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The plausibility of extreme high discharges in the river Rhine

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1220042-004

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Client	Project	Reference	Pages
Rijkswaterstaat (Water, Verkeer en Leefomgeving)	1220042-004	1220042-004-ZWS-0008	82

Keywords
River Rhine, floods, GRADE, climate change.

Summary
This report describes the contents and findings of an expert panel that discussed the underlying assumptions of the results of the study performed by the KNMI and Deltares: *Implications of the KNMI'14 climate scenarios for the discharge of the Rhine and the Meuse.* The focus of the discussions was the plausibility of extreme high discharges of the River Rhine at Lobith. The discussion was structured around three main assessments:

1. Assessment of the climate change and associated weather conditions leading to extreme discharges.
2. Assessment of the runoff volumes in the basin produced during these weather events.
3. Assessment of the propagation of the flood wave through the main river.

In the new KNMI’14 scenarios, the computer simulations suggest the occurrence of precipitation events leading to discharge events, exceeding 20,000 m^3/s in the Rhine at Lobith. There is no empirical experience that can support or reject the occurrence of such runoff events. The projected climatic changes are comparable with the CMIP5 climate model runs that were used by the IPCC AR5 report. The simulated response of the basin to the enormous precipitation volume seems reasonably as under extremely wet conditions almost all rainfall will very rapidly come to discharge. There is no obvious reason to assume a completely different response if the rainfall amounts become even larger.

Still, the panel considered the discharge events higher than 20,000 m^3/s as events beyond imagination. Such flood events will lead to extensive flooding in the Oberrhein and Niederrhein valley. This flooding effect is taken into consideration in the simulations; however, its effect is widely underestimated by GRADE in the river section between Wesel and Lobith. The panel considers an amount between 17,000 and 18,000 m^3/s as the most likely maximum discharge that could arrive at Lobith, where 18,000 m^3/s should be considered as very high upper end estimation.

The panel strongly recommends (1) an extensive international study that uses 2-D hydraulic modelling to provide scientifically sound information on the hydraulic effects in the Rhine and that makes better use of the currently available high resolution geographical data, new model codes and computing power; (2) to elaborate on alternative approaches to understand the causes and consequences of the extreme events such as deterministic simulation of very extreme single weather events under changed climate conditions and analysis of their hydrological effects (3) to include the area downstream of Bonn in the flood assessments in The Netherlands. Since the extreme events analysed here might not exceed the maximum discharge capacity of the Rhine branches in the Netherlands, water could also enter the Netherlands via unexpected pathways. Ignoring this effect may lead to an incorrect assessment of the risk of flooding.

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References
Sperna Weiland, F., M. Hegnauer, L. Bouaziz & J. Beersma, 2015. *Implications of the KNMI'14 climate scenarios for the future discharge of the Rhine and Meuse*. Deltares report 1220042-000-ZWS-0004, Delft, the Netherlands.

Version	Date	Author	Initials	Review	Initials	Approval	Initials
1.0	nov. 2015	Mark Hegnauer		Nathalie Asselman		Gerard Blom	
		Jaap Kwadijk					
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List of abbreviations

AR5	IPCC Fifth Assessment Report
CMIP5	Coupled Model Intercomparison Project Phase 5
GRADE	Generator of Rainfall And Discharge Extremes
HBV	Hydrologiska Byråns Vattenbalansavdelning
IPCC	Intergovernmental Panel on Climate Change
NRW	Nord-Rhein Westfalen

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Appendices

1 Introduction

The Netherlands are implementing strategies developed during the Delta programme to prepare the country for climate change and sea level rise. Protection against flooding is a major issue in this programme. This has led to the development of new flood protection standards, which require a much higher protection level against flooding along the rivers Rhine and Meuse than the current standards.

Next to these new flood protection standards, the Royal Netherlands Meteorological Institute (KNMI) presented in 2014 a new set of climate scenarios for the Netherlands and for the Rhine and Meuse river basins. These climate scenarios are used to derive future discharge projections for the Rhine (at Lobith) and the Meuse (at Borgharen), relevant for flood risk management in the Netherlands.

Both the new scenarios for climate change as well as the new flood protection standards have renewed the political interest in the (extreme) discharges of the Rivers Rhine and Meuse as the new estimates may affect flood protection projects in The Netherlands. The interest is particularly on the changes in frequency and magnitude of the very rare events that are used to design the flood protection measures, since the new standards are higher than those used so far. The current interest is in flood events with a probability of occurrence in the order of 1:1,000 per year. In the new standards, the interest is to floods with a probability of occurrence of 1:30,000 to even less than 1:100,000 per year. In the new standards the interest is not only the water level, but also the duration and flood volumes. Moreover, the interest is not limited to these very rare floods, but to all floods that potentially could lead to flooding if the flood protection infrastructure would fail.

KNMI and Deltares have performed a study about the implications of the new KNMI scenarios for flood frequencies and magnitude of the Rivers Rhine and Meuse (Sperna Weiland et al., 2015). Here we focus on the River Rhine. The current design discharge of the River Rhine in The Netherlands is 16,000 m^3/s at Lobith, having an estimated return period of 1250 years. The study shows that when flooding in Germany is not taken into account the estimated discharge at Lobith for a return period of e.g. 30,000 years is 20,000 m^3/s. This when assuming the current climate conditions. The 20,000 m^3/s would increase to 26,000 m^3/s assuming a change in climate conditions towards the end of this century that complies with the KNMI W_H scenario. According to the study of Sperna Weiland et al. (2015), flooding along the river stretches Maxau-Kaub and Bonn-Lobith will reduce the flood peaks considerably. Due to flooding a discharge peak of 20,000m^3/s at Lobith will be reduced to a peak between 15,500m^3/s and 16,000m^3/s. Due to flooding a discharge peak of 26,000 m^3/s would be reduced to a peak between 17,000 and 17,500m^3/s. Assuming the KNMI W_H scenario, for the longest return period, 100,000 years, the estimated discharge at Lobith is 18,000m^3/s.

The highest flood observed since 1901 at Lobith is approximately 12,000 m^3/s, far below the flood peaks relevant for the design of the Dutch flood protection system. Since these extreme discharges are unprecedented, our assessments on the characteristics of the design flood peaks are largely based on the results of simulations by numerical models. The simulations by the numerical models are based on a series of scenarios and assumptions. To discuss the plausibility of the results of the study, KNMI and Deltares invited a group of Dutch and German experts from different organizations. The experts were selected based on their experience with research to floods in the Rhine basin.

1.1 The expert panel

The panel discussed underlying assumptions of the results of the KNMI-Deltares study. The focus of the discussions was on the climate scenarios and assumptions determining the effects of upstream flooding on the reduction of the discharge peaks. These topics were discussed in view of other studies carried out in the Rhine basin.

The members of the expert panel that attended the meeting, and their expertise are:

- Prof. Dr. Huib de Vriend (emeritus TU Delft, Chair ENW-rivers, Chair).
- Prof. Dr. Hans Middelkoop (Utrecht University, river morphology and paleo floods).
- Prof. Dr. Ir. Matthijs Kok (TU Delft, flood risk, Chair ENW-safety).
- Dr. Karin de Bruijn (Deltares, flood risk management).
- Ir. Hendrik Buiteveld (RWS-WVL, the Rhine/Meuse discharges and climate change).
- Dr. Jules Beersma (KNMI, climate scenarios).
- Dr. Enno Nilsson (BfG, climate impact studies).
- Dr. Aline te Linde (Twijnstra-Gudde, climate change and Rhine River floods).
- Ir. Hermjan Barneveld (HKV, climate change, hydraulic modelling and effects of flooding).
- Dr. Rita Lammersen (RWS-WVL, Hydraulic modelling, effects of flooding along the Rhine).
- Mr. Bernd Mehlig (Landesamt für Natur, Umwelt und Verbraucherschutz, Nordrhein-Westfalen, flood risk management).

The members of the expert panel responsible for writing this report:

- Prof. Dr. Jaap Kwadijk (Deltares, Technische Universiteit Twente, climate change and water management).
- Prof. Dr. Frans Klijn (Deltares, Technische Universiteit Delft, Adaptive Delta management).
- Ir. Mark Hegnauer (Deltares, main author of the report).

Included in the report are the comments of Ir. Wim Silva, who is a retired expert on river management, working formerly for the Dutch Rijkswaterstaat. He reviewed and added his comments to the minutes.

1.2 Scope of the report

This report summarizes and describes the outcome of the discussions in the expert panel. This discussion, however, was not completed during the meeting, but continued on the basis of the submission of two versions of the minutes. More information was added by different panel members to clarify their opinions. Also an analysis of the generation of four flood waves as simulated by GRADE was added (Appendix A). Therefore the scope of the report is an extended version of the minutes of the meeting.

1.3 Genesis of flood waves in the Rhine

The build-up of large flood events at Lobith occurs in sections of the Rhine, the Oberrhein, Mittelrhein and Niederrhein (Figure 1-1).

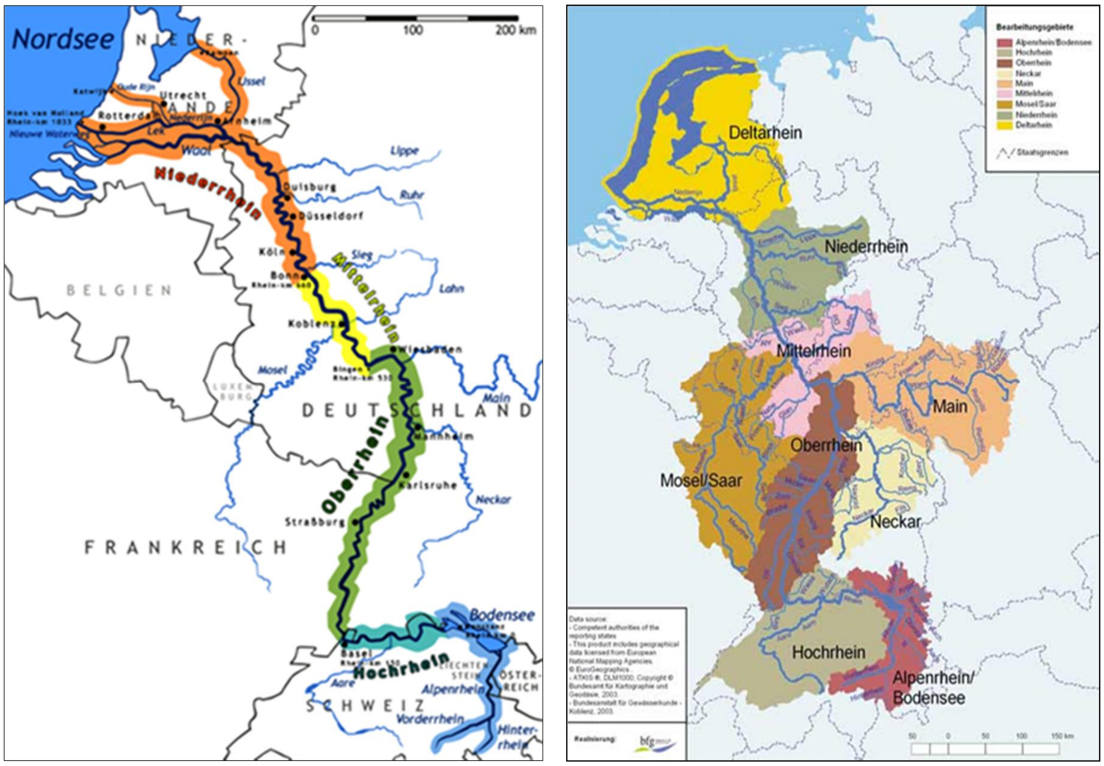

Figure 1-1. The Rhine and its tributaries

These sections are fed by different tributaries. Historic flood events at Lobith show a considerable different development along the sections of the Rhine. Annex A shows the genesis of three high simulated high flood events (> 20,000 m^3/s at Lobith when not taking into account the effect of flooding). In volume, the long stretch upstream Karlsruhe (Maxau) produces between 15% and 30% of the peak floods. Along the long Oberrhein stretch the Neckar and Main add between 35% and 40%. In the Mittelrhein section over a relatively short stretch a lot of water is added via the Mosel, Lahn and Nahe. These tributaries add another 30-40%. In the Niederrhein section the contributions of the tributaries, Ruhr and Lippe are relatively small, in this section the very large flood waves are reduced, despite the added water via the tributaries. This nicely illustrates the effect of flooding in this section.

The Oberrhein and Niederrhein have broad valleys, where flood waves can be reduced due to flooding or breaching of embankments. In the Mittelrhein, the Rhine flows through a relatively narrow valley incised into the low mountain range of the Rhenish Slate Mountains. There are hardly any (embanked) floodplains, and reduction of flood waves due to flooding plays a minor role in this river reach. Since the conveyance capacities of the three sections differ, it matters what the main sources of the floods are. Water that is added in the Mittelrhein section will contribute to the discharge in the Niederrhein without attenuation.

Events where the contribution upstream Bingen/Kaub is dominant and the contribution of the Mittelrhein is relatively low, will be affected much more by flooding, both in the Oberrhein and in the Niederrhein. Apart from the origin of the water, the duration and discharge volume prior to the flood peak determine the peak volume arriving at Lobith. When the discharge volume prior to the flood peak is large, and the retention capacity along the retention/floodplains is filled up prior to the peak and flood attenuation will be minimised.

1.4 Key Questions that were discussed.

The discussion was structured around three main assessments:

1. Assessment of the climate change and associated weather conditions leading to extreme discharges.
2. Assessment of the runoff volumes in the basin produced during these weather events.
3. Assessment of the propagation of the flood wave through the main river.

To come to conclusions about the previously mentioned assessments, the experts discussed three questions, each related to one or more assessments:

1. Is it plausible that discharges of 18,000 m^3/s or even larger are generated upstream of the Niederrhein (Bonn)? (assessment 1 and 2).
2. Can discharges of 18,000 m^3/s (or higher) be conveyed through the Niederrhein until Lobith? (assessment 3).
3. What will be the consequences of discharges larger than 18,000 m^3/s arriving in the Niederrhein? (assessment 3).

Chapter 2 describes the set up of the meeting. The outcomes of the discussion and the answers to these questions are given in Chapter 3 of this report. In Chapter 4 the reasoning behind these answers is given from different perspectives with the presentations given during the meeting. The presentations that were given during the meeting can be found in the appendices B-E. Appendix A illustrates the results of the simulations of GRADE by an analysis of the characteristics and genesis of four flood waves that were simulated by GRADE.

