enw | expertisenetwerk waterveiligheid

# Is there a maximum discharge for the Rhine at Lobith?

March 2017



## Summary

Is there an upper limit to the discharge of the Rhine river at Lobith, which cannot be exceeded even under extreme conditions? The Delta Programme is based on an upper limit to the discharge of the Rhine at Lobith. Recent model studies conducted using the GRADE modelling system, which translates precipitation in the watershed into river flood levels, do not indicate a maximum discharge. An international group of experts claims that the modelling of floods in Germany is not entirely correct, and has concluded that there is in fact an upper limit (Hegnauer et. al., 2015a).

This memo deals with the modelling of floods in Germany in more detail, and comes to the conclusion that – within the reach of discharges at Andernach – there is in fact an upper limit to the discharge at Lobith, which is approximately 17,500 $m^3/s$. This value is consistent with the conclusions of the expert group (maximum of between 17,000 and 18,000 $m^3/s$), and considering the uncertain factors, it does not materially deviate from the limit of 18,000 $m^3/s$ used by the Delta Programme. The value of 17,500 $m^3/s$ is based on the situation in which the flood defences along the stretch between Wesel and Lobith have been reinforced in accordance with the plans, which at the current rate should be completed no later than 2025. A crucial factor in the existence of this maximum is the 'pressure valve action' provided by the dike rings 42 and 48, which will have to deal with large volumes of water under extreme discharge conditions at Wesel.

# 1 Introduction

The Rhine discharge at Lobith is an important input for the flood risk computations for the Netherlands. One question that regularly arises is whether the discharge is subject to a maximum level (sometimes referred to as a 'physical maximum' or 'hydraulic maximum'), with the logical follow-up question of what this maximum level is, exactly, and why the discharge cannot exceed it. In order to provide a meaningful recommendation, the ENW requires insight into the manner in which high water levels in the Rhine watershed occur, and what happens to the water along its course to Lobith. Studies using the GRADE modelling system, with current climate conditions (Hegnauer et. al., 2014), as well as the effects of climate change, have provided important material for this consideration. An expert discussion organised by Deltares (Hegnauer et. al., 2015a) has also provided a major contribution to this insight. Nevertheless, several open questions remain, especially regarding the effects of flooding in Germany and the flow to the Waal along dike ring 42 and the IJssel along dike ring 48. In order to provide clarity about this situation, ENW has commissioned this study, which has been carried out by J. Pol (HKV) under the leadership of Prof. H.J. de Vriend (Chairperson of the ENW Working Group Rivers) and Prof. M. Kok (Chairperson of the ENW Working Group Safety), with support from M. Hegnauer (Deltares).

GRADE (Generator of Rainfall and Discharge Extremes) is a modelling system that consists of a precipitation generator, a hydrological model (HBV) and a hydraulic model (SOBEK). This system is used to study the probability of extreme discharges in the Rhine and Maas rivers, with or without the effects of climate change. The results of these exploratory studies and the expert discussion referred to above do not give cause to assume that the simulated precipitation and the discharge from the tributary watersheds are subject to a maximum. If there is in fact an upper limit to the Rhine discharge at Lobith, then it is related to the behaviour of the flood wave in the Rhine itself (hence the term 'hydraulic maximum'), and the height of the flood protection works in the watershed (hence the term 'physical maximum'). This memo therefore deals with aspects of the hydraulic model (including the height of the flood protection measures), which could influence the maximum discharge at Lobith, with special attention to the effects of flooding along the various stretches of the Rhine.

In illustration: the Delta Programme assumes that there is an upper limit to the discharge of the Rhine at Lobith, which is 18,000 $m^3/s$. Computations using the GRADE modelling system (Hegnauer et. al., 2014) using the current climate conditions show that even with extremely unlikely probabilities of occurrence ($10^{-5}$), this value cannot be reached, but also that the resulting line does not tend to a finite upper limit (see also ENW recommendation 'GRADE and discharge statistics', d.d. 1 May 2015). This is even stronger if effects of climate change are included in the computations. Figure 1 shows the discharge according to GRADE as a function of return period: the white lines are without correction, and the coloured lines are with a correction assuming a maximum discharge of 18,000 $m^3/s$ at Lobith. Doubts about how GRADE deals with floods, especially at dike rings 42 and 48, justify a closer study of the effects of such flooding, and the question of whether there is in fact an upper limit to the Rhine discharge at Lobith.

**Figure 1** KNMI'14 climate scenario GH for 2050 (Hegnauer et al., 2015a)

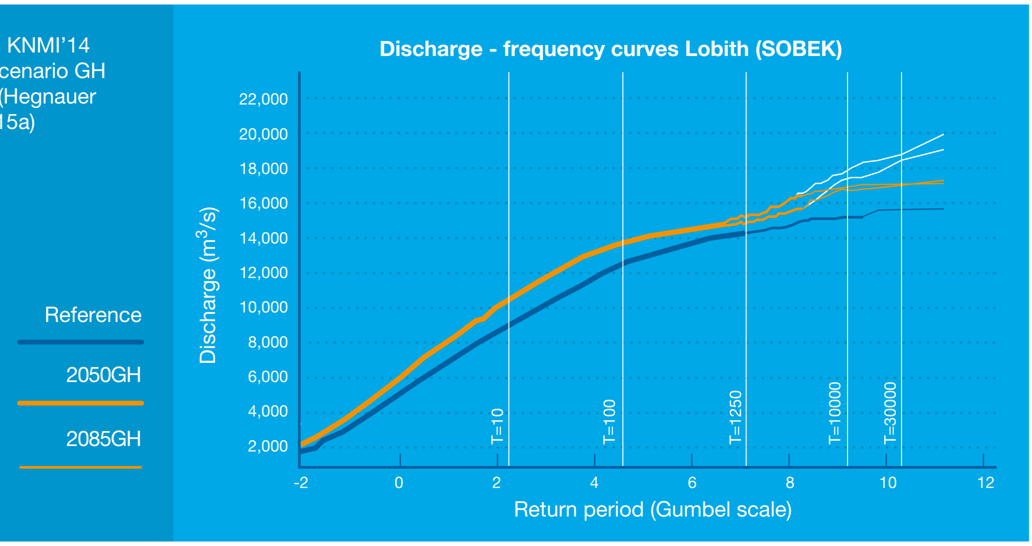
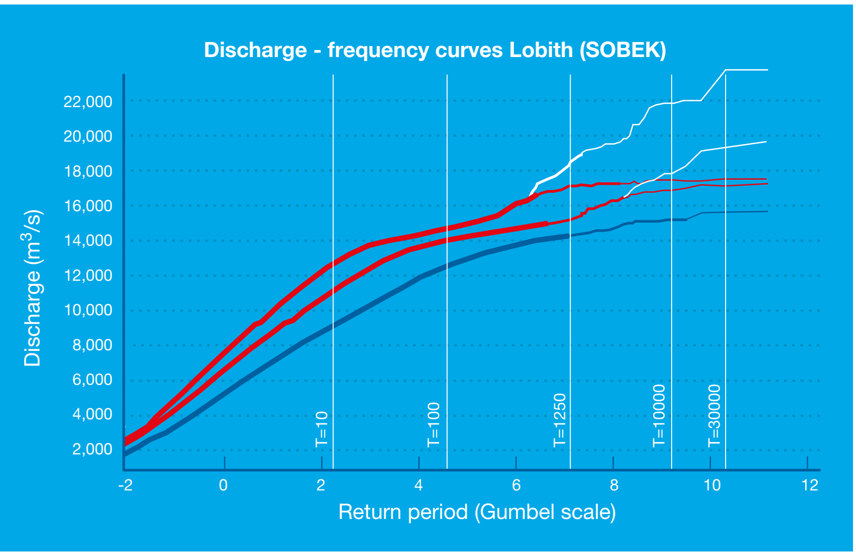


**Figure 1** KNMI'14 climate scenario WH for 2050 (Hegnauer et al., 2015a)




This memo deals with the various stretches of the Rhine (Figure 2). Each paragraph provides a description of the section, the modelling of floods in GRADE and a reflection on the assumptions made and their effects on the resulting discharges. It will conclude with a paragraph dealing with other points of concern, and the most important conclusions regarding a possible upper limit to the discharge at Lobith.


