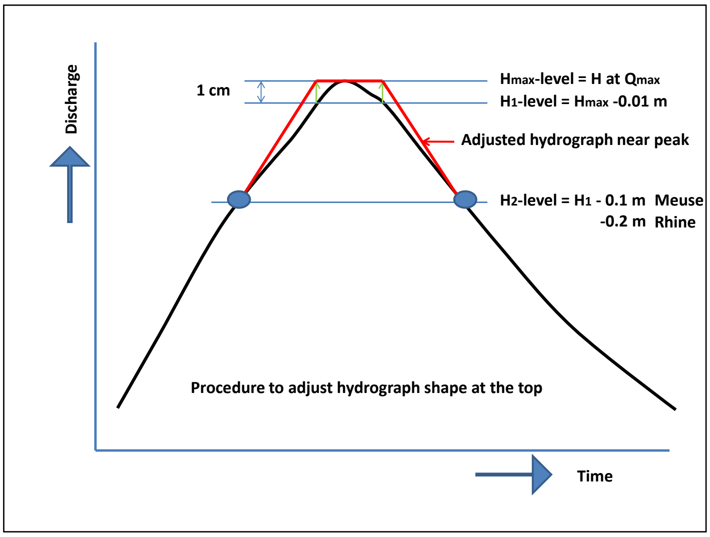

Figure 3-15 adjusting the peak of a hydrograph in order to translate daily to hourly values.

The output of GRADE also gives daily data. However, it is not advised to use the method proposed in Wijbenga et al. (2004), since this method seems little founded and the adaptation of the water level at one centimetre is even smaller than the measurement uncertainty.

An alternative method to translate daily to hourly values is to use a “spline”-function. In Figure 3-16 an example is given. Instead of using interpolation between two successive discharge values (orange line), a more smooth function is used. For some cases this results in an increase of the peak value (left example), but not for all (see right example). This is comparable with the natural behaviour.

A second alternative method is to analyse the peak duration of measured waves, and adjust the peak duration accordingly. It is only necessarily to change the peak of the wave when this is relevant for the failure mechanism of interest (for design water level computation the hydrograph shape near the peak is of importance). The analysis of the peak duration is not part of the current study.

For further analysis we recommended to use the “spline” function. The disadvantage of the analysis using measured waves is the use of two sources of information, an approach that should be avoided.

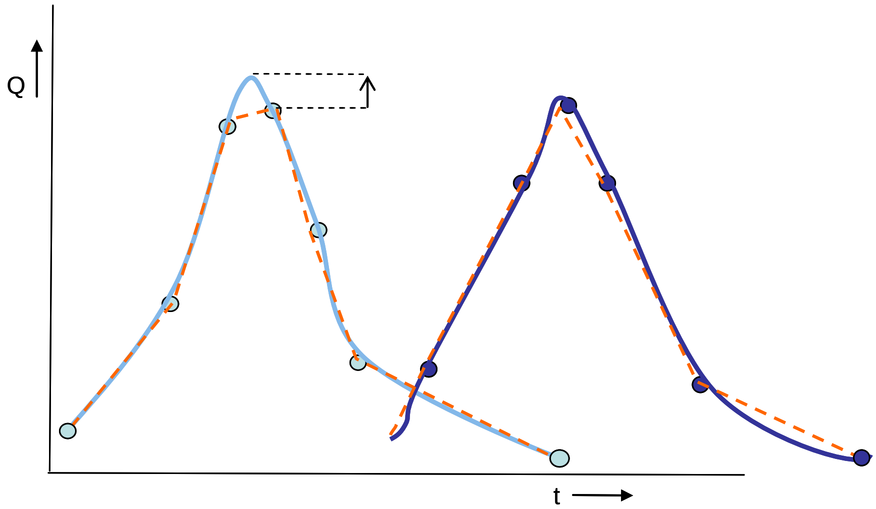

Figure 3-16 Spline function, the orange dotted lines gives normal extrapolation.

Note:
In Deltares (2008b) it was found that the most reliable method to calculate hourly peak values is to multiply the daily peak values by 1.01 and add 80 m^3/s. However, since for the discharge hydrograph especially the shape and not the peak-value is important, adaptation of the peak-value is not necessary.