2 Set up of the meeting

To inform each member of the panel on the background of the new flood protection standards, the climate change scenario's, the hydrologic and hydraulic models used, the different assumptions made in the assessments as well as on the results of other related research, the meeting started with a series of presentations. The presentations can be found in the Appendices B through E of this report. The program of the day was as follows:

1. **Introduction to the meeting (Jaap Kwadijk).**

2. **Presentations on the different perspectives relevant for high discharges in the Rhine:**
   a. *Historical perspective (Hans Middelkoop, University of Utrecht).*
   Historic floods in the Rhine basin. The question addressed is whether historic and sedimentary archives provide any evidence that floods of, or larger than, 18,000 m^3/s occurred in the past.
   b. *Meteorological perspective (Jules Beersma, KNMI).* The new KNMI'14 climate scenarios. The question addressed is the plausibility of the presented very high precipitation extremes.
   c. *Hydrological perspective (Mark Hegnauer, Deltares).*
   The hydrological response of the Rhine basin to extreme precipitation events. The discussion was about the validity of the models for such extreme events.
   d. *Hydrodynamic perspective (Hermjan Barneveld, HKV Consultants).*
   The history of flood modelling in the river Rhine and the major outcomes of these studies. The discussion was about the conveyance capacity that could be derived from these studies, mainly for the last stretch of the Rhine between Wesel and Lobith.
   e. *The new flood protection standards in the Netherlands (Nathalie Asselman, Deltares).*
   The new flood risk management strategy in the Netherlands and the new flood protection standards for the Dutch dike (rings). This presentation showed why it is of utmost importance to have more information on the low probability floods.
   f. *The Dutch perspective (Hendrik Buiteveld).*
   The Dutch perspective of flood risk management and the main questions that live at the level of the ministry about the impact of the new flood standards and the new climate scenarios.
   g. *The German perspective (Bernd Mehlig).*
   The German perspective of flood risk management of the Rhine and pointing out the differences in their flood management approach compared to the Netherlands.

3. **Discussion on the three main questions as stated in the introduction.**

4. **Summary and first draft of the conclusions.**

3 The main findings

3.1 Is it plausible that discharges of 18,000 m^3/s or more are generated upstream of the Niederrhein (Bonn)

More details on the reasoning can be found in sections 4.2, 4.3, 4.4, appendix A, C and D

- A combination of very high discharges in the Oberrhein and very high discharges from Mosel, Nahe and Lahn could lead to very large discharge volumes entering the Niederrhein. From the discussions, it appeared that to produce a flood as high as 18,000 m^3/s at Lobith (see 3.2), a flow of more than 20,000 m^3/s is needed at Bonn.

- Following the GRADE results, also today under current climatological conditions, very extreme discharge events can occur. Assuming the current climate conditions the maximum discharge arriving at Bonn according to the GRADE simulations (50,000 year period) is approximately 16,000 m^3/s. Assuming climate change conditions according to the KNMI W_H scenario the maximum discharge arriving at Bonn according to GRADE is approximately 24,000 m^3/s. 19,000 m^3/s origins from the Oberrhein and 5,000 m^3/s is added from the Mittelrhein.

- A large number of CMIP5 climate model runs (which are also assessed in the IPCC AR5 report) were analysed on their effect on the discharge of the River Rhine. This analysis showed comparable increases in extreme discharges. According to the climate projections of KNMI for the coming century, extreme rainfall events will increase and occur more frequently in winter. These climate projections seem plausible as (a) the largest increase of almost 30% in mean winter precipitation in the KNMI W_H scenario in 2085 is in line with the simple rule of thumb that for every degree temperature rise, the amount of water in the atmosphere increases with ~4-8%. For the W_H scenario a temperature increase of about 4.5°C is projected for 2085, corresponding to an increase of the amount of water in the atmosphere of up to about 30%, (b) it is physically not implausible that the changes in extreme multi-day precipitation (to which changes in extreme river discharges are most sensitive) are of the same order of magnitude as the changes in mean (winter) precipitation.

- Analysis of historic flood events reveals that different events can have a different genesis. Floods can e.g. be generated as a result of large amounts of rainfall on frozen soils, a combination of melting snow in the Alpine sub-basin and heavy rainfall over the German-French part of the basin and an unfortunate coincidence of peak floods from different tributaries. In all cases, however, generation of high discharges at Lobith requires a series of consecutive days with heavy rainfall over large parts of the basin. This is typically associated with a series of low pressure areas passing over the basin. In winter, after a series of very wet days, the soils reach their maximum storage. Additional rain will fall on a basin where the storage is already full. Considering only the hydrological relation between precipitation and runoff, this additional water will come to runoff very fast, leading to extreme discharge peaks. This is the reason that in winter a good correlation exists between the 10 day basin-precipitation sum and the discharge peak at Lobith. The model (HBV) that is used to simulate the runoff produced in the basin is validated for the 2nd and 3rd highest flood events in the 20th century in the Rhine and its tributaries. However, the maximum peak flows used in the validation are far less than 18,000 m^3/s at Lobith. The simulated response of the basin to the enormous precipitation volume seems reasonably as under extremely wet conditions almost all rainfall will very rapidly come to discharge. There is no obvious reason to assume a completely different response if the rainfall amounts become even larger.

- Extremely large water volumes produced in the Rhine basin can reach Bonn, although the flood peaks will be reduced considerably due to flooding in the stretch Maxau-Kaub. A study of HKV (Barneveld, 2011; see 4.4) assesses the impact of flooding of dike-protected areas downstream of Maxau. For a peakflow of 9,000 m^3/s at Maxau, the peakflow at Bonn was lowered by about 4,000 m^3/s (from 16,000 to 12,000 m^3/s) due to flooding along the river stretch between Maxau and Kaub. Between Kaub and Bonn no extensive flooding can occur because of the narrow shape of the river valley. All water that passes Kaub reaches Bonn without substantial attenuation of the peak flow. Moreover, large amounts of water may be added to the Rhine discharge by the Mosel, Nahe and Lahn tributaries. The hydrodynamic model used in the assessments takes the flooding along the stretch between Maxau and Kaub into account. For all peak flows that exceed 16,000 m^3/s at Lobith, the flood reduction upstream of Kaub as simulated by GRADE is between 0 and 4500 m^3/s depending on the timing, duration and flood volume of the events.

Given the material that is available the panel considered it is not implausible that discharges as high as 20,000 m^3/s can arrive at Andernach/Bonn.

3.2 Can discharges of 18,000 m^3/s (or higher) be conveyed through the Niederrhein until Lobith?

Details on the reasoning can be found in 4.1, 4.4, 4.5, Appendix A, B an E

- In the last 5,000 years at least two events have occurred with discharges around or higher than 15,000 m^3/s in the Rhine area near the German-Dutch border. Given the current embanked state of the river, these discharges would lead to higher discharge peaks now. There is no conclusive evidence of discharges as large as 18,000 m^3/s.

- Flooding in the Niederrhein starts at discharges above ~12,000 m^3/s near Bonn. With increasing discharge, flooding progresses downstream (Bonn, Cologne, Dusseldorf, Ruhrort and until Wesel). Between Wesel and Lobith flooding starts between 16,500 m^3/s and 17,500 m^3/s. The maximum reduction of the simulated discharge peaks between Bonn and Wesel is in the order of 4,000 m^3/s, depending on the timing, the duration and the height of the flood wave. Only when the discharge at Bonn is much higher than 18,000 m^3/s, the Rhine discharge at Wesel could become also higher than 18,000 m^3/s, because the flooded areas between Bonn and Wesel are then completely filled.

- The protection standards in Germany increase over the stretch of the river between Bonn and Lobith from ~1/200 yr^{-1} near Bonn to ~1/500 yr^{-1} downstream Düsseldorf. In the assessment, it is taken into account that the levees in Germany are designed with a freeboard of 1 meter, compared to 0,5 meter in the Netherlands. The embankments along the Niederrhein are designed to convey a discharge of at least 14,500 m^3/s. Taking into account the freeboard of the embankments this would add 2000 – 3000

m^3/s, leading to 16,500 – 17,500 m^3/s discharge capacity. The model simulations with Sobek suggest (much) higher discharges than the 16,500 – 17,500 m^3/s at Lobith (up to a maximum of 24,000 m^3/s (see Appendix A)) but Sobek is known to underestimate widely the overtopping in the stretch Wesel-Lobith. These amounts would lead to water levels exceeding the level of the embankments at several locations along the stretch Wesel-Lobith (Figure 4-1). Based on the information and discussion presented by the experts, the maximum discharge of the Rhine just before Lobith would be between 17,000 and 18,000 m^3/s, with a best estimate of around 17,500 m^3/s. Water that leaves the Rhine via the eastern embankment will flow into The Netherlands via other pathways (see 3.3).

- Other uncertainties and issues not taken into account in the present assessments can also affect the discharges:

  - Additional emergency measures may lead to higher discharges, but this will be limited. Adding 30cm to the dike levels between Wesel and Lobith by sand bags would theoretically increase the conveyance capacity by approximately 1000 m^3/s.
  - The measures carried out in Room for the River do not only lead to lowering of water levels in the Netherlands. A 30-cm lowering of the water levels at Lobith as a result of the Room for the River measures would locally increase the conveyance capacity with about 1000 m^3/s. This will also increase the discharge capacity in the section Wesel-Lobith since the effect of these measures will extend upstream Lobith and fades out upstream.
  - The hydraulic roughness is difficult to estimate. A higher hydraulic roughness will result in increased water levels and hence in a lower discharge capacity. This implies that other roughness values may increase or decrease the conveyance estimates (Prinsen et al., 2015). By a lack of these events in historic series, validation of the roughness values is not possible.
  - Changes in bed level of the main river channel (Frings et al., 2013) will affect the conveyance capacity of the river. Since there appears to be a downward tendency (erosion) of the channel bed, the conveyance capacity might slightly increase. If the current scour of 2cm/yr would continue, this would increase the conveyance capacity at Emmerich by approximately 500 m^3/s in 25 years (Silva, 2009). At Düsseldorf erosion of the river bed is estimated between 16-32 cm in the next 25 years which would increase locally the capacity by 300-600m^3/s (Van de Veen et al. 2004).

- Above the maximum capacity, the surplus of water will spill over the embankments, entering dike rings 42 and 48. At some locations, such as Emmerich, water starts spilling over the embankments when discharges are around 16,000 m^3/s. Assuming the highest estimates of flood volumes arriving in the Niederrhein section, and assuming that the embankments will not collapse, the flow over the embankments over a length of about 20-30 km between Wesel and Lobith could become very high, in the order of 100-200 $ls^{-1}m^{-1}$, resulting in about a total diverted flow of 4,000 m^3/s. If the levees would break under these conditions, a considerable additional amount of water (>>2000 m^3/s per dike breach) will flow through these breaches which inevitably leads to a significantly lower discharge than 18,000 m^3/s in the main branch Rhine River.

- Due to the characteristics of the dike rings 42 and 48 there seems no physical limit on the storage capacity in the dike rings. Water spilling over the embankments in this stretch enters dike-rings 42 and 48 (resp. DR42 and DR48) and will flow towards the Waal (DR42) and the IJssel (DR48). So, this water will bypass Lobith but enters the Netherlands more downstream where it will cause significant flooding. If the spilling over the embankments leads to breaching of the embankments between Wesel and Lobith, the discharge at Lobith will be significant lower than 18.000 m^3/s, but flooding hazard will not be alleviated.

Based on the considerations in the meeting and discussions later, the panel concluded that discharges of 20,000 m^3/s at Andernach/Bonn are needed to produce discharges more than 18,000 m^3/s at Lobith. Based on these considerations, the panel considers an amount between 17,000 and 18,000 m^3/s as the most likely maximum discharge capacity of the Niederrhein, where 18,000 m^3/s should be considered as a very high upper end estimation.

3.3 What will be the consequences of discharges larger than 18,000 m^3/s in the Niederrhein?

Discharges higher than 17,000-18,000 m^3/s cannot be conveyed via the Niederrhein without overtopping of the embankments along the stretch between Wesel and Lobith. The remainder of the water also flows into the Netherlands, but not through the river, but over land. This water will not pass at the gauge Lobith, but will enter the river again downstream of Lobith, e.g. in the IJssel valley, or downstream in the river Waal.

The study Risicoanalyse grensoverschrijdende dijkringen Niederrhein / Risikoanalyse für die grenzüberschreitenden Deichringe am Niederrhein (Silva et al., 2009) estimated the potential damage in case of a dike breach along this stretch. According to this study the potential damage resulting from a breach in the right bank is between 4.5 and 6 Billion Euro. The flood damage as a result of a breach at the left bank is between 1.5 and 4.5 Billion Euro, both cases depending on the location of the breach.

4 Viewpoints from the different experts on extreme discharges in the Rhine

4.1 (Pre-) historical Floods (see also appendix B)

Hans Middelkoop presented an overview of evidence of extreme flood events during the last 8000 years. This (pre) historical perspective sheds light on questions 1 and 2, about the plausibility of the generation of such extreme floods and conveyance of the flood wave to Lobith.
In a recent study by Toonen (2015) the discharge variations for the River Rhine for the period 6000 BC to 2010 AD were studied. Long historical discharge series were created based on:

1. Gauging discharge data from Lobith (1901 – now)
2. Gauging discharge data from Cologne (1817 – now)
3. Water level data at stations near the Rhine bifurcations (1772 – now)
4. Historical flood reports (1350 – 2013)
5. Sedimentary record (~6000 BC – 2010)

By using all data sources, a discontinuous record of extreme peak floods in the Rhine was generated covering an approximately 8200 year period representative for Lobith. Although the uncertainty in the associated discharge estimates is large compared to the uncertainty in the discharge measurements of the recent past, the created discharge series gives extra information about the extreme discharges that have occurred in the past.

According to this study discharges in the order of >15,000 m^3/s in the Niederrhein region occurred at least twice in the last ~5,000 years. There was no conclusive evidence of discharges as large as 18,000 m^3/s. However, in this period the River Rhine was in pristine conditions. When taking changes in the river (e.g. improved embankments and straightening of the river) into account, the current day equivalent discharge will be between 15,000 – 18,000 m^3/s according to the experts (see also Toonen, 2013).

4.2 Climate change in the Rhine basin (see also appendix C)

Jules Beersma from the KNMI presented the background of the new KNMI’14 scenarios and focussed on the changes in precipitation. This climatological perspective sheds light on question 1 about the plausibility of (future) rainfall events sufficiently large to generate such large flood events.

The new KNMI’14 climate scenarios make use of the newest generation of global climate model results collected in the CMIP5 data set. This CMIP5 also formed the basis for the IPCC 5th assessment report (IPCC, 2014). Together the KNMI’14 scenarios cover a large part of the range of all the climate projections for the Rhine and Meuse basins. The expert group considered them better suitable than the previous KNMI’06 scenarios as they include specifically the changes in Rhine and Meuse basins, where the KNMI’06 scenarios were in principle projections for The Netherlands only. In the new KNMI’14 climate scenarios, increases of the basin-average 10-day precipitation (in the winter half year) up to ~20% in 2085 are projected (in the W_H scenario).

The methods used to generate the KNMI'14 scenarios have been extensively reported in the scientific literature. The expert group considered the scenario changes in the 10-day precipitation plausible and not excessive since:

1. There is a number of CMIP5 climate model runs that project comparable increases extreme discharges.
2. The largest increase of the mean winter precipitation in the W_H scenario in 2085 of almost 30% is in line with the simple rule of thumb that for every degree temperature rise, the amount of water(vapour) in the atmosphere increases with ~4-8%. For the W_H scenario a temperature increase is projected of about 4.5°C in 2085, corresponding to an increase of the amount of water in the atmosphere of up to about 30%.
3. It is physically not implausible that the changes in extreme basin-average 10-day precipitation are of the same order of magnitude as the changes in mean (winter) precipitation.

The delta-change approach used to construct the future precipitation and temperature time series alters the statistical properties of observed time series based on the changes in the scenarios. It does not allow for new weather patterns that may occur in future. This may be regarded as a limitation in the context given here.