**Figure 2** Overview of the Rhine watershed (source: http://www.lanuv.nrw.de/veroeffentlichungen/sondersam/hochwa/hochwa_s18.pdf)

# 2 Oberrhein between Basel and Maxau

At Basel, the Rhine changes from a steep mountain stream into a slightly incised river in a wide valley, with some areas protected by dikes. The section between Basel (Rhine-km 160) and Maxau (Rhine-km 360) is not yet included in the SOBEK models, but flood wave propagation has been modelled using hydrological Muskingum routing. This propagation is determined by calculating the runtime (K) and the attenuation rate (x) in five sections of the river between Basel and Maxau. GRADE uses K=0.3 days and x=0.2 (Hegnauer, 2015b) for each section. This method does not take flooding into consideration. The results have not been validated with a more advanced hydraulic model such as SOBEK or a 2D model.

Floods play a limited role here for discharges up to approx. 6,000 $m^3/s$. This appears from charts of water depths for an average return period of approximately 200 years, i.e. a peak discharge of 6,000 $m^3/s$ (IKSR, 2015). The Muskingum method seems sufficient for modelling discharges up to that level. GRADE has much higher flow rates, up to 10,000 $m^3/s$ at Maxau, which would result in much higher water levels than for 6,000 $m^3/s$. An analysis of an elevation model shows that the valley includes some low-lying areas (Figure 3). In the event of such high water levels, these areas would probably flood, which would reduce the peak discharge at Maxau. This analysis is based on a fairly inaccurate elevation model, without taking into account the volumes of the areas or the time evolution of the lateral flow to those areas. This makes it difficult to precisely quantify the effect on the discharge. However, the reduction in peak discharge is expected to be relatively minor compared to the effects of floodings further downstream.

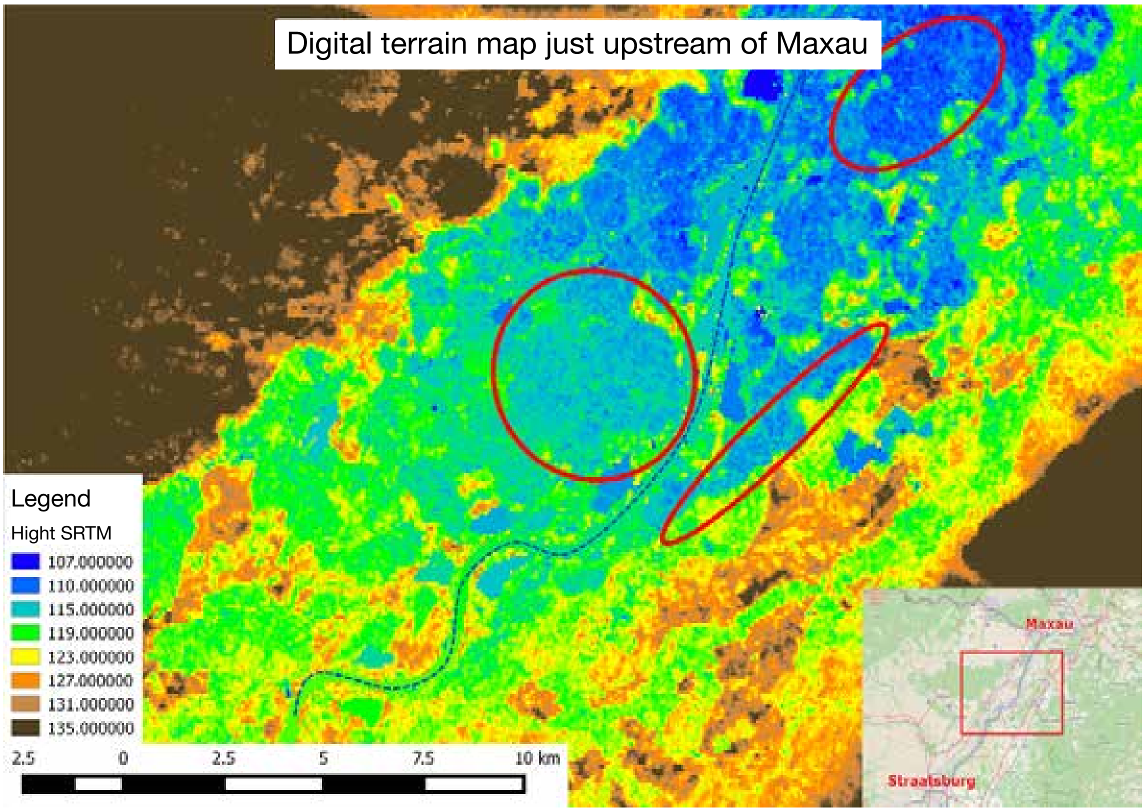



**Figure 3** Digital terrain map just upstream of Maxau, from SRTM data, 30 m resolution, no correction for vegetation or buildings (http://www.opendem.info/download_srtm.html)

# 3 Oberrhein between Maxau and Kaub

The river valley between Maxau and Kaub (Rhine-km 540) is relatively flat, with large areas behind the dikes that could be inundated if the dikes break or overflow. Important tributaries include Neckar, Main and Nahe. From Maxau, GRADE uses the 1D SOBEK model, in which flood areas are modelled using ‘basins’: areas adjacent to the river with a fixed surface area, where water can flow in and out via intakes. Information about the surface area, the average elevation and the maximum volume of water that can be stored in these areas was provided by German government agencies (Barneveld, 2011). The assumption is that the areas will be inundated when the water level reaches the local design discharge +500 $m^3/s$ (the design discharge at Maxau is approx. 5,000 $m^3/s$), and over a width of 10% of the dike length along the course. Once the maximum volume of the polder has been reached, the SOBEK model shuts the intake and the water level in the area no longer matches that of the river. For this maximum volume value, the model has chosen 50% of the potential volume, on the one hand because the entire area cannot be filled due to slanting elevations, and on the other because part of the water behind the dike will flow back to the river. The manner in which the potential flood volume is determined, as well as the level of accuracy of that calculation, differs per federal state (Figures 4 and 5). In Baden-Württemberg, the volume has been calculated relatively accurately with a stationary discharge of 5,000 $m^3/s$ in an operational 2D model. In Rheinland-Pfalz, the volume has been calculated using a GIS analysis. The method used for this calculation is not known, but the form of several areas does not seem to correspond to what can be expected based on the elevation model and the water depth charts produced by IKSR. This suggests a less accurate determination or a compensation of other effects. The method for determining the surface areas and volumes in the federal state of Hessen is not known.