4 Results

4.1 Method

The results of the analysis in chapter 3 leads to the following procedure to define the design hydrograph for different discharge classes and the failure mechanisms overflow and wave overtopping:

1. Generate e.g. 20.000 year discharge series using the GRADE instrument;
2. Select waves per discharge class based on annual maxima;
3. Scale all waves to the design discharge per class.
4. Determine the design hydrograph using the mean of the vertical averaging method.
5. Determine the confidence interval using the log-normal distribution;
6. Change the peak duration of the hydrograph using the “spline” function.

4.2 Results river Meuse at Borgharen

Figure 4-1 shows the results for the river Meuse at Borgharen for different intervals. In Figure 4-2 the results are compared with the design hydrograph of HR2001 and HR2006. As expected the wave is narrower than the HR2001 and HR2006 line, because of the use of the vertical averaging method.

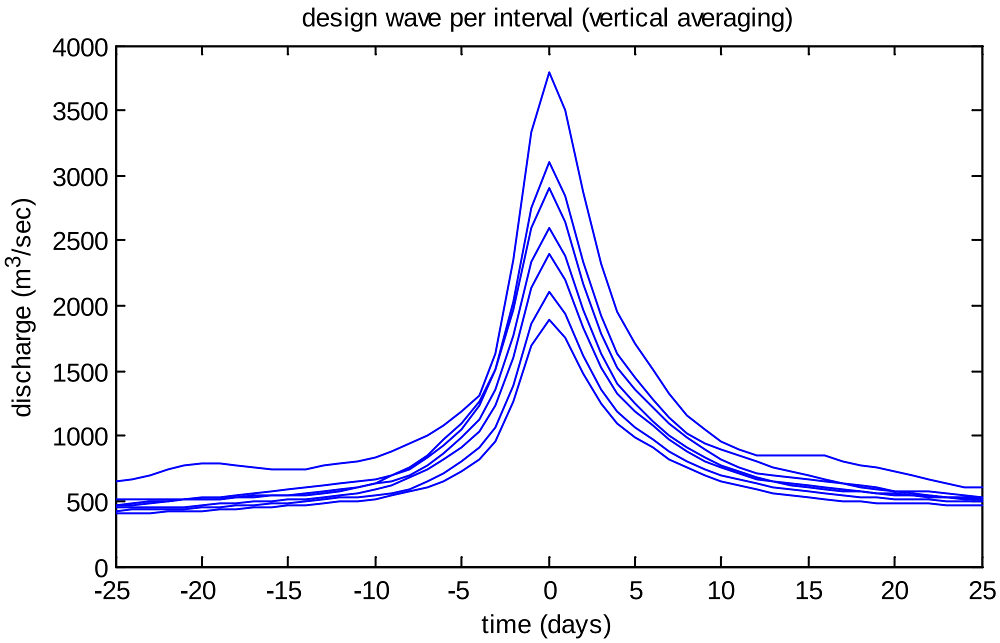

Figure 4-1: design wave for the river Meuse at Borgharen per discharge- interval.