4.3 Simulation of basin runoff (see also Appendix D)

Mark Hegnauer presented the results of the GRADE simulations. The Generator of Rainfall and Discharge Extremes (GRADE) is used to simulate very extreme discharges in the Rhine basin (Hegnauer et al., 2014). GRADE uses a historical time series of daily observed weather (precipitation and temperature) and provides synthetic weather series from this data by resampling, The focus was on the basin runoff. This hydrological perspective also sheds light on question 1 about the plausibility that such large rainfall events may lead to the production of sufficiently large amounts of water in the Rhine basin.

The hydrological processes leading to extreme flood peaks in the Rhine basin are strongly dominated by precipitation amounts that fall over many consecutive days over large parts in the river basin. The relation between increase in precipitation and increase in generated runoff is not linear per se. In dry conditions much rainfall will enter the soil and will not come to discharge directly. However, especially in very wet conditions, the discharge will rapidly increase with increasing precipitation, as the soil is saturated with water. For the most extreme situations all the storage capacity for water in the catchment is already full and nearly all precipitation that falls additionally will completely contribute to the runoff. This is the reason that in winter a good correlation exists between the 10 day precipitation sum and the discharge peak at Lobith.

The hydrological model (HBV) used to simulate the runoff series for the Rhine has been extensively validated for a period that includes the 2nd and 3rd highest flood event since 1901, up to 12,000 m^3/s, observed in the Rhine at Lobith. The version used in the KNMI-Deltares study is based on the rainfall-runoff model that provides daily discharge forecasts for many gauging stations in the entire basin, in Switzerland, Germany as well as in the Netherlands. The set-up, validation and performance of the rainfall-runoff model have been reported in the scientific literature. Although well validated, the maximum peak flows validated for are far less than those needed to produce discharges higher than 18,000 m^3/s at Lobith.

Today, under current climate conditions, very extreme precipitation events could lead to very extreme discharges at Lobith. Using GRADE to simulate 50,000 years of runoff, discharges higher than 20,000 m^3/s (and up to 21,000 m^3/s) are calculated for the current climatological conditions, when the effect of flooding is ignored. In the new KNMI'14 scenarios, these precipitation events become more severe, leading to even higher discharge events, exceeding 26,000 m^3/s (Sperna Weiland et al., 2015). There is no empirical experience that can support or reject the occurrence of such runoff events.

Still, the expert group considered the discharge events higher than 20,000 m^3/s at Lobith as events beyond imagination. An earlier study (Silva, 2003) added up the maximum discharges observed in the main tributaries for the period 1880-1995, which would result in a discharge of 16,900 m^3/s at Lobith. They also made an expert-estimation of the maximum discharge that could be conveyed through the tributaries. Adding up the latter series of discharges would lead to a discharge of 22,860 m^3/s at Lobith. More recently, BfG and other authorities in Germany combined adverse atmospheric situations for German rivers including the Rhine to construct a catastrophic snow melt flood event as a basis for emergency management (Deutscher Bundestag, 2013). All three are very hypothetical maximum estimates as these maxima did not occur during the same event. Moreover these figures are still well below the maximum simulated discharge. The production of water volumes above 17,000 m^3/s at Lobith assumes lateral inflows from tributaries (far) beyond any recorded discharge in these tributaries. This makes the potential for (future) validation of the models used to simulate these flows very limited.
Although we are talking about 'events beyond imagination', the simulated response of the basin to the enormous precipitation volume seems plausible, as under extremely wet conditions almost all rainfall will very rapidly come to discharge. There is no obvious reason to assume a completely different response if the rainfall amounts become even larger.

4.4 Propagation of flood waves through the River Rhine (see also appendix E)

Hermjan Barneveld showed an overview of the results of studies that were performed to analyse the flood wave propagation through the Rhine. This perspective sheds light on question 2, about the conveyance capacity of the Rhine valley and most particularly about the conveyance capacity of the Niederrhein region.

In the Rhine, there are mainly two regions where (major) flooding can occur when embankments are overtopped, the Upper Rhine (between Basel and Kaub) and the Lower Rhine (or Niederrhein) between Bonn and Lobith. Water overtopping the embankments and as a result attenuation of the flood peak is taken into account in hydrodynamic models downstream of Maxau. Between Basel and Maxau this is not taken into account. The Sobek model of the Rhine starts at Maxau and runs until the Pannerdensche Kop bifurcation in the Netherlands (just downstream of Lobith). Areas of potential flooding between Maxau and Wesel are taken into account in the Sobek model.

From a hydrodynamic point of view, there is no limitation for these amounts of water to reach Bonn. Studies were carried out to assess the effect of overtopping of levees along the river stretches downstream of Maxau. 23 flood areas were taken into account (7 in Baden-Württemberg; 11 in Rheinland-Pfalz and 5 in Hessen). For a situation, assuming a peak flow of 9000 m^3/s at Maxau, the peak flow at Bonn was lowered by about 4000 m^3/s due to flooding of these 23 areas (from 16,000 to 12,000 m^3/s). Between Kaub and Bonn no flooding could occur because of the narrow shape of the river valley.

All water that flows at Kaub reaches Bonn without any substantial flood peak attenuation. In this section during floods the lateral inflow from the Mosel tributary is also often very large.

Downstream of Bonn again two stretches can be distinguished. Between Bonn and Wesel, flood water can be stored or discharged parallel to the river. First, water will only be stored behind the embankments, once the storage capacity is exceeded, most of the flood water will flow back (however with some delay) to the Rhine River at various locations. Downstream of Wesel the water overflowing the embankments enters an area that spills towards the Old IJssel in the Netherlands and/or to the Waal via the Duffelt/Ooijpolder.
The embankments along the Niederrhein in the section Wesel-Lobith are designed to convey a discharge of at least 14,500 m^3/s. Taking into account the freeboard (1 meter) of the embankments this would add 2000 – 3000 m^3/s, leading to 16,500 – 17,500 m^3/s discharge capacity. The model simulations suggest that 18,000 m^3/s would lead to water levels exceeding the level of the embankments at several locations along the stretch Wesel-Lobith (Figure 4-1).

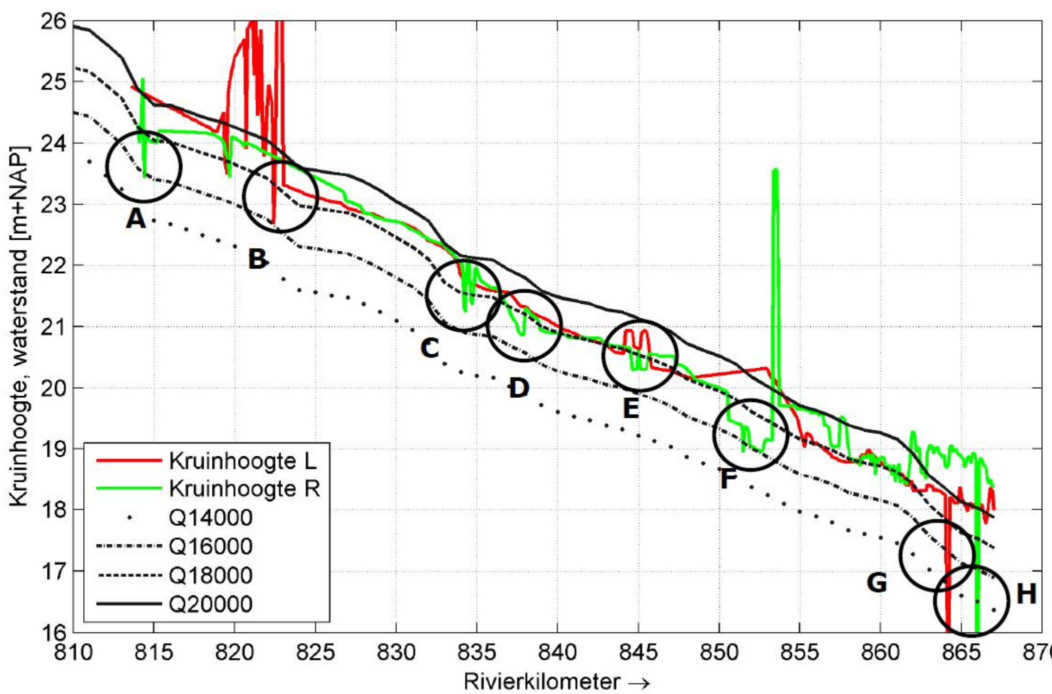

Figure 4-1 Overview of the height of the top of the levee at the left (red) and right (green) banks of the Rhine at stretch between Wesel and Pannerdensche Kop (NL). In black the steady state water levels for 4 discharge scenarios calculated with the WAQUA model without flooding are given (source: Paarlberg, 2014)

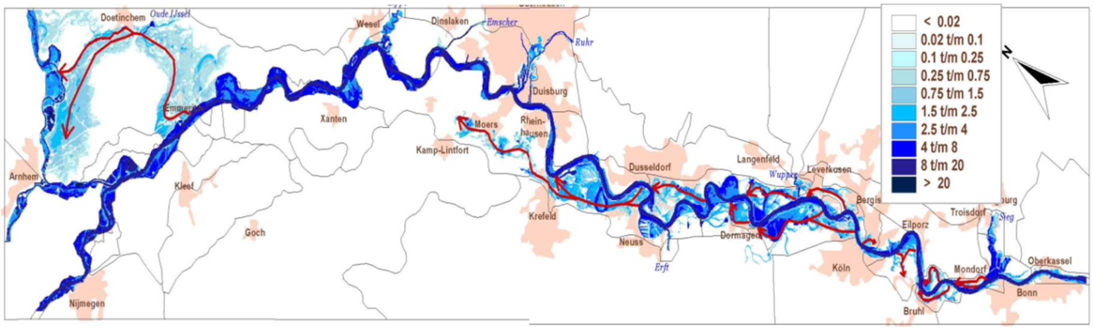

Figure 4-2 *2D overview of the flooding pattern in the Niederrhein at discharges when overtopping of embankments occurs between Bonn and Lobith. In the left, the shortcut towards the (old) IJssel is shown (Source Lammersen et al. 2004)*

In the Niederrhein section Lammersen et al. (2004) and Gudden (unpublished), quantified the effects of flooding on the propagation of flood waves in the Rhine (Figure 4-2). They applied a 2-D hydrodynamic model (Delft-FLS). In these studies it was shown that the effect of flooding along the Niederrhein starts above 12,000 m^3/s and becomes more and more substantial when discharge increases. The exact effect depends on the flood wave characteristics, such as the height and the duration. Lammersen (2004) showed for a flood peak of 17,800 m^3/s at Bonn/Andernach the peak discharge at Lobith would be reduced to 16,500 m^3/s. For a flood peak of 22,000 m^3/s at Bonn the estimated reduction was around 4,000 m^3/s (Gudden unpublished). Above discharges of 22,000 m^3/s at Bonn no 2-D simulations were made.

To reduce computing time and allow for evaluating large series of flood waves, the 2-D model was replaced by a 1-D model. This 1-D Sobek model was used to simulate the effect of flooding for the KNMI'14 scenarios. This 1-D model was calibrated with the use of this Delft-FLS and a 2D Waqua model. Vieira da Silva et al. (2013) compared the Sobek results to the Waqua results for 5 discharge events with peak discharges at Bonn/Andernach up to 20,000m^3/s. It was shown that up to approximately 17,000 m^3/s at Bonn, the Sobek model results correspond well to the Waqua model results. For higher discharge events, the Sobek model, for these specific events seems to overestimate the discharge at Lobith with up to 1000 m^3/s.

Figure 4-3 shows that when the peak discharge of a flood at Bonn/Andernach is around 20.000 m^3/s, the peak discharge at Lobith with the WAQUA model with dike overflow (dikes 2020 situation) would be around 18,000 m^3/s. This is calculated with the WAQUA model which is probably the best 2-D-schematisation available at this moment (although there is room for improvement of this model, e.g. with respect to the elevation data used).

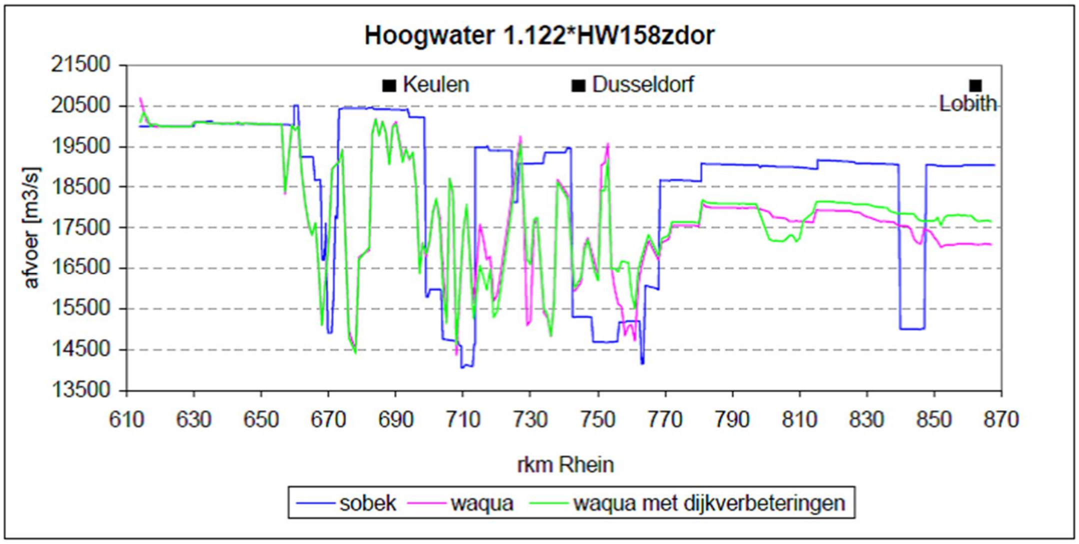

Figure 4-3. Comparison of discharges along the stretch Andernach/Bonn – Lobith between the 1-D sobek model and the 2-D Waqua model. From “Grade - Dijkoverstroming Niederrhein: SOBEK versus WAQUA” (HKV, March 2013)

The overestimation of the discharge at Lobith is most likely caused by the underestimation of the flooded area (and corresponding volume) in the Sobek model that was derived from previous Delft-FLS model results. Another reason for the underestimation of the attenuation of the flood peak is that the location where flooding could occur is pre-defined in the Sobek model. In reality (which is more easily represented in a 2D model) other locations where overtopping could occur may show up in case of (much) larger floods.

One of the sections where the 1-D model clearly underestimates the overtopping is in the section downstream of Wesel. Via overtopping of the embankments downstream of Wesel, water may leave the Rhine valley or will return into the Rhine branches far downstream Lobith. Overtopping of the right bank of the Rhine, leads to flooding of dike ring 48 and water could flow over the IJssel dikes (near Doesburg) and into the IJssel (see Figure 4-4, blue arrows). Overtopping the left bank leads to flooding of dike ring 42. This water could flow as far as Nijmegen. There it may return into the Waal (see Figure 4-4, orange arrows). This implies that the gauging station Lobith is probably not the most adequate reference point to assess the consequences of such extreme flood events. During these extreme flows, water will pass-by this station. Thus, for adequate analysis of the peak flows that may reach the delta, the entire reach between Bonn and the Rhine delta should be considered.