The flooding areas were dimensioned in SOBEK based on the local design conditions (5,000 - 6,000 $m^3/s$). In the event of extreme flow rates (from approx. 8,000 $m^3/s$), the prescribed maximum volume will be reached and the intakes will be closed before the peak discharge occurs. If the intakes are not closed, more water could be stored in these areas as the water level rises. Calculations using a specific flood wave show that in this case an extra reduction in peak discharge of up to 1,000 $m^3/s$ could be attained (Barneveld, 2011), although this could vary depending on the form of the wave. In the event of these flood levels, all of the dikes would overflow, but this extra storage is not included in the model.

Closing the intake earlier, taking 50% of the volume, assuming overflow over 10% of the dike length and neglecting the increasing flood volume in the event of increasing water levels all create uncertainties in the estimated flood volumes under extreme discharge conditions. The extent to which the schematic representation of the floodplains is representative of reality can only be validated with a 2D model based on an accurate elevation model. This makes it difficult to quantify the effect on the discharges along this stretch of the river. However, an overestimation of the peak discharge in the order of magnitude of 1,000 $m^2/s$ for the highest floods does not seem unrealistic.

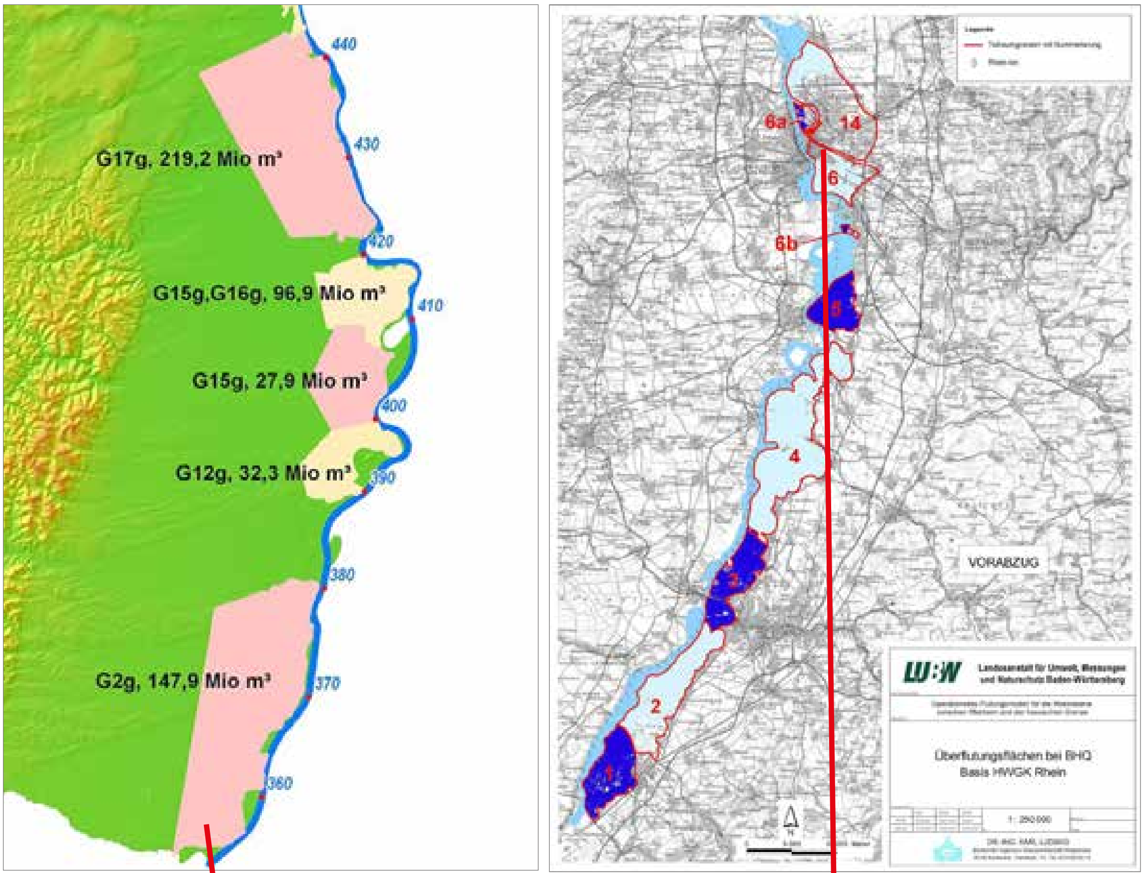



**Figure 4** Flood storage areas in Rhineland-Pfalz (left) and Baden-Württemberg (right) as provided by the government agencies. Barneveld (2011)

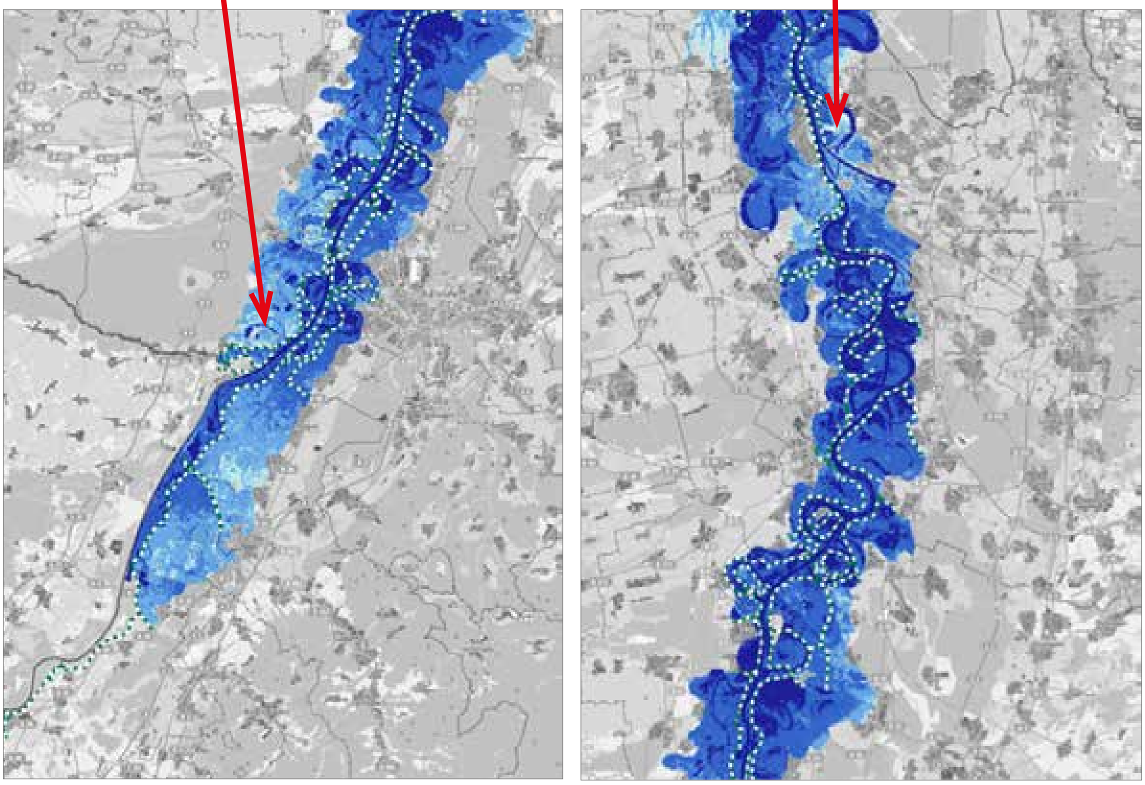


**Figure 5** Flood prone areas from IKSR maps around Speyer (left) and Karlsruhe (right). IKSR (2015)

# 4 Middle Rhine between Kaub and Bonn

Between Kaub and Bonn (Rhine-km 655), the Rhine flows through a deep, narrow valley. Only the area between Koblenz and Andernach, after the confluence with the Moselle, is somewhat flat. Due to the limited surface area of this flat region, we can assume that flooding does not play an important role at this location. There is also little room for flooding along the Moselle and Lahn tributaries, which make significant contributions to the Rhine discharge.