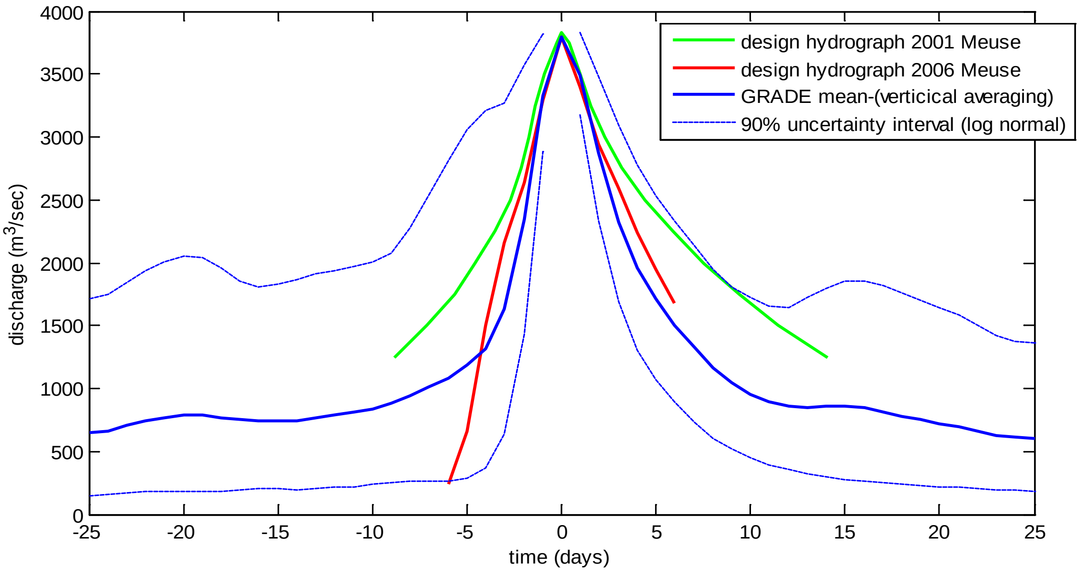

Figure 4-2 1/1250 year design hydrograph for the river Meuse at Borgharen.

4.3 Hydrograph in WTI 2017

As described in section 1.2, the hydrograph is used as upstream boundary condition in the hydraulic SOBEK/WAQUA models and for the determination of the trapezium.

The hydrographs generated by the newly proposed method can be applied directly as an input to WAQUA and SOBEK.

The trapezium for the discharge is used in the probabilistic instruments Hydra-Zoet and Hydra-Ring to take into account the time-aspect. The trapezium for the discharge is schematized by four aspects: the peak, the top duration, the base duration and potential also a restriction factor (in Dutch: insnoeringsfactor) (Figure 4-3). The determination of these four variables is not part of this study.

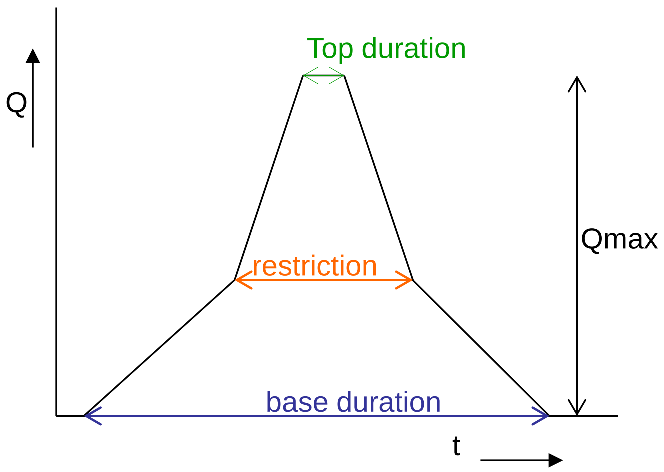

Figure 4-3 Trapezium of the discharge

5 Conclusion and recommendations

5.1 Conclusions

This report proposes a procedure to derive the shape of the design discharge hydrograph and the accompanying uncertainty width using the synthetic GRADE discharge series for the river Meuse at Borgharen. The focus is placed on the derivation of a design hydrograph for the failure mechanisms overflow and overtopping. The procedure consists of the following steps:

1. Generate e.g., 20.000 year discharge series using the GRADE instrument;
2. Select waves per discharge class based on annual maxima;
3. Scale all waves to the design discharge per class.
4. Determine the design hydrograph per class using the mean of the vertical averaging method.
5. Determine the confidence interval per class using the log-normal distribution;
6. Change the peak duration of the hydrograph using the “spline” function

5.2 Recommendations

The new proposed method will be evaluated by the project WTI2017, where the hydrograph is used as input for the assessment of the Dutch primary flood defences. Next year, the procedure will be improved. For next years analyses it is recommended to:

- Apply the method using discharge series of the Rhine at Lobith.
- In this analysis we mainly focussed on the failure mechanisms overflow and wave overtopping. It is recommended to pay also attention to the determination of the normative hydrograph for other failure mechanisms in a future study.
- In this analysis the volume of the flood wave was chosen as one of the selection criteria. It is recommended to analysis the effect of the volume of a flood wave on the hydraulic boundary conditions downstream.

In order to apply the hydrograph in the Hydra calculation, the hydrograph need to be schematized by four aspects: the peak, the top duration, the base duration and potential also a restriction factor (in Dutch: insnoeringsfactor). This step has not been investigated in this study.

6 References

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