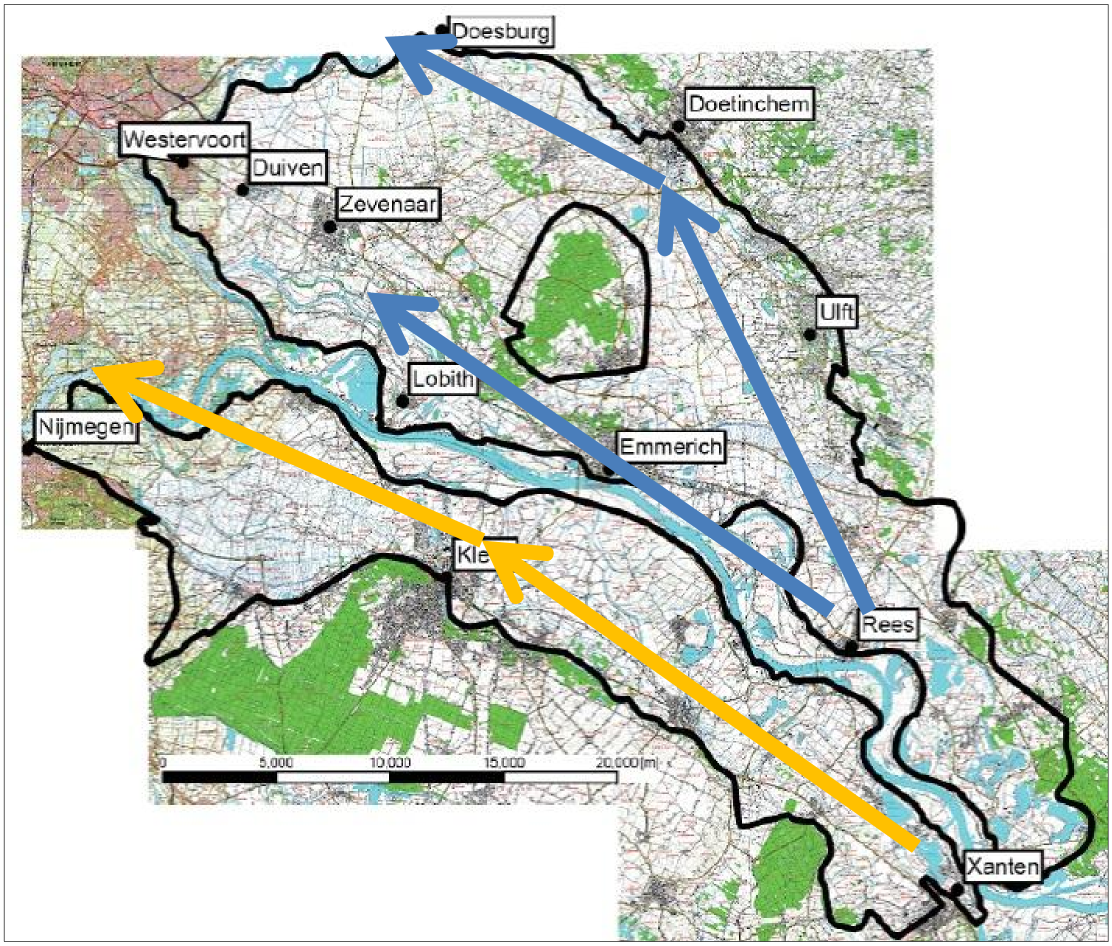

Figure 4-4 Map with an indication of the direction the water will go when a dike breaches in Germany, just upstream of Lobith

4.5 Flood risk strategy in Nord-Rhein Westfalen (no slides)

Bernd Mehlig presented the flood risk strategy in Nordrhein-Westfalen. The assessment of the effect of flooding depends also on the (future) flood risk strategy in Nordrhein-Westfalen (NRW). The protection standards in NRW are not defined by law (Mehlig, this meeting). In practice, the standard is a protection to floods that have a return period of 100 years or more. The current standards for flood protection along the Rhine in NRW are between 1/200 and 1/500 annually. This seems lower than the standard in the Netherlands (1/1250 yr^{-1}). However, in practice the height of the embankments in NRW along the River Rhine is comparable with the height in the Netherlands. This is because in NRW the additional height (freeboard, in Dutch: “waakhoogte”) is larger than in the Netherlands.

Regarding floods higher than design discharges The current flood risk management policy in NRW has the focus on managing the residual risk rather than improve the flood protection of areas. This means that the focus is to minimize or avoid damage and/or damage potential of flooding.

This seems a robust policy for NRW now and in the future since:

- The potential for technical measures to raise dikes is limited in NRW. This would mean an operation along very large stretches of the River Rhine. Raising a dike also means widening of its basis. Along these stretches the space for raising dikes is very limited.
- Moreover, in some stretches raising dikes is simply not feasible since the sub-surface consists of very coarse sediments. In these areas “gaps” in the dike lines would remain, which nullifies the effects of raising dikes elsewhere.
- Along the River Rhine in NRW measures to mitigate the impact of flooding seem generally economically more viable and sustainable than measures to reduce the flood probability. Therefore the flood management strategy of NRW regarding extreme floods aims more at reducing the potential damage as compared to the Dutch policy. The conclusion is that the (future) flood management measures focused on extreme floods in NRW differ from the (future) Dutch flood management measures.
- Realizing additional protection to specific areas would easily lead to more extensive flooding of areas elsewhere in NRW. This is considered undesired.

Based on this it seems that the current flood risk approach in NRW is robust in view of both the current and future flood risk. For the time there seems little reason to change the current policy in NRW.

5 Recommendations and future research

5.1 Improve the knowledge about the consequences of flooding on the Rhine discharges

From the discussions it appears that the largest uncertainties in the estimates of water arriving in The Netherlands via the River Rhine are related to the effects of flooding along the Rhine between Wesel and Lobith. Also, the retention capacity of the Oberrhein upstream of Kaub and in the main tributaries plays a role. Since the first estimates by Lammersen (2004) the availability of topographic data has increased at an incredible pace. This counts particularly for the availability of elevation data such as LIDAR. These can provide us with elevation data at a horizontal resolution of 30 cm with a vertical accuracy in the order of 10 cm or better. Next to the growing data availability, computing speed has increased by a factor 50 or more since 2003. Also new computer codes for inundation modelling have been developed that can handle these large data sets and make use of the increased computing power. Examples are 3Di, Sobek 1D-2D, Sobek3-FlexibleMesh (all in the Netherlands). Alternative, computationally very fast codes exist such as LISFLOOD-FP (UK-Uni-Bristol; (Bates and De Roo, 2000)) and GLOFRIS (Winsemius et al, 2013). These may be used to advance the issue with fast and simplified but reasonable Monte Carlo approaches which allow many runs in order to better take into account uncertainties and to understand their effects on flood probabilities/risks (see e.g. De Bruijn, Diermanse & Beckers, 2014; Straatsma and Baptist, 2008).

It seems obvious that we should explore the potential of these “new” developments for increasing our understanding of these flood events.

Thus the panel strongly recommends an extensive international study as a follow up of the study by Lammersen et al. (2004) that uses 2-D hydraulic modelling to provide scientifically sound information on the hydraulic effects in the Rhine.

With respect to this three initiatives need to be mentioned:

- The project “Floods of the Past” that combines past landscape and flood level reconstructions with 2D modelling to reduce uncertainty in past flood magnitude estimates: improve estimates of past extreme floods of the Rhine, flooding and timing of the flooding in the Niederrhein and the Bovenrijn in the Netherlands, with and without dike breaches. This is a co-operation between Utrecht University, Twente University, Deltares, Rijkswaterstaat, Lievense-CSO, Water Boards, RCE and NRW.

- The EU project SYSTEM-RISK that builds upon the entire risk chain, from the source of hazard to consequences. The Niederrhein region will be a pilot in this project. This is cooperation between a series of European research centres. In Germany this is the GFZ-Potsdam and in the Netherlands Deltares and Futurewater.

- There is an initiative both from NRW and the Netherlands in actualisation, improving and extending the existing flood modelling system for the Niederrhein

5.2 Improve the understanding of causes and consequences of extreme flood events

So far we have tried to capture the origin and consequences of extreme flood events in terms of rainfall volumes, return periods, probabilities of discharge volumes, water levels etc.

Particularly for extreme events as are considered here, these estimates are beset with uncertainties. Often the authorities (and researchers) are concentrated on simulated values at one or another location of interest. As is stated in this report, the panel considered such events beyond their imagination, which means that our understanding of the causes and assessment of the consequences is limited. This means that other approaches might add to the traditional ones. More narrative approaches where single events are simulated and more thoroughly analysed may add to a better understanding of the conditions than estimated return periods and probabilities. In view of this two interesting initiatives are:

- Recently, BfG and other authorities in Germany combined adverse atmospheric situations for German rivers including the Rhine river to construct a catastrophic snow melt flood event as a basis for emergency management (Deutscher Bundestag, 2013);
- The KNMI and Deltares are preparing a programme called “Future Weather” which focusses on the deterministic simulation of very extreme single weather events under changed climate conditions and analysis of their hydrological effects and consequences for water management. A comparable research project has started in Germany under the name WETRAX (https://idw-online.de/de/news637724).

The panel recommends to elaborate on alternative approaches to understand the causes and consequences of the extreme events.

5.3 Include the region between Bonn and Lobith in assessing the flood risk in the Netherlands.

Determining the boundary conditions for the flood risk strategy in the Netherlands starts typically at Lobith (for the Rhine) and Borgharen (for the Meuse) since the rivers pass the administrative boundary at these locations. The current interest focusses on the maximum discharges that may arrive at these stations. Focus on flood analysis in the entire delta (starting from Bonn) is needed for a consistent and complete analysis of flood water levels along the Rhine. The extreme events analysed here may not lead to exceedence of the maximum capacity that can be conveyed safely between the embankments in the Netherlands. This may lead to a false awareness of the risk of flooding, since water could also enter the Netherlands via unexpected pathways (i.e. historical but currently inactive channels).

The panel recommends including the area downstream of Bonn in the flood assessments in The Netherlands

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A Genesis of Flood waves in the Rhine basin

A.1 Introduction

To illustrate the results of the simulations of GRADE we analyse in some detail the characteristics and genesis of four flood waves. Three of them were selected from the 50,000 simulations made assuming a climatic change according to the KNMI'14-W_H scenario. The lowest (fourth) one was selected from the simulations assuming current climate conditions. The flood peaks simulated at Lobith are approximately 26,000; 25,000; 23,000 and 16,000, all figures in m^3/s. The estimated annual probability of occurrence of the three highest peaks derived from the GRADE simulations for the KNMI'14-W_H scenario (projection for the year 2085) is respectively, 1/25,000 ; 1/8300 and 1/6300.

For the analysis the Rhine basin is divided into 3 sections, the Oberrhein, Mittelrhein and Niederrhein (Figure A-1, left panel). These sections are fed by different tributaries (Figure A-1, right panel). The Oberrhein and Niederrhein have broad valleys, where flood waves can be reduced due to flooding or breaching of embankments. In the Mittelrhein the Rhine flows through a relatively narrow valley incised into the Eifel mountains. In the Mittelrhein there are hardly (embanked) floodplains, and reduction of flood waves due to flooding plays a minor role.

Four reference stations are used in the analysis: (1) Maxau as most upstream station, (2) Kaub as downstream station of the Oberrhein and upstream station of the Mittelrhein; (3) Bonn/Andernach as downstream station of the Mittelrhein and upstream station of the Niederrhein and (4) Lobith as downstream station of the Niederrhein.

In the analysis we focus on three issues:

- The hydrograph at Lobith (duration, peaks).
- The genesis of the flood waves along the Rhine (where does the water come from).
- The reduction of the waves in the three sections (effect of flooding).

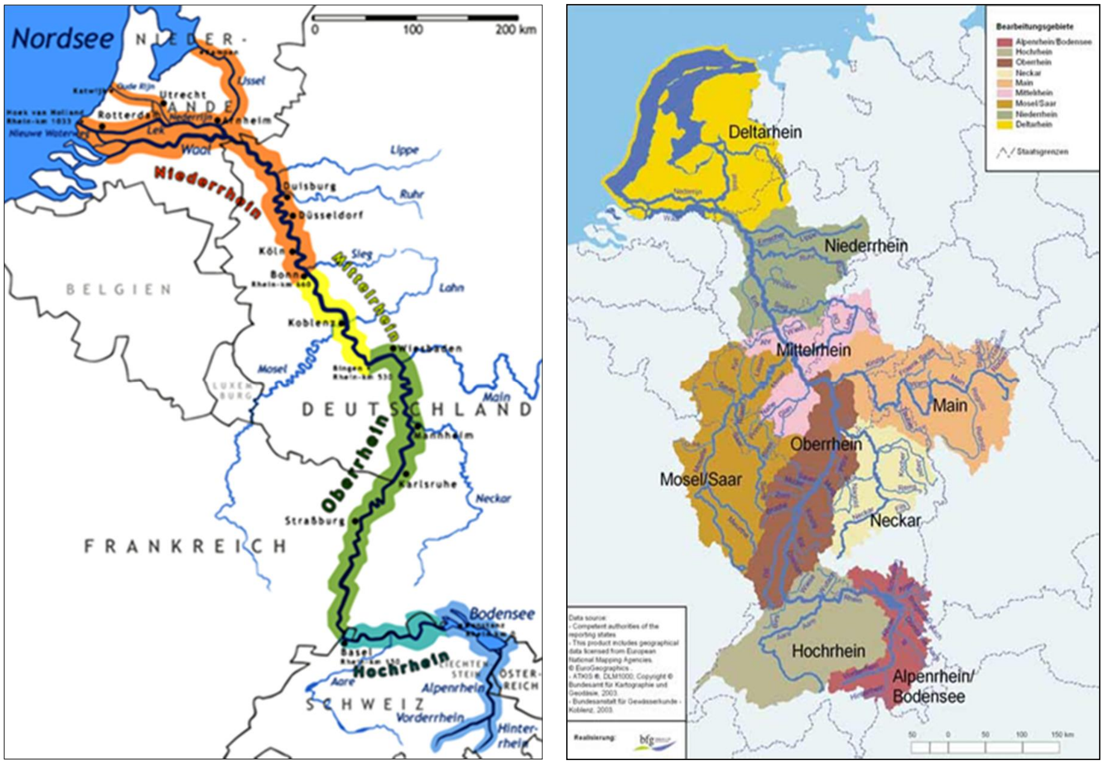


Figure A-1 The river Rhine basin. Left panel: Sections; right panel main tributaries

A.2 Analysis of the Hydrographs at Lobith

Figure A-2 shows the hydrographs at Lobith for the three high flood waves as simulated with GRADE. The characteristics are quite different.

The duration of the flood event showing the highest peak is extremely long. More than 90 consecutive days the discharge remains above 5000 m^3/s, 15 days in total the discharge is above 10,000 m^3/s. During the flood period, two marked peaks occur. Flooding reduces the first peak substantially (~4000 m^3/s (difference between HBV and Sobek)). However, the second peak is less reduced (~ 2000 m^3/s). In the simulation, the floodplains/retention areas are filled during the first wave and cannot store extra water during the second peak. They are not emptied between the first and the second flood peak because the discharge remains (very) high in between the peaks. The second peak is much larger and the floodplains/retention areas are already nearly filled completely while the peak of the flood wave has not yet passed. A only restricted volume of flood water can be stored and the reduction of the real peak is therefore limited.