# 5 Lower Rhine between Bonn and Wesel

Between Bonn and Lobith (Rhine-km 862), there are large flood prone areas behind the dikes along the river. The discharge from tributaries such as the Ruhr and the Lippe is relatively limited, as they together contribute approx. 1,000 $m^3/s$ during even the most extreme floodevents. The protection level in this region ranges from 1/200 between Bonn and Düsseldorf, up to 1/500 between Düsseldorf and the Dutch border.

The floodplains between Bonn and Wesel have been modelled in SOBEK as basins and bypasses, but in this section the flow to and from the areas is regulated based on 2D calculations using Delft-FLS (Lammersen, 2004; Gudden, 2004; van der Veen et al., 2004) and WAQUA (Brinkmann, 2011) for discharge waves of 16.000 $m^3/s$ and 17.800 $m^3/s$ at Andernach. An important floodplain along this stretch of the river is the mining subsidence area between Düsseldorf and Wesel. In SOBEK, this region has a surface area of 69 $km^2$, and can provide a reduction in flow rates of 1,000 - 3,000 $m^3/s$ for discharge waves of 15,000 - 18,000 $m^3/s$. However, the highest waves in GRADE show that the area will be full before the maximum discharge is reached. Hence there will be almost no effect on the peak discharge downstream from this area, which can reach values up to 24,000 $m^3/s$.

Up to discharges of 17,800 $m^3/s$ at Andernach (approx 17,000 $m^3/s$ at Lobith), the SOBEK model largely corresponds with the WAQUA model, but for higher discharges of 19,000 and 20,000 $m^3/s$ at Andernach, SOBEK produces higher values for the discharge at Lobith (Vieira da Silva et al., 2013). At these higher flow rates, more areas between Düsseldorf and Wesel would be flooded. As the calculations in SOBEK based on WAQUA only uses waves of up to 17,800 $m^3/s$, these flooding areas are not included in SOBEK, although they do provide an additional reduction of the peak discharge. In WAQUA, the waves of 19,000 and 20,000 $m^3/s$ both produce a discharge of approx. 18,000 $m^3/s$ at Lobith, which corresponds to a discharge of 18,500 $m^3/s$ at Wesel. The study does not indicate the extent to which this reduction continues at higher discharge rates. The WAQUA calculations were also conducted using discharge waves with a standard form, so they offer no insight into the peak discharge reduction for more complex flood waves like those calculated in SOBEK.

In order to be able to make a prognosis about how the reduction continues at higher flow rates, an exploratory computation has been conducted in the WAQUA model using a wave of 24,000 $m^3/s$ at Andernach. This model used the schematization including dike breaching from Paarlberg (2014).
The discharge at Andernach was replaced by the higher wave from GRADE (Figure 7), but for practical reasons the laterals were kept the same as those of the '20s' wave (narrow 20,000 $m^3/s$ wave) from Paarlberg (2014). Figure 6 shows that the flooded area continues to increase compared to the computations using the 20,000 $m^3/s$ wave. At certain locations, the water even approaches the model boundaries, which means that the effect of flooding on the discharge in these locations may be underestimated. However, for this wave the discharge is no longer limited to 18,000 $m^3/s$, but rather increases to 22,200 $m^3/s$ at Lobith (22,700 $m^3/s$ at Wesel) (Figures 7 and 8). Note, however, that the WAQUA model calculates almost no flooding along the course of the river between Wesel and Lobith, because the areas protected by dike rings 42 and 48 there are not included as flooding areas in the model. The computed discharges for this stretch of the river are therefore not representative (see also point 6).

Flooding between Bonn and Wesel has a clear effect on peak discharges, especially around 16,000 $m^3/s$, but the most extreme waves in GRADE will fill most of the flooding areas before the peak discharge is reached. As a result, in the event of a 24,000 $m^3/s$ wave at Andernach, the discharge may reach 22,000 - 23,000 $m^3/s$ at Wesel.

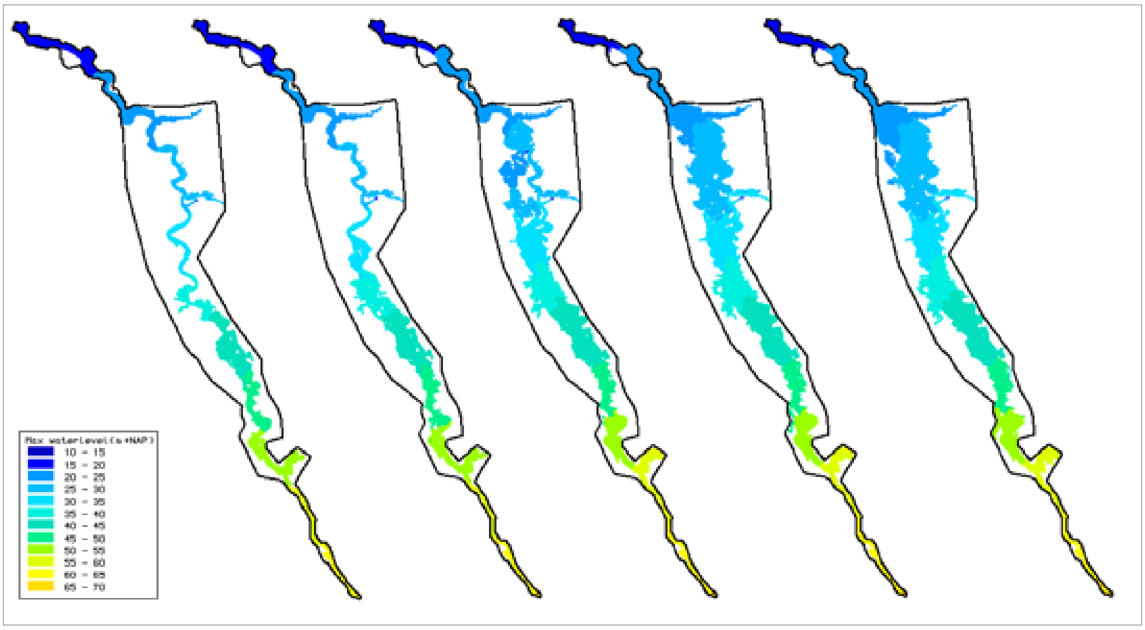



**Figure 6** Flooded areas at peak discharges of (from left to right) 14,406 m³/s, 15,323 m³/s, 17,822 m³/s, 19,000 m³/s and 20,000 m³/s at Andernach (source: Vieira da Silva et al., 2013). Supplemented with results from the 24,000 m³/s wave described above (far right).