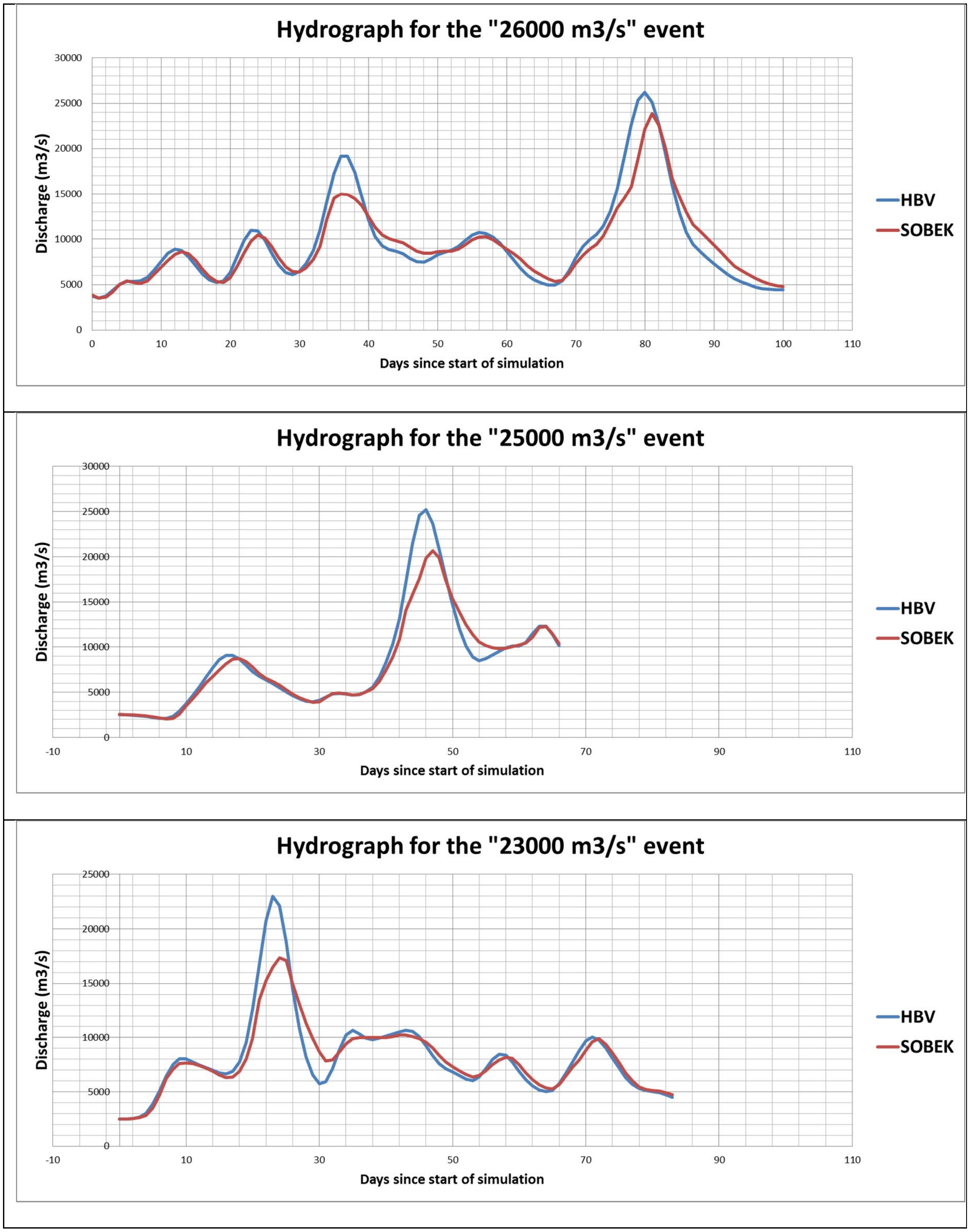


Figure A-2 Hydrographs of the three largest floods as simulated with GRADE. The difference between Sobek and HBV illustrates the reduction of the flood peaks due to flooding

The second and third floods show only one marked flood peak, respectively at the end (for the 25,000 m^3/s peak) and at the start of the event (for the 23,000 m^3/s event). In both cases the peak is reduced considerably by flooding (~5,000 m^3/s and~6,000 m^3/s). The simulations of Sobek and HBV are not very different because the discharge in the period before the peak is below the 12,000 m^3/s and reduction of flood peaks due to spilling of water over the levees has not yet started.

This behaviour is important to realize when interpreting the results of the experiments where 2-D simulations are applied. Since 2-D simulations are demanding in computing time, typically synthetic single peak waves having a limited duration are simulated. At the start of the simulation, areas where retention may occur are assumed to be empty. From such experiments we estimate the attenuation of the peaks due to flooding. According to the GRADE experiments, however, there will be rare events that comprise multiple peaks and discharges that lead to flooding may have occurred for many days before the highest peak arrives. If the first peaks that occur are sufficiently high, they will fill the space available for retention and the attenuation capacity will be reduced for later peaks. Ignoring such more complicated events may very well lead to an over-estimation of the peak reducing capacity. For a reliable estimation of the effects of flooding on the reduction of flood waves also these more complicated events need to be evaluated in the 2-D experiments.

A.3 Analysis of the genesis of the flood waves

Figure A-3 illustrates the genesis of the flood waves between Basel and Lobith. If no flooding is taken into account these waves would reach respectively 26,000 m^3/s, 25,000 m^3/s, 23,000 m^3/s and 16,000 m^3/s at Lobith. The lines show the results of GRADE simulations where the effect of flooding is taken into account. The figures show that the discharge between Andernach and Lobith is not increasing, or is even decreasing. This illustrates the effect of flooding in this river section since in this section there is a significant contribution of water via tributaries (Figure A-4). The timing differences in flood peaks mask the effect of flooding, which makes that the Figure A-3 and Figure A-4 are not completely comparable.

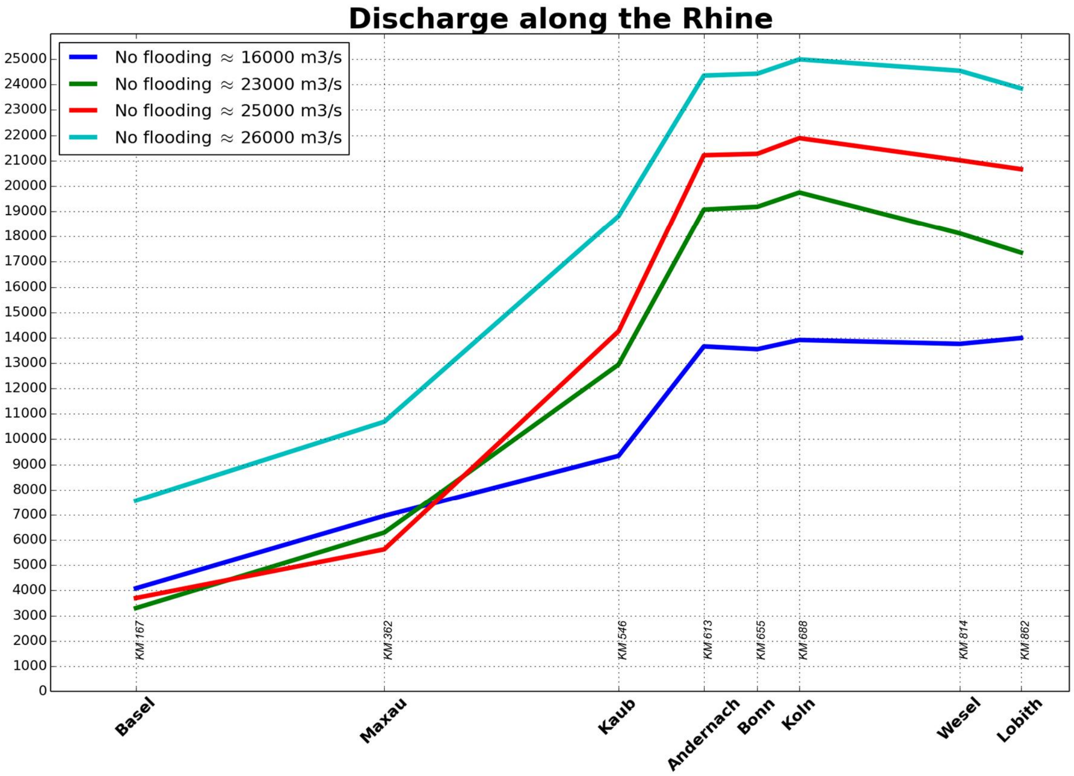


Figure A-3 Genesis of the maximum flood peaks between Basel and Lobith (lines include flooding, while the reference discharges mentioned in the legend ignore flooding

In Figure A-4 the contributions of the main tributaries are plotted, both in volume (m^3/s) (upper panel) and in percentages of the peak at Lobith (lower panel). The discharge in the Oberrhein section (Karlsruhe/Maxau-Bingen/Kaub) is fed by Basel, the Main and Neckar; the discharge in the Mittelrhein section (Bingen/Kaub –Bonn/Andernach) is fed in addition by the Mosel, Lahn and Nahe; The Niederrhein section (Bonn/Andernach-Lobith) is fed in addition by the Ruhr and the Lippe.

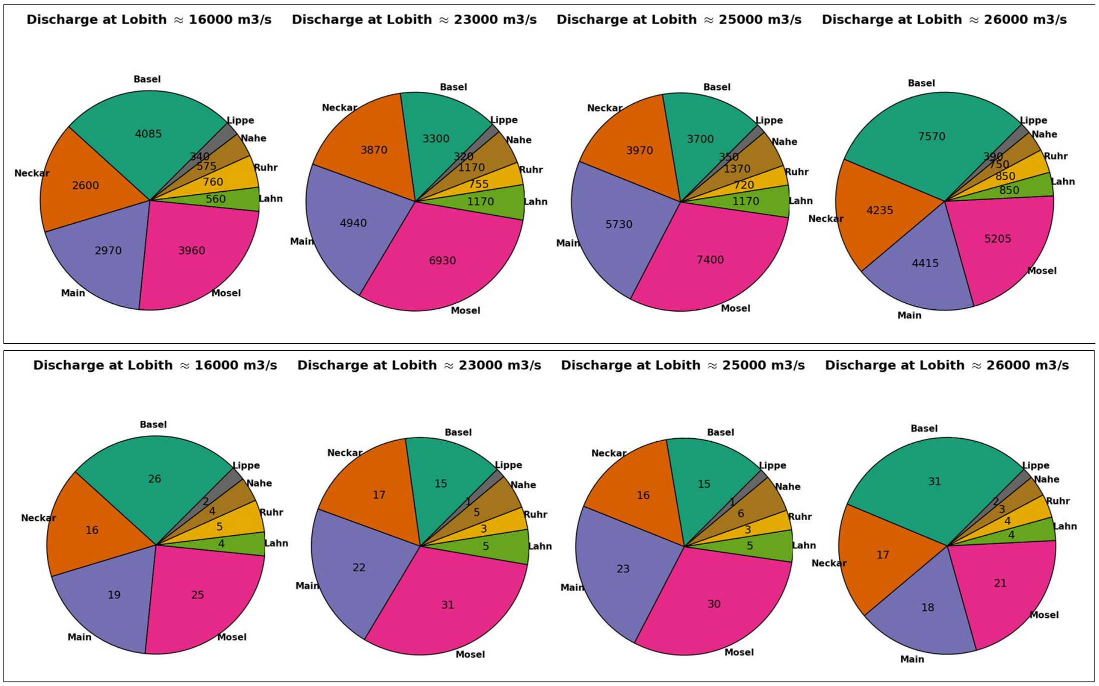


Figure A-4 Contribution of tributaries to the flood waves. Upper row: discharges in m3/s; lower row: % of total peak discharge at Lobith

Figure A-3 and Figure A-4 illustrate that GRADE simulates considerably different genesis of the flood waves arriving at Lobith along the sections of the Rhine. The long stretch upstream of Maxau produces between 15 and 30% of the peak floods. Along the long Oberrhein stretch the Neckar and Main add between 35 and 40%. However, in the MittelRhein section over a relatively short stretch a lot of water is added via the Mosel, Lahn and Nahe. These tributaries add another 30-40%. In the Niederrhein section, the flood waves are reduced, despite the added water via the tributaries Ruhr and Lippe. Their contributions are relatively small compared to the Mosel and Main (Figure A-3, Figure A-4). This nicely illustrates the effect of flooding in this section.

Figure A-4 also shows that according to the GRADE simulations the contribution of the tributaries, both in percentage as in absolute volumes can vary a lot between the individual flood events. Illustrative is the difference between the highest and second highest flood. The highest flood wave is fed by a huge amount of water from far upstream (Basel: ~ 7500 m^3/s (31%)) and the contribution of the Mosel is relatively small (~ 5200 m^3/s (21%)). In the 2nd highest wave the Basel contribution is limited to 3700 m^3/s (15%) while the Mosel produces a flood of 7400 m^3/s (30%).

To put the contribution of the Mosel in perspective, we provide Figure A-5. Discharges upto 5500 and 6000 m^3/s have been observed, the probability of more extreme events can only be assessed via extrapolation or synthetic series.

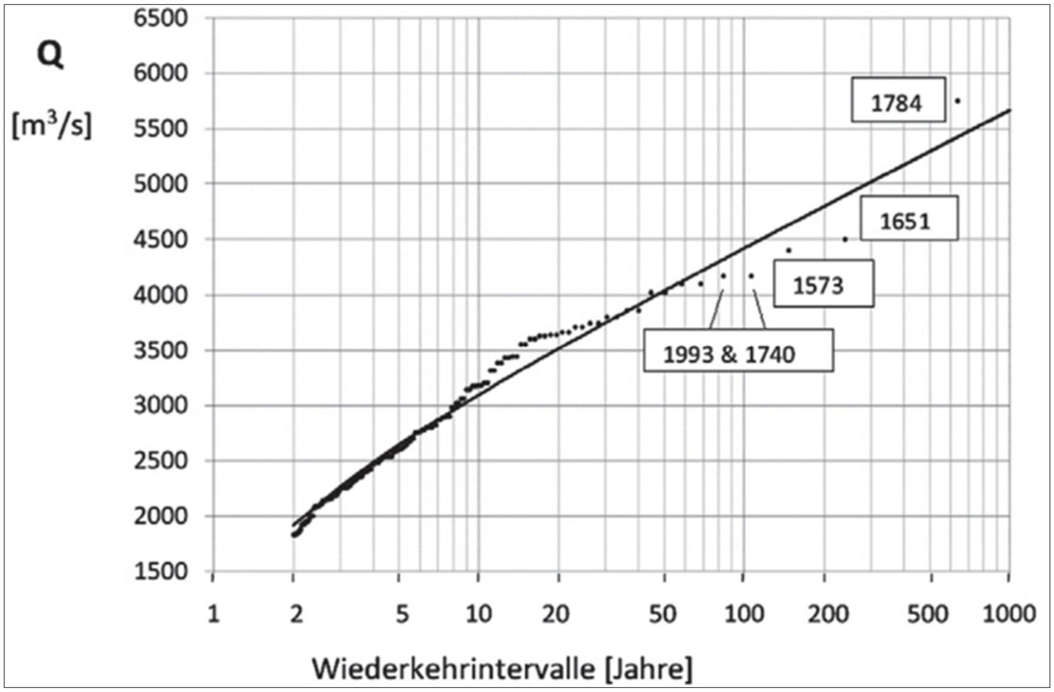


Figure A-5 Estimated return periods of floods from the Mosel (Cochem near the confluence with the Rhine) (source: Sartor et al., 2010)

A.4 The reduction of the waves

The conveyance capacities of the three sections differ. Thus it matters what the main sources of the floods are. Water that is added in the Mittelrhein section will contribute to the discharge in the Niederrhein without the effect of flooding. Events where the contribution upstream Bingen/Kaub is dominant and the contribution of the Mittelrhein is relatively low will be affected much more by flooding in the Oberrhein as well. Analysis of the three floods does not provide an accurate figure for the effect of flooding. An accurate figure of the maximum storage capacity is difficult to provide as its effect depends on the origin of the water, the duration of the flood as well as discharge volume prior to the flood peak. Timing of the peaks of the tributaries also determines the maximum discharge arriving at Lobith. An assessment of the maximum reduction of the flood peak at Lobith is provided in Figure A-6. This figure shows the differences between the peaks as simulated by a combination of HBV and Sobek versus the peaks as simulated by HBV for the entire basin, the Oberrhein and the Mittel-Niederrhein sections. The figure comprises all events that resulted in discharges higher than 20,000 m^3/s at Lobith according to HBV (flooding not taken into account). The figure illustrates that the reduction of peaks differs considerably between the events, which was also illustrated in the Figure A-6. Events showing similarity with the 26,000 m^3/s example that was described above, will be hardly reduced since preceding smaller events have filled the retention capacity before the highest flood wave arrives. Contrary, an equally high flood wave that occurs while the retention capacity is still available will be reduced considerably.

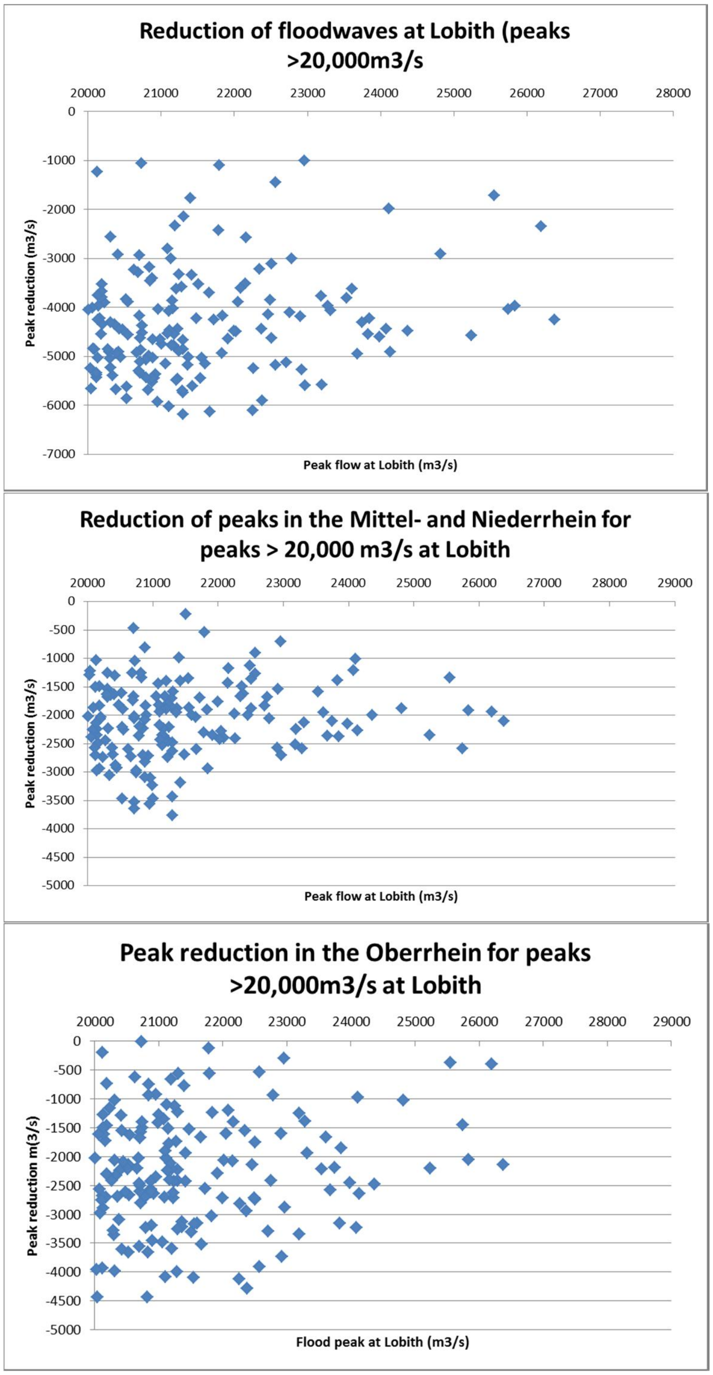


Figure A-6 Difference between the peaks as simulated by a combination of HBV and Sobek versus the peaks as simulated by HBV for the entire basin, the Oberrhein and the Mittel-Niederrhein sections. The figure comprises all events that resulted in discharges higher than 20,000 m^3/s at Lobith according HBV (flooding not taken into account)

From the upper panel in Figure A-6 the maximum peak reduction at Lobith due to upstream flooding according to GRADE is approximately 6000 m^3/s. In the Oberrhein (lowest panel) this is 4500 m^3/s, in the Mittel-Niederrhein section (central panel) the maximum is close to 4000 m^3/s. The sum of the maxima in Oberrhein and Niederrhein is larger than the value estimated from comparison of HBV and Sobek results at Lobith. This suggests that the theoretical maximum reducing effect at Lobith due to upstream flooding according to GRADE is larger than 6000 m^3/s.

As a comparison an assessment from a study on the Oberrhein and Niederrhein, using a 2-D inundation model.

For the Oberrhein, this study of HKV (Barneveld, 2011) assessed the impact of flooding of dike-protected areas between Maxau and Kaub. For a peakflow of 9,000 m^3/s at Maxau, the peakflow at Bonn was lowered by about 4,000 m^3/s (from 16,000 to 12,000 m^3/s) due to flooding along the river stretch between Maxau and Kaub. For the Niederrhein Figure A-7 shows via the length profile between Andernach/Bonn and Lobith the effect of flooding in this Rhine stretch. For discharges up to between 14,000 and 20,000 m^3/s at Bonn/Andernach the peak reduction is 0 to 2500 m^3/s.

The reducing effects as simulated by GRADE are in some cases larger, in some cases smaller. This can be expected since GRADE simulates much higher discharge peaks, peaks that have longer durations, larger volumes, complex events with more than one peak etc. for both river sections to assess the maximum reduction. Unless the Rhine valley would be entirely filled with water, it is reasonable to expect that there will occur peaks that show larger reductions than shown in Figure A-7.

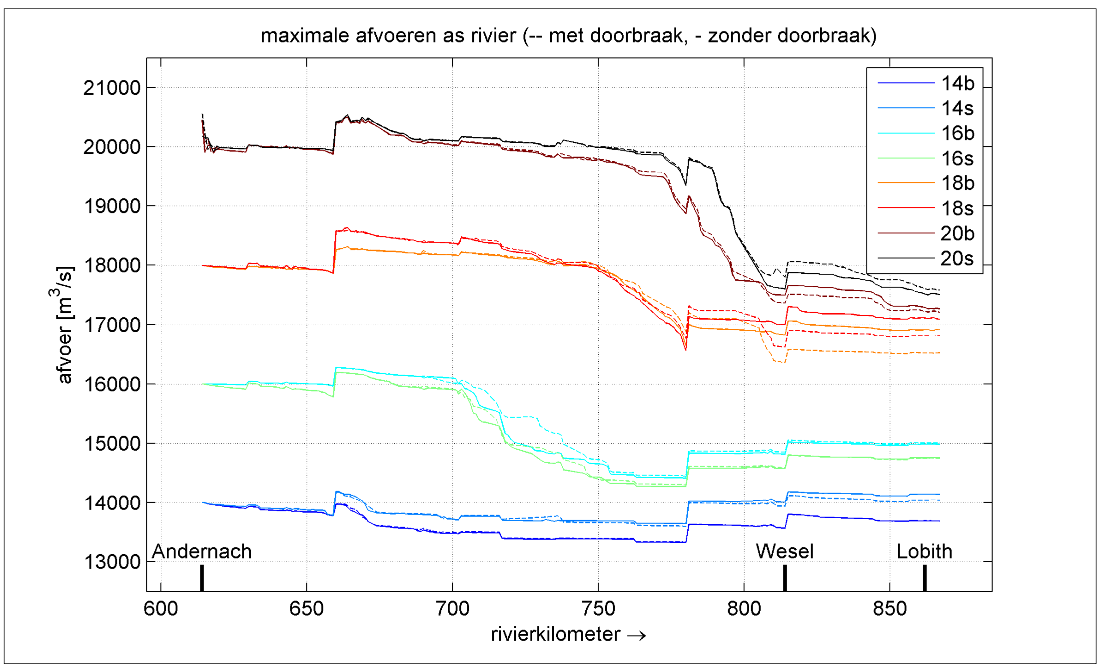
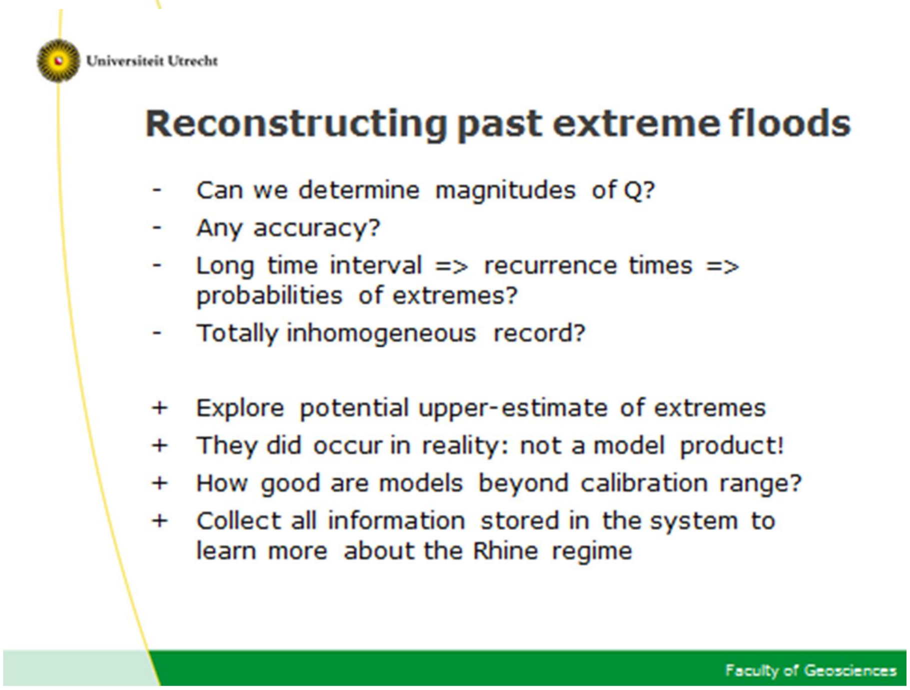


Figure A-7 Length profile of maximum discharges assuming floodwaves between 14,000 and 20,000 m^3/s at Bonn/Andernach along the Niederrhein (Bonn (Andernach) – Wesel-Lobith) (Source: Paarlberg, 2014)

B Slides about historic perspective



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Reconstructing past extreme floods

- Can we determine magnitudes of Q?
- Any accuracy?
- Long time interval => recurrence times => probabilities of extremes?
- Totally inhomogeneous record?

+ Explore potential upper-estimate of extremes
+ They did occur in reality: not a model product!
+ How good are models beyond calibration range?
+ Collect all information stored in the system to learn more about the Rhine regime

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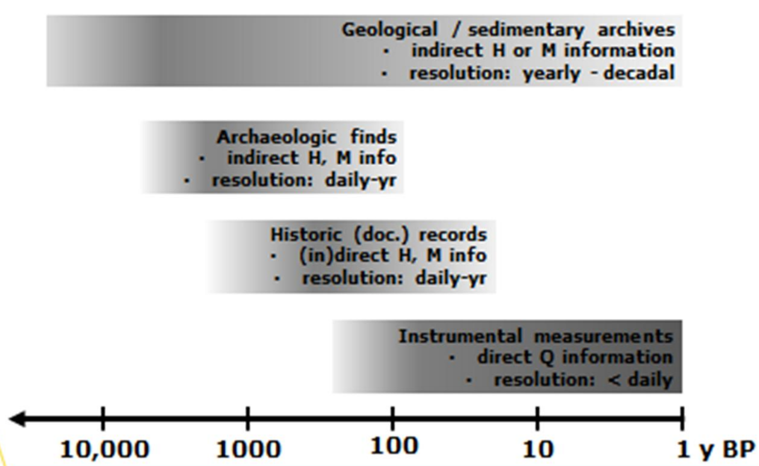
Combining data sources