**Figure 7** Discharges from the supplemental computation with WAQUA-Niederrhein for 24,000 m³/s at Andernach (blue line). Peak discharge at Wesel = 22,750 m³/s (green) and at Lobith = 22,150 m³/s (white)

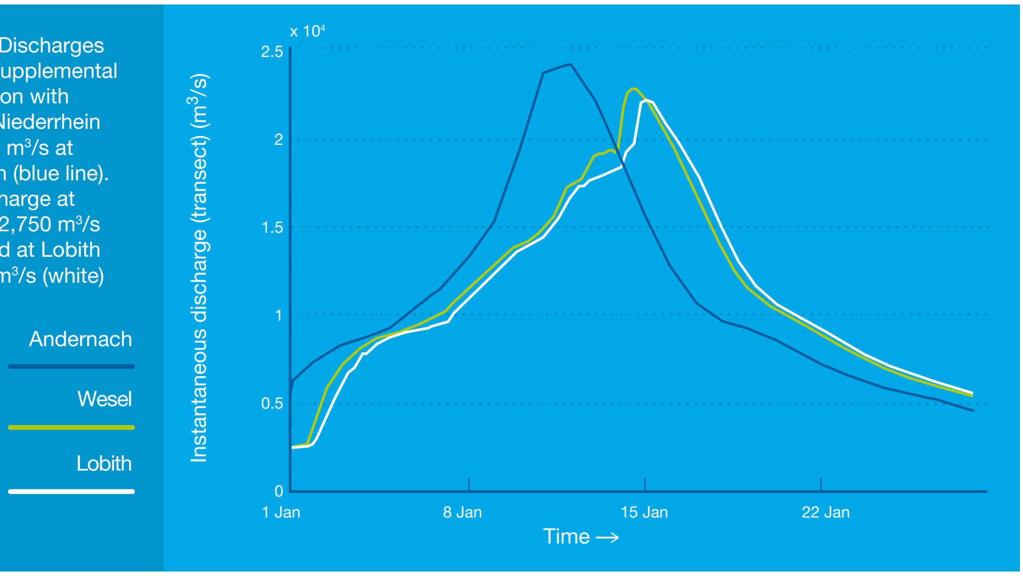
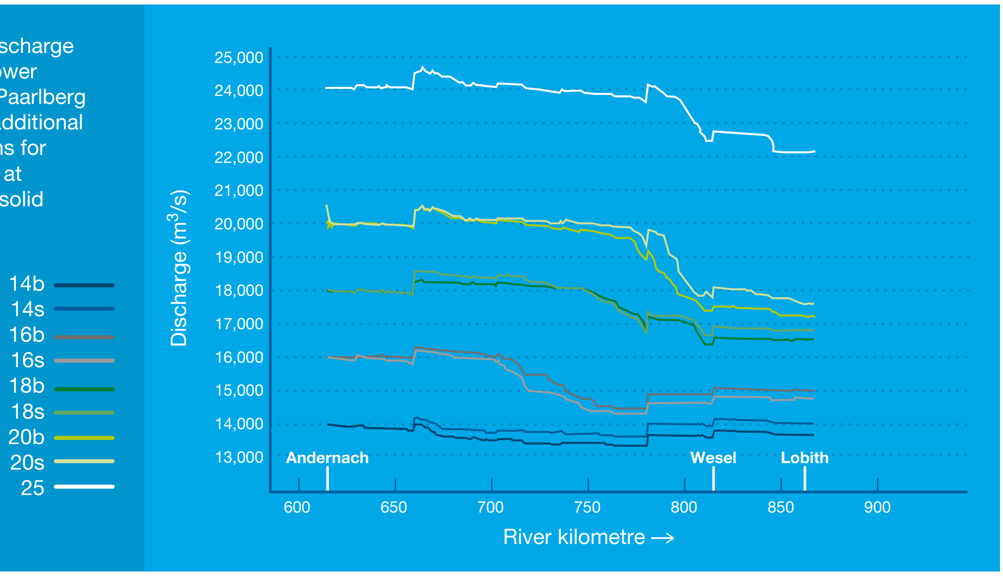



**Figure 8** Discharge along the Lower Rhine from Paarlberg (2014) and additional computations for 24,000 m³/s at Andernach (solid white line)



# 6 Lower Rhine between Wesel and Lobith

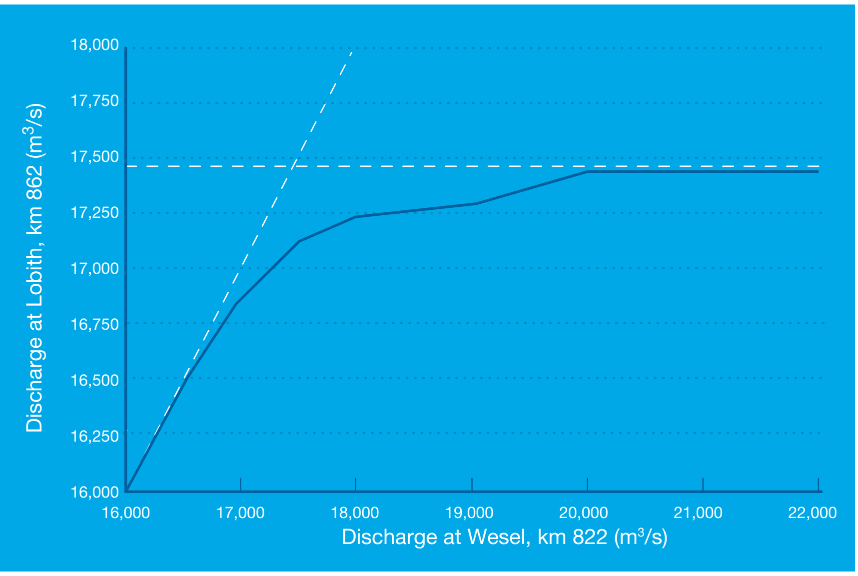
Between Wesel and Lobith, two flooding areas were included in the SOBEK model: the border dike rings 42 (left bank) and 48 (right bank) The first is modelled as a basin with a surface area of 174 km², and an intake width of 200 m. At the highest waves in GRADE, the water level in the basin of dike ring 42 will rise to a maximum of one meter, but the flow of 700 m³/s through the intake is not enough to completely cap the wave. For discharges up to 5,000 m³/s over the conveyance capacity (the discharge at which the dikes just do not overflow), it is unrealistic to assume that the dikes will only flood over a width of 200 meters. The water will flow over a much longer stretch of the dike (if the dike does not fail), which will result in a much larger lateral outflow from the river. Floods on the right bank (floodprotection wall in Emmerich) have been modelled in SOBEK as a water level-dependent lateral outflow of 0-60 m³/s. This outflow does not seem realistic in the event of the extreme discharges mentioned above, along a 2-km floodprotection wall and a crest height of 0.5-0.8 m under the neighbouring dikes. The calculations described below show that the outflow over the wall will rather be in the range of 600 m³/s.