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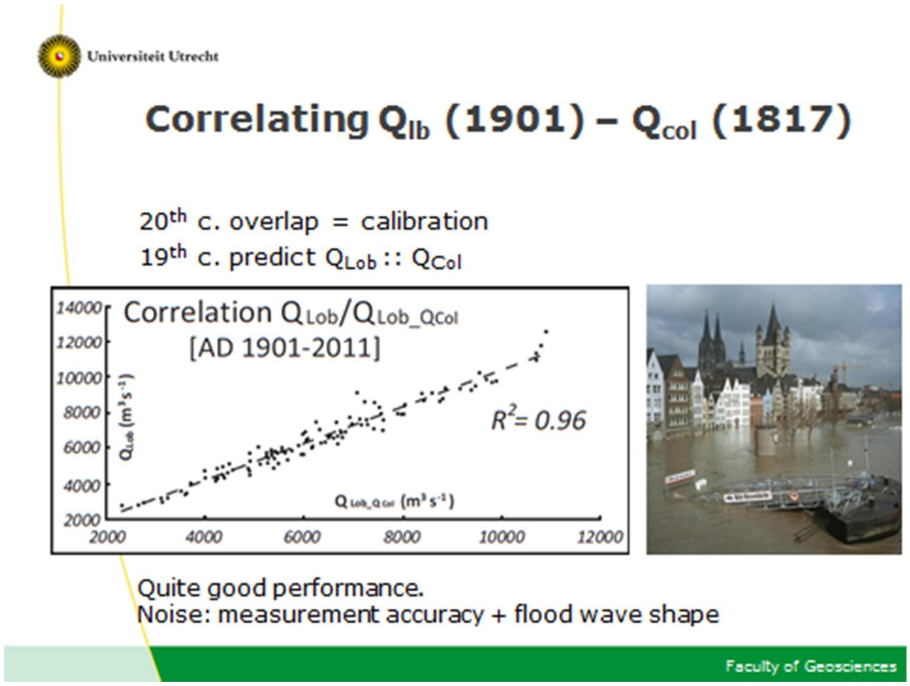
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Correlating Qlb (1901) – Qcol (1817)
20th c. overlap = calibration
19th c. predict QLob :: QCol
Correlation QLob/QLob_QCol
[AD 1901-2011]
R2= 0.96
QLob (m3 s-1)
QLob_QCol (m3 s-1)
Quite good performance.
Noise: measurement accuracy + flood wave shape
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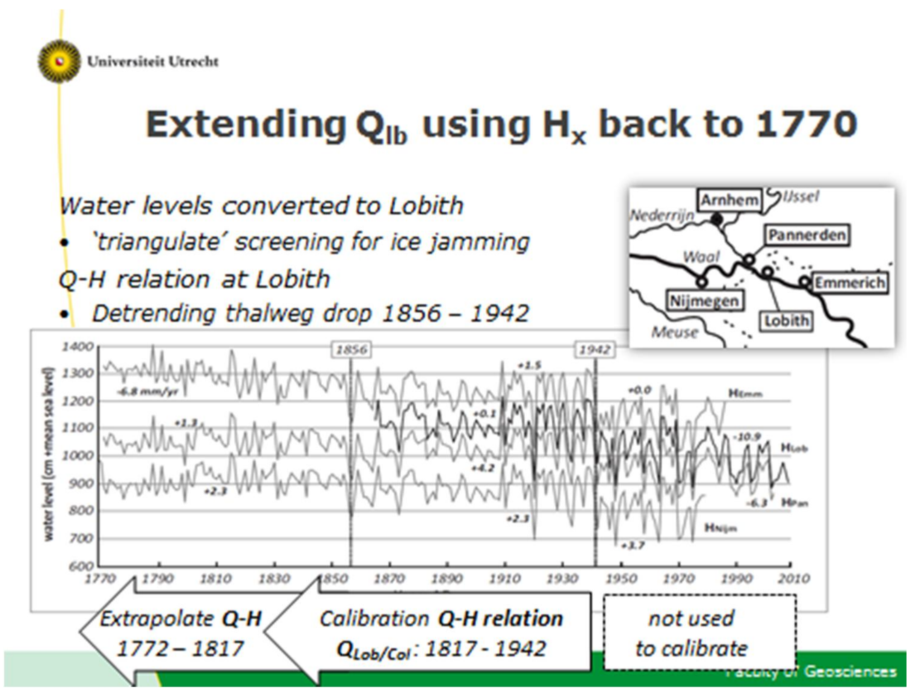
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Extending Qlb using Hx back to 1770
Water levels converted to Lobith
• 'triangulate' screening for ice jamming
Q-H relation at Lobith
• Detrending thalweg drop 1856 – 1942
Arnhem
IJssel
Nederrijn
Pannerden
Waal
Emmerich
Nijmegen
Lobith
Meuse
1856
1942
water level (cm +mean sea level)
Extrapolate Q-H
1772 – 1817
Calibration Q-H relation
QLob/Col: 1817 - 1942
not used
to calibrate
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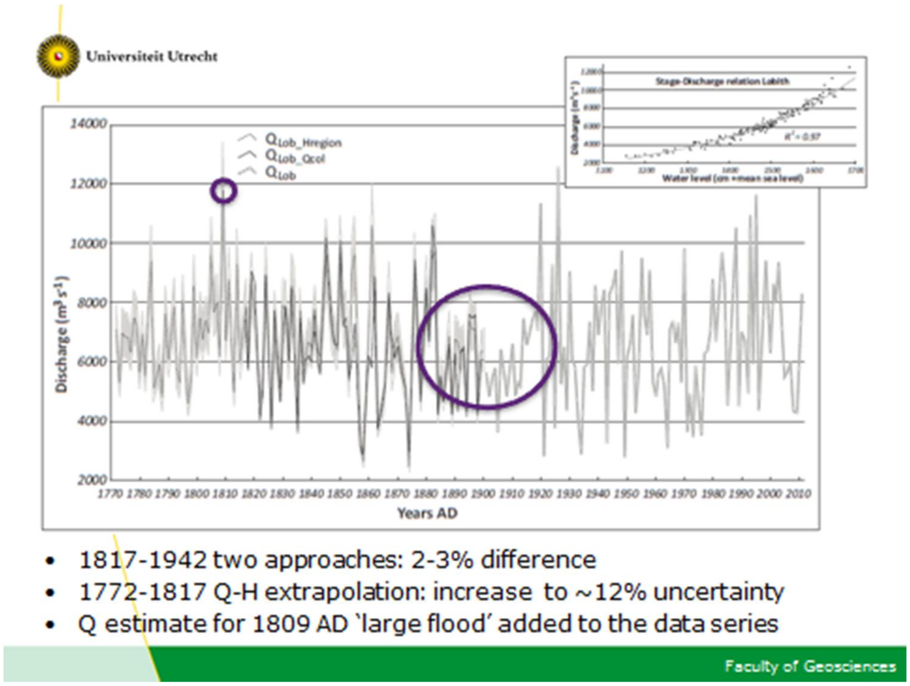
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Stage-Discharge relation Lobith
Discharge (m³s⁻¹)
Water level (cm +mean sea level)
R² = 0.97
Q_Lob_Hregion
Q_Lob_Qcol
Q_Lob
Discharge (m³s⁻¹)
Years AD
• 1817-1942 two approaches: 2-3% difference
• 1772-1817 Q-H extrapolation: increase to ~12% uncertainty
• Q estimate for 1809 AD 'large flood' added to the data series
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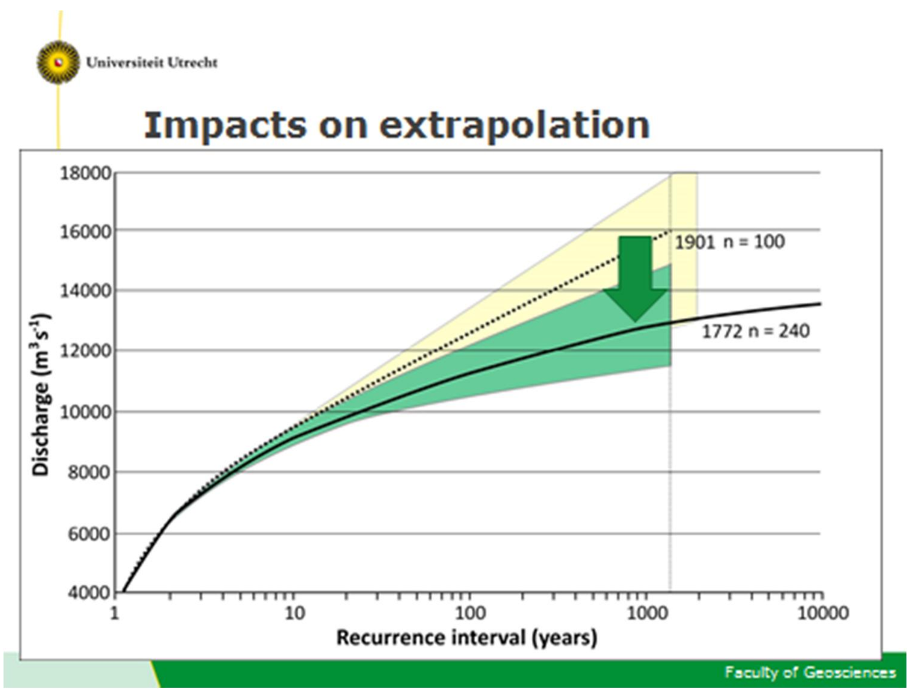
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Impacts on extrapolation
1901 n = 100
1772 n = 240
Discharge (m³s⁻¹)
Recurrence interval (years)
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Historical flood reports since 1350

Score	1350 – 1772	1772 – 2013
1 **modest**	~2.5 years	7160 m^3s^{-1}
2 **considerable**	~5.0 years	8100 m^3s^{-1}
3 **really big**	~11.4 years	9170 m^3s^{-1}

Glaser & Stangl, 2003; Buisman series; Herget & Euler, 2010; Toonen, 2013

Classification based on flood magnitudes: Qualitative data
1: Single dike breach
2: Multiple dike breaches, local impact, minor damage
3: Multiple dike breaches, regional impact, major damage

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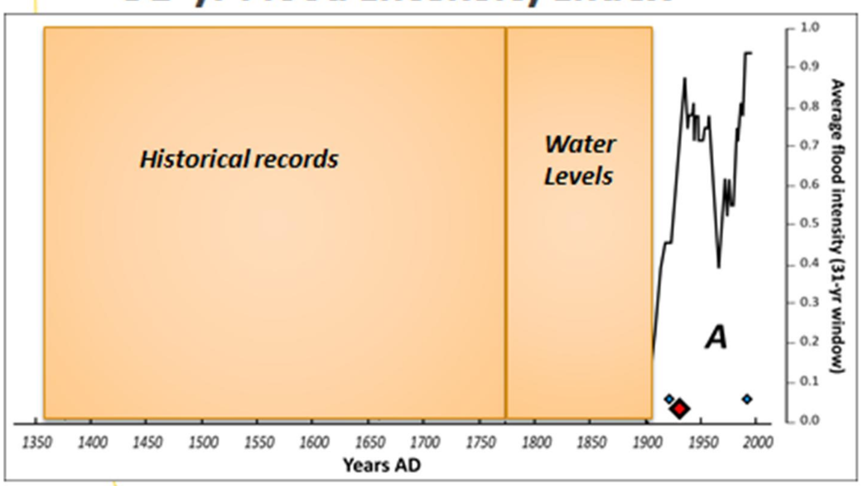
31-yr Flood Intensity Index



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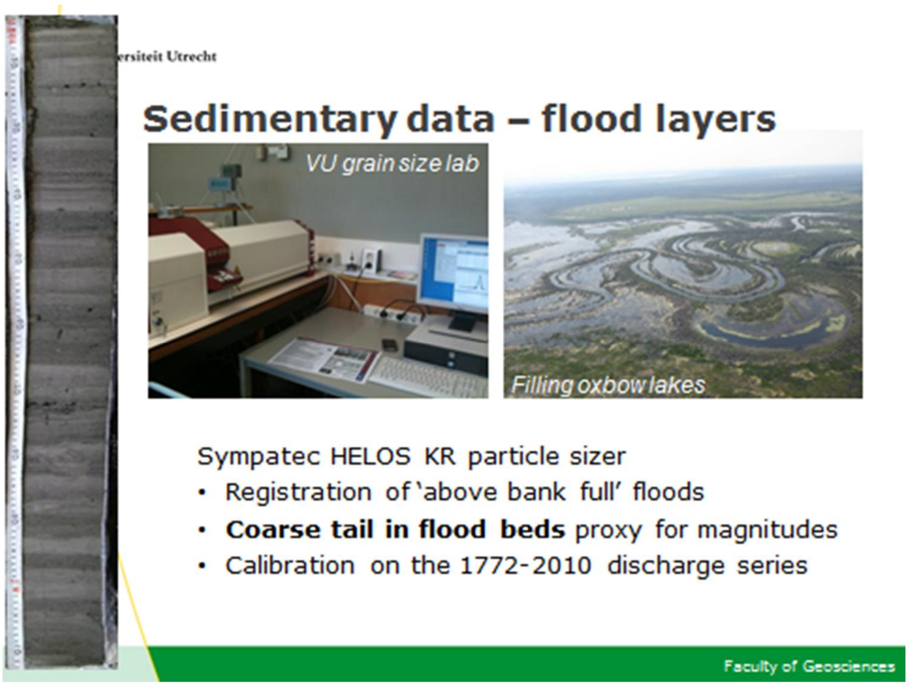
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Sedimentary data – flood layers
VU grain size lab
Filling oxbow lakes
Sympatec HELOS KR particle sizer
• Registration of 'above bank full' floods
• Coarse tail in flood beds proxy for magnitudes
• Calibration on the 1772-2010 discharge series
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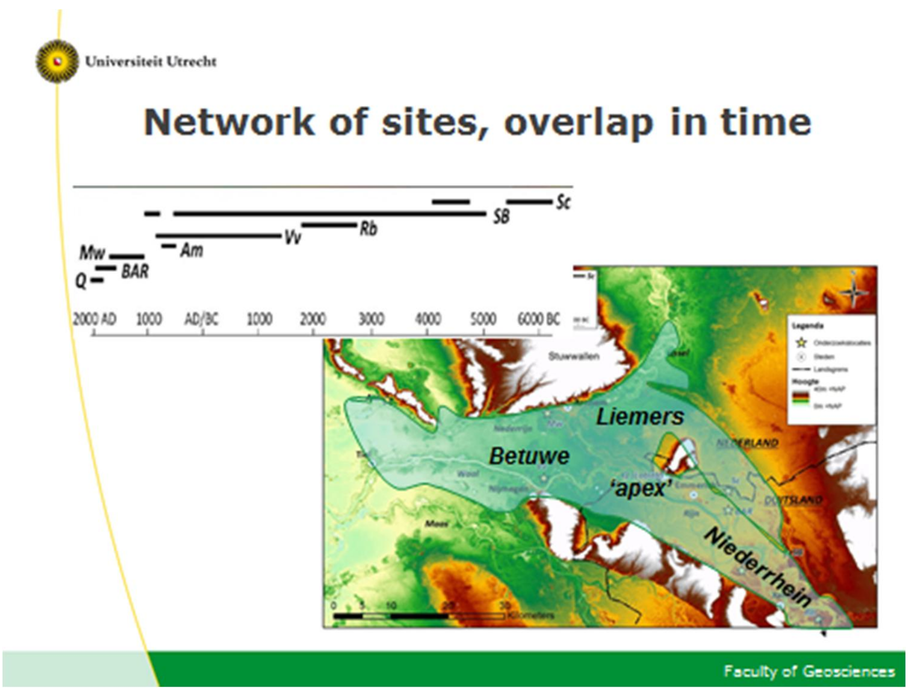
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Network of sites, overlap in time
Sc
SB
Rb
Vv
Am
Mw
BAR
Q
2000 AD 1000 AD/BC 1000 2000 3000 4000 5000 6000 BC
Liemers
Betuwe
'apex'
Niederrhein
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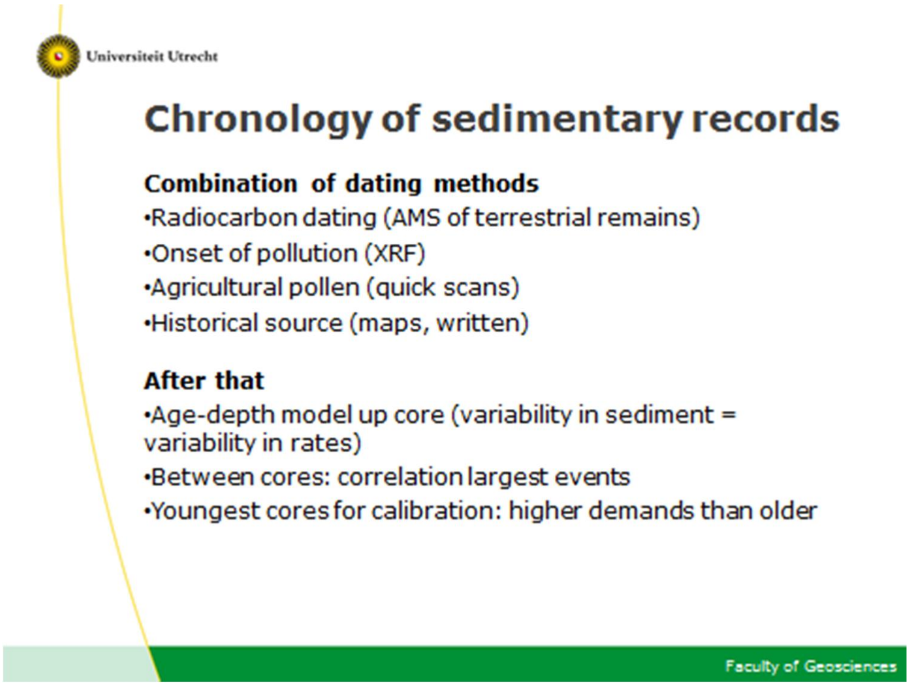
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Chronology of sedimentary records
Combination of dating methods
•Radiocarbon dating (AMS of terrestrial remains)
•Onset of pollution (XRF)
•Agricultural pollen (quick scans)
•Historical source (maps, written)
After that
•Age-depth model up core (variability in sediment = variability in rates)
•Between cores: correlation largest events
•Youngest cores for calibration: higher demands than older
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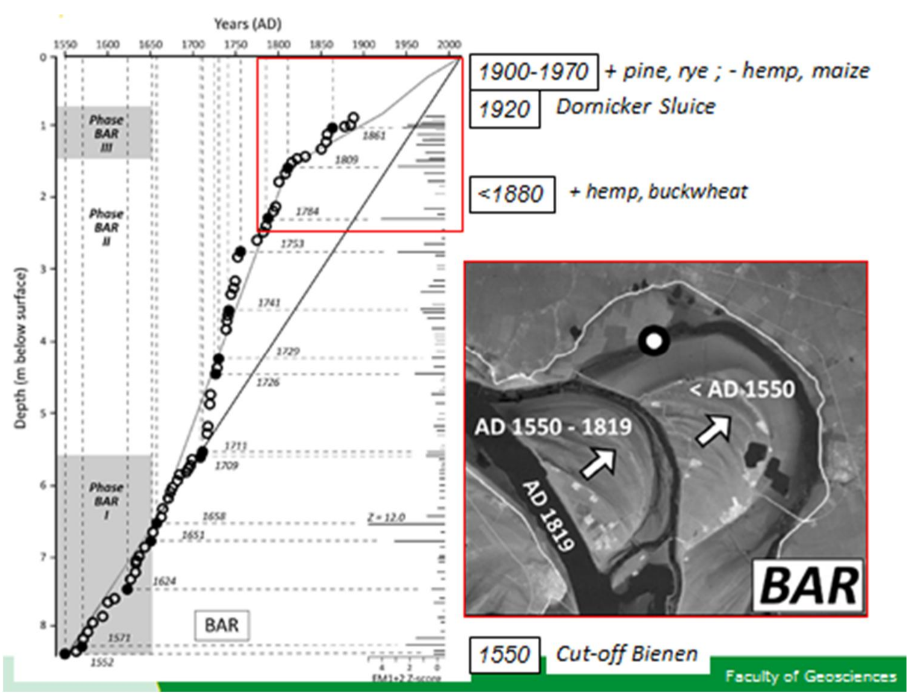
Years (AD)
Depth (m below surface)
Phase BAR III
Phase BAR II
Phase BAR I
BAR
1900-1970
+ pine, rye ; - hemp, maize
1920
Dornicker Sluice
<1880
+ hemp, buckwheat
< AD 1550
AD 1550 - 1819
AD 1819
BAR
1550
Cut-off Bienen
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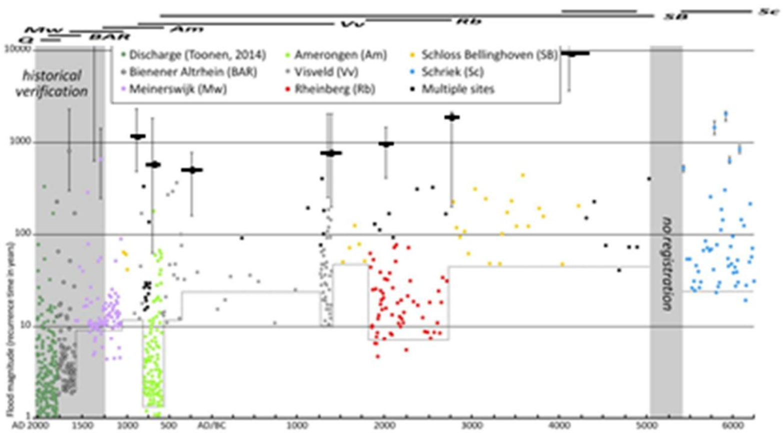