The WAQUA model of the Lower Rhine does not include areas protected by dikes downstream from Wesel. In order to make a more accurate estimate of the development of the discharge between Wesel and Lobith, a highly simplified calculation model has been conducted based on the crest heights and the WAQUA computations from Paarlberg (2014). Appendix B provides a brief description of the analysis. The results show that the dikes along this stretch of the river will begin to overflow at flow rates of 16,500 m³/s. This corresponds to the estimate by Lammersen (2004). As discharge increases, a longer section of the dike will overflow. With the assumption that the volume of the flooded area is not a limiting factor (large dike rings and the water can drain off to the Achterhoek region, for example), then the projected maximum discharge at Lobith is 17,500 m³/s. In order to attain this 17,500 m³/s, approximately 18,000 - 20,000 m³/s is needed at Wesel (km 822) (Figures 9 and 13).

This calculation is based on the situation in which the flood protection measures along the stretch between Wesel and Lobith have been reinforced in accordance with the plans announced in 2005. According to this schedule, the reinforcements should be completed by 2025. At the moment, some of the planned dike reinforcements remain to be completed, so the maximum discharge at Lobith may be lower than the upper limit of 17,500 m³/s calculated based on the planned reinforcements. It is not yet certain when the remaining improvements will be completed, but the ENW considers it realistic to base the determination of the maximum discharge at Lobith on the reinforced flood defences.

We should note, however, that the calculated overflow over the dikes in this situation is extremely high. At many locations, it is greater than 50 l/s/m, but on the right bank there are outliers of 400-500 l/s/m at Rees and Emmerich. Under such conditions, a flood protection failure should be considered probable.

**Figure 9** Discharge at Lobith as a function of the discharge at Wesel



# 7 Other issues

In addition to the modelling of floods, there are other issues that are important in determining the maximum discharge at Lobith.

### Simultaneous peak discharge in the main river and tributaries

An important factor in the height of the peak discharge is the time difference between the occurrence of peak discharges in the Rhine and its major tributaries. In some of the extreme flood waves analysed, the peak discharges from the Neckar, Main and Moselle were virtually simultaneous with that in the main stem of the river (Figure 12, Appendix A). These tributaries achieved their peak 0 - 2 days earlier than the main stem. From this, we can conclude that the major tributaries cannot give rise to even higher extreme discharges in the main stem due to unfavourable timing. The downstream sections of the tributaries, such as the last 52 km of the Moselle, are included in the SOBEK model, so that it includes impoundment in the tributaries.

### Overflows or dike failures

In the event of a discharge of 20,000 $m^3/s$ at Andernach, so much water will overflow the dikes that failures are highly likely. Previous research by Gudden (2004) and Paarlberg (2014) has shown that it is strongly dependent on the wave form and the breach location whether dike breaching between Bonn and Wesel result in lower or perhaps higher discharges. In the case of a dike breach between Wesel and Lobith, the water probably will not flow back into the Rhine before Lobith. Such a breach would therefore result in a lower discharge than simple flooding. As the probability of dike failure for a given discharge is unknown, we assume that no dikes will breach at the maximum discharge between Wesel and Lobith. This leads to a conservative (i.e. high) estimate of the maximum discharge rate at Lobith.

### Shunting through dike rings 42 and 48

The maximum discharge rate at Lobith is due to flooding in Germany. However, this does not mean that more extreme circumstances cannot occur. Such circumstances would be expressed in flooding of the dike rings 42 and 48, and the water may flow back into the Waal or the IJssel. This increases the load on the Dutch river system, despite the limited discharge at Lobith.

### Wave form at Lobith

One must also take into consideration that there is no clear maximum to the volume of a flood, which means that the wave form becomes wider as the probability of occurrence is reduced. If we only look at peak discharge and not at the wave form as a function of the probability of occurrence, then we will obtain an incomplete image of the load on the flood protection measures, and the effects of extreme high water levels on piping and macrostability may be underestimated.

### Policy changes

German government agencies are already investing in limiting the consequences (Hegnauer et al, 2015a), and not in making dikes higher. When they do raise the dikes, it may have an influence on the maximum discharge. In general, raising the dikes between Wesel and Lobith will lead to higher maximum discharges at Lobith, but raising dikes further upstream may also ensure more effective reduction of extreme discharge peaks (as the flooding areas are not flooded ‘too early’), and therefore lower peak discharge for a specific probability of occurrence.

# 8 Conclusion

In case of the overflowing of the dikes and floodprotection walls between Wesel and Lobith – and then within the range of discharges considered at Andernach – there is in fact an upper limit to the discharge at Lobith of approx. 17,500 $m^3/s$. Extra water will flow into the dike rings 42 and 48, even if the dikes do not fail. In order to reach this upper discharge limit, the discharge at Wesel must be at least 18,000 - 20,000 $m^3/s$.

Floods between Bonn and Wesel will reduce the peak discharge, but as these areas can only store a limited volume of water, most of them will be full by the time peak discharge is reached in the event of the most extreme waves in GRADE. As a result, in the event of a 24,000 $m^3/s$ discharge at Andernach, the discharge at Wesel may reach 22,000 - 23,000 $m^3/s$. This means there is no physical or hydraulic maximum at that point.

There are various reasons to assume that GRADE underestimates the effect of flooding on the Upper Rhine, and therefore overestimates the discharge at Andernach. The upper discharge limit between Wesel and Lobith, however, lessens the importance of the discharge rate at Andernach. This is because a 24,000 $m^3/s$ discharge at Andernach leads to approximately the same discharge at Lobith as a wave with a peak discharge of 22,000 $m^3/s$. So even if the discharge at Andernach has been overestimated by 2,000 $m^3/s$, it will have no influence on the discharge at Lobith even at the highest flow rates.

From this, we can conclude that the course of the river between Wesel and Lobith, especially the ‘pressure valve action’ effect of the dike rings 42 and 48, is decisive for the highest discharges at Lobith. The calculated upper limit of 17,500 $m^3/s$ is a best estimate according to the current insights, based on the planned reinforcements along this section of the river up to 2025, and within the range of discharges considered. This value may change as the underlying principles change. Major sources of uncertainty include the degree to which planned reinforcements are actually implemented, the bed roughness under extreme discharge conditions, the occurrence of dike failures between Wesel and Lobith and the degree to which the water can drain away freely in the event of a flood.

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## Appendix A **Extreme discharge waves from GRADE**

| # | WITHOUT flooding Maxau | WITHOUT flooding Kaub | WITH flooding Kaub | WITHOUT flooding Cochem | WITH flooding Bonn | WITH flooding Lobith |
|---|---|---|---|---|---|---|
| 1 | 10.690 | 19.220 | 18.810 | 5.550 | 24.360 | 23.850 |
| 2 | 7.770 | 18.030 | 17.650 | 6.540 | 24.650 | 23.830 |
| 3 | 8.560 | 18.800 | 16.650 | 7.790 | 23.280 | 22.120 |
| 4 | 7.550 | 14.410 | 13.430 | 6.130 | 20.350 | 22.120 |
| 5 | 7.560 | 15.110 | 14.810 | 5.850 | 21.230 | 21.950 |
| 6 | 10.140 | 17.810 | 16.780 | 6.440 | 22.830 | 21.900 |
| 7 | 7.080 | 17.430 | 15.380 | 6.630 | 22080 | 21.870 |
| 8 | 6.980 | 17.690 | 16.240 | 6.570 | 22.910 | 21.710 |
| 9 | 5.170 | 14.740 | 14.200 | 7.060 | 21.580 | 21.120 |
| 10 | 6.060 | 14.140 | 13.580 | 5.590 | 19.440 | 20.700 |

**Tabel 1** GRADE output (in m³/s) for climate scenario 2085WH (source: Deltares, Mark Hegnauer)

**Figure 10**
Data from Table 1 (source: Deltares, Mark Hegnauer, pers.comm.)

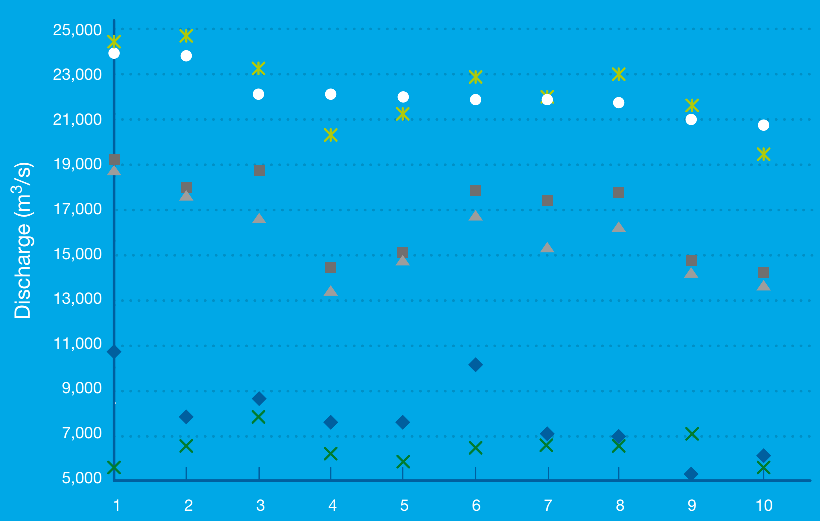



**Figure 11** Overview of the different contributions (in m³/s) to the Rhine for four extreme flood events. (source: Deltares, Mark Hegnauer, pers. comm.)

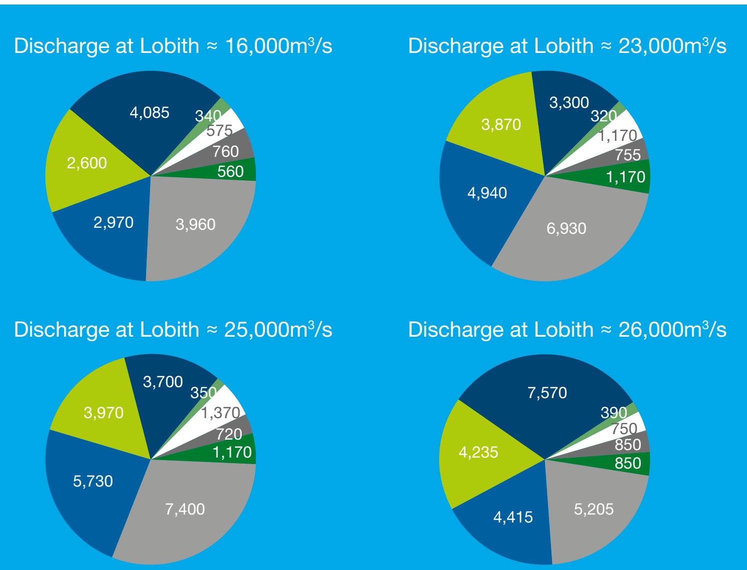
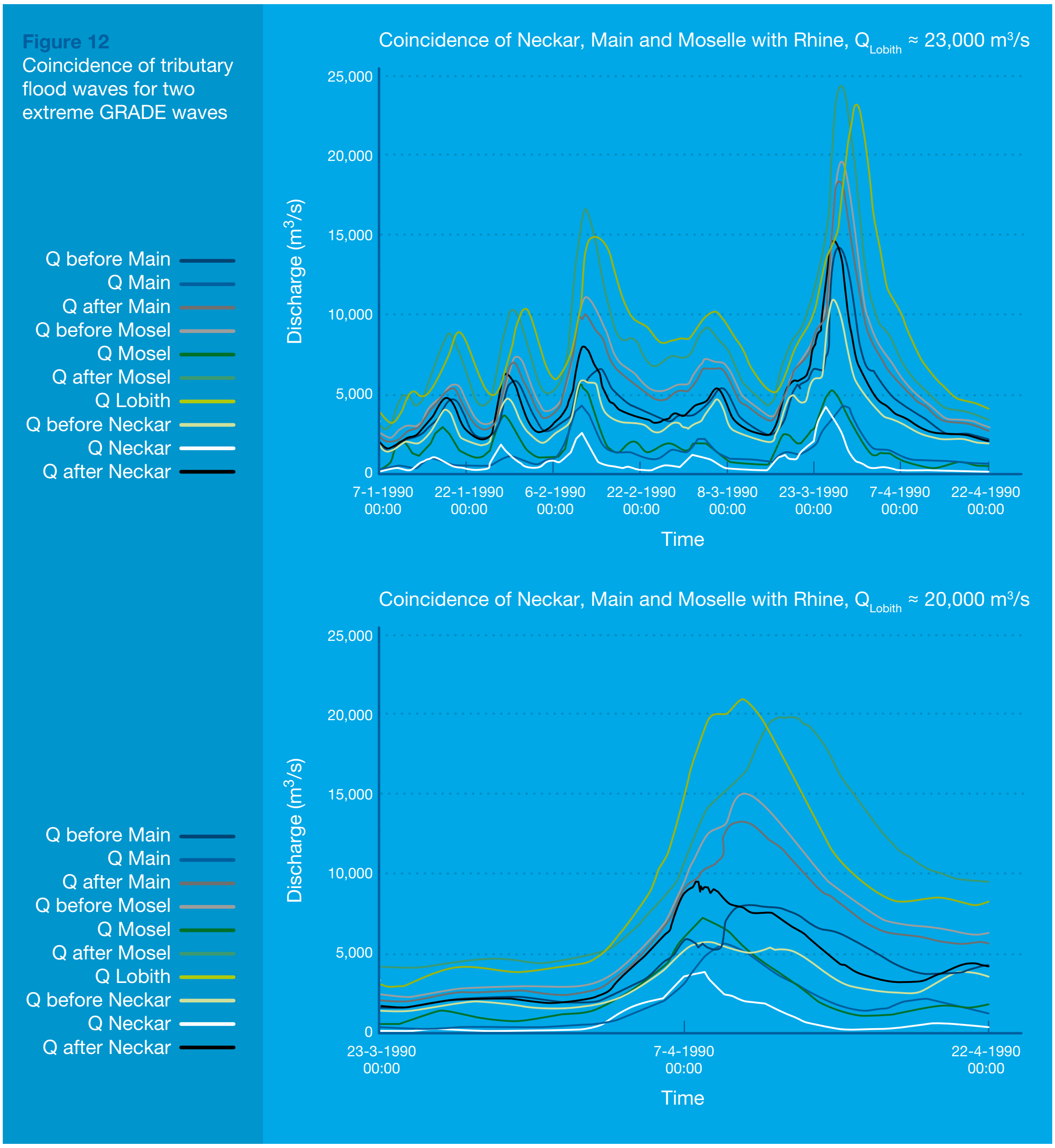


**Figure 12**
Coincidence of tributary flood waves for two extreme GRADE waves



# Appendix B Discharge between Wesel-Lobith

The stretch of the river between Wesel and Lobith seems to be decisive for the maximum discharge at Lobith, because the storage capacity of the protected areas along this stretch is virtually unlimited (Sperna Weiland et al., 2015), in contrast to stretches of the river farther upstream. There is no WAQUA model that includes flooding of this area. In order to provide a quick estimate of the maximum discharge along this part of the river, a highly simplified model was created. Between river km 822 and 862, the river is divided into 100-m segments, and for each segment the amount of overflow over the dike is calculated, given a constant discharge in the river at the upstream end of the segment:

$$Q_{uit} = Q_{in} - Q_{ov,links} - Q_{ov,rechts}$$

$$Q_{ov} = 1.7 \cdot L \cdot (H - h_{kr})^{1.5}$$

in which for each segment:

| | |
|---|---|
| $Q_{uit}$ and $Q_{in}$ represent the river discharge that flows in and out of the segment, respectively | [m³/s] |
| $Q_{ov}$ is the flow rate over the dikes | [m³/s] |
| *L* is the dike length | [m] |
| *H* is the local water level at the dike | [m+NAP] |
| $h_{kr}$ is the average crest height | [m+NAP] |

The water level at the dike is taken the same time as in the axis of the river, which is derived from $Q_{in}$ and the rating curves from Paarlberg (2014). Schematization, roughness and other model characteristics are therefore the same as in the study by Paarlberg.

The crest heights along both sides of the river are known from Baseline, for the situation in which the flood protection measures along the section between Wesel and Lobith have been reinforced in accordance to the plans for the period until 2015 (indicated with dh15 in Wijbenga et al., 2009). Paarlberg (2014) has allocated these dike points to hectometers along the axis of the river. For each hectometer, the dike length L is the sum of the dike lengths of the allocated points, and the crest height hkr is the average of the crest heights of those points.

Figures 13 and 14 show the results for different discharge levels. This calculation results in a maximum discharge at Lobith of approx. 17,500 m³/s.

This maximum discharge is highly dependent on the water level at the dike for a given flow rate. In the event of higher water levels for the same discharge, overflow will occur at lower discharges, which would lower the maximum discharge. Actual water levels may vary from the value used here, for example due to:

a. the simple approach: in sharp bends with broad forelands, the water level at the dike can deviate up to some 10 cm from the axis of the river.
b. roughness: the summer bed roughness at very extreme discharges is relatively difficult to determine. The WAQUA models are based on observed (and therefore significantly lower) discharges. This has led to different roughness values in the Netherlands and in Germany. The consistency of the roughness values in GRADE and the models used for flood safety assessments in the Netherlands (WBI) is a point of concern (see also the ENW recommendation pertaining to GRADE, 12 August 2015).

In order to gain insight into the sensitivity of the maximum discharge to changes in water levels, the local water level over the entire course of the river was varied by ± 10 cm compared to the WAQUA calculations by Paarlberg (2014). If the water level is 10 cm lower, then the maximum discharge rate at Lobith is 17,800 m³/s; if the water level is 10 cm higher, then it is 17,100 m³/s. Note that this is not a range of uncertainty, because it does not include the probability of the variations.

At the moment, the planned dike reinforcements are still incomplete, so the current maximum discharge at Lobith is lower than the value of 17,500 m³/s calculated above, which is based on the planned improvements.

**Figure 13** Discharge Wesel - Lobith for discharges of 16,500 - 21,000 m³/s at Wesel

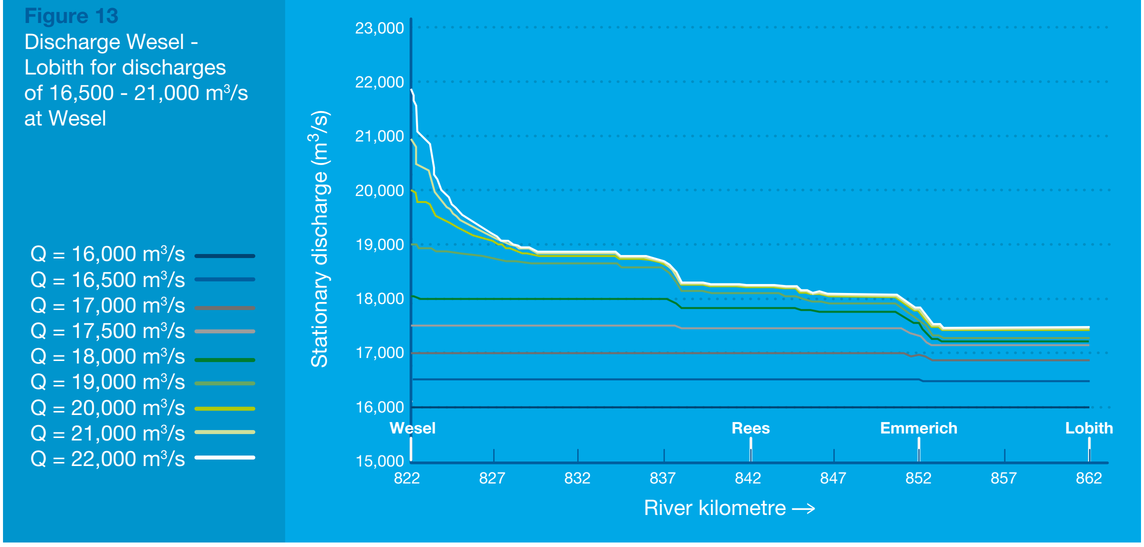
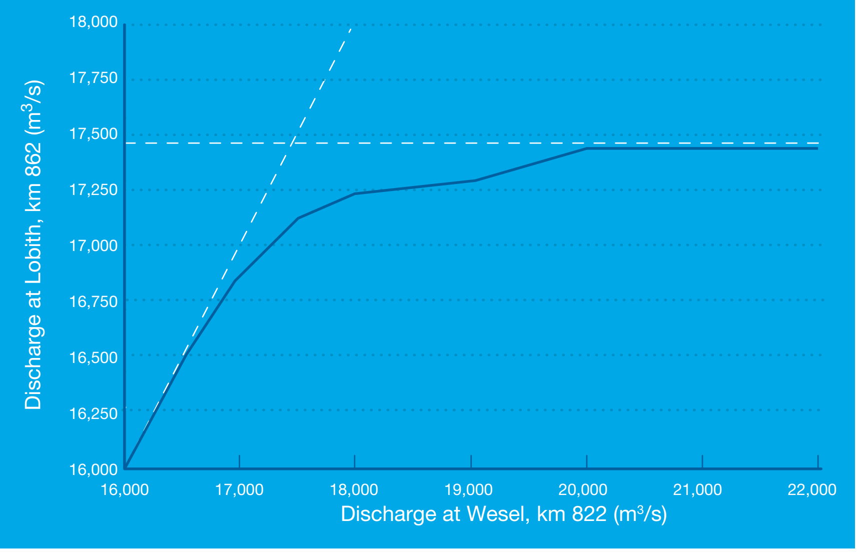



**Figure 14** Discharge at Lobith as a function of the discharge at Wesel







## Colophon

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