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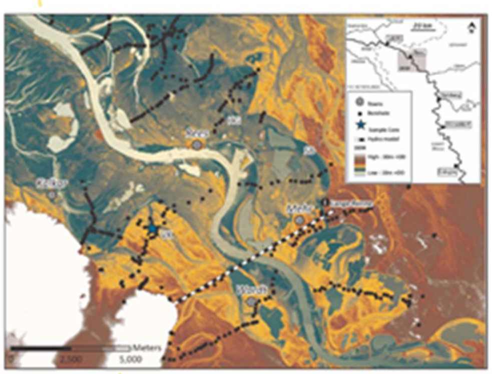
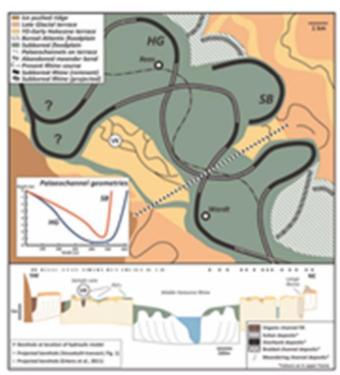
Estimating past extreme Q

- Valley cross section with highest flood layers = H
- Hydraulic equations -> estimate Q





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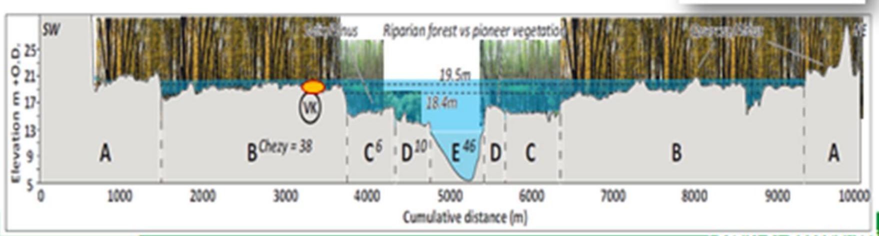
Cross-section Q calculation

- Rheinberg oxbow site = initiated at 4.7 ka
- 10 scenarios evaluated (sensitivity range)
- Best guess: $Q_{4.7ka}$ exceeded 13,250 m^3s^{-1}
- Corresponds with present ~15,000 m^3s^{-1}
- Recurrence time of at least 1250 years (?)

$$\bar{u} = C\sqrt{Ri}$$

$$C = 18\log\frac{12h}{k_s}$$

$$C = \sqrt{\frac{2g}{C_D m D k}} + 2\sqrt{g}\ln\left(\frac{h}{k}\right)$$



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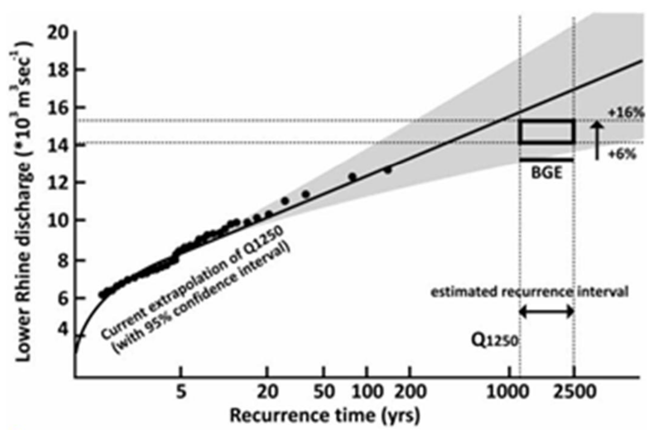
Which estimate is worse?



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Conclusions

- Floods bigger than in 1926 AD have occurred
- Most extreme floods likely overtopped 15,000 m^3s^{-1} (e.g., 1374 AD, 4700 BP)
- No historic or sedimentary evidence for 18,000 m^3s^{-1}
- Extreme peak flows did not occur in periods with increased moderate floods
- Next to non-stationarity due to human impact, non-stationarity due to climate appears real

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Prospects - challenges

- Improve Q-estimates for more (pre-) historic large floods
- Quantify and split Atlantic climate vs. human non-stationarity
- Combine reconstructions of past floodplain characteristics, flood marks and hydraulic modeling

NWO-Water proposal:

Floods of the Past – Design for the Future

With UU, UT, Deltares, RWS, NRWF-LUW, CSO

Integration: geomorphology, archaeology, hydraulic modeling

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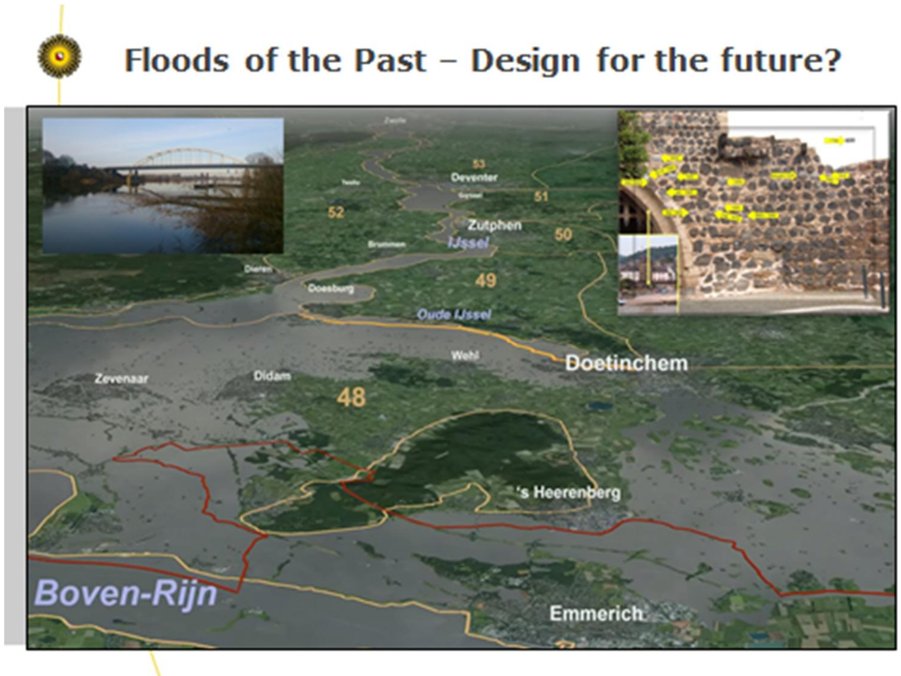
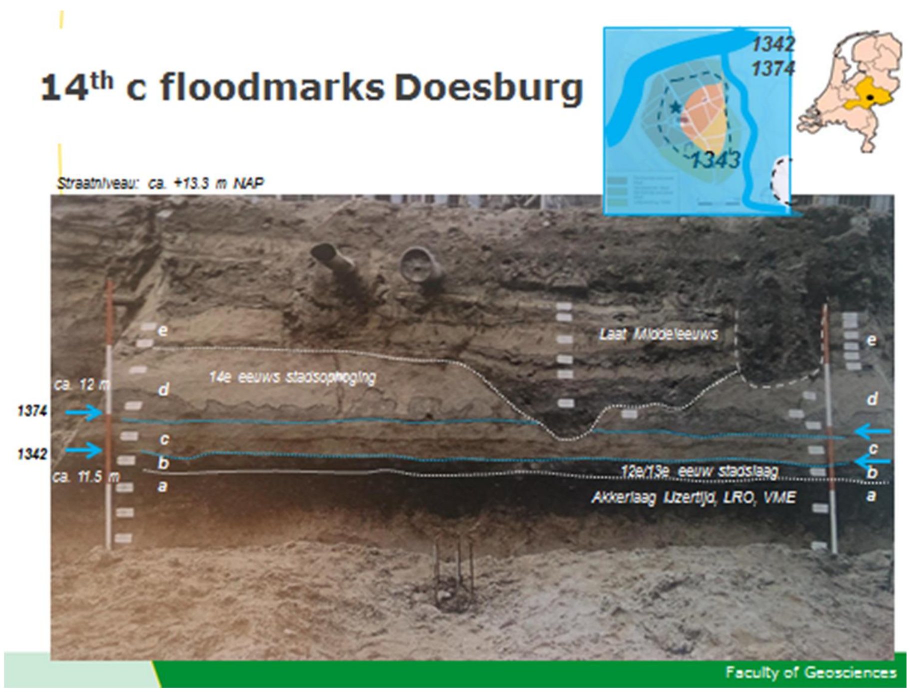

Floods of the Past – Design for the future?
Deventer
Zutphen
IJssel
Doesburg
Oude IJssel
Wehl
Doetinchem
Zevenaar
Didam
's Heerenberg
Boven-Rijn
Emmerich
53
52
51
50
49
48


14th c floodmarks Doesburg
1342
1374
1343
Straatniveau: ca. +13.3 m NAP
Laat Middeleeuws
14e eeuws stadsophoging
ca. 12 m
1374
1342
ca. 11.5 m
12e/13e eeuw stadslaag
Akkerlaag IJzertijd, LRO, VME
e
d
c
b
a
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C Slides about meteorological perspective

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

(KNMI) climate scenarios for the Rhine and the Meuse basins

Jules Beersma

Expert group on extreme river Rhine discharges
22 September 2015
Deltares, Delft

Climate scenarios for the Rhine

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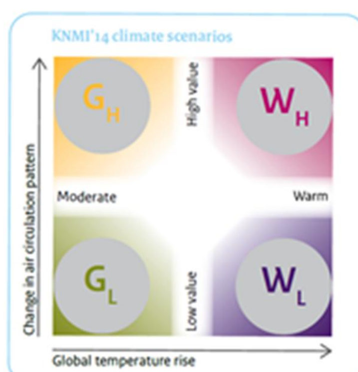
Meteorological Institute
Ministry of Infrastructure and the Environment

- KNMI'14 (2015)
- CMIP5 (2014)
- RheinBlick2050 (2010)

- *KNMI'06 (2006)*



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History KNMI'14 scenarios for the Rhine and the Meuse basins

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- KNMI'14 NL: 4 scenarios
- KNMI'14 Rhine & Meuse (R&M): 4 + 1 scenarios (complementary)
- Both KNMI'14 NL and R&M based on EC-Earth-RACMO2 (regional climate model)
- The spread in CMIP5 (RCP4.5 to RCP8.5) seasonal mean changes in precipitation and temperature is a reference for the set of KNMI'14 (both for NL and for R&M)
- 'Resampling' from the 8 members of EC-Earth-RACMO2 is used to derive the 'desired' spread in the scenarios (Lenderink et al. 2014)

~ 50 – 80% of CMIP5 spread covered in KNMI'14

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Overview of scenarios

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	KNMI'14	CMIP5	KNMI'06
# scenarios	4 (+1)	183	4
horizons	2050 & 2085	2050 & 2085	2050 & 2100
NL	yes	(possible)	yes
Rhine & Meuse	yes	yes	No
Construction of precipitation series for hydro model	ADC (Non-linear transformation of hist. P series)	ADC (Non-linear transformation of hist. P series)	KNMI'06 TP (Non-linear transformation of hist. P series)
Construction of temp. series for hydro model	Lin. Transf. of hist. T series using change in mean and std. dev.	Lin. Transf. of hist. T series using change in mean and std. dev.	Non-Lin. Transf. of hist. T series using change in 3 quantiles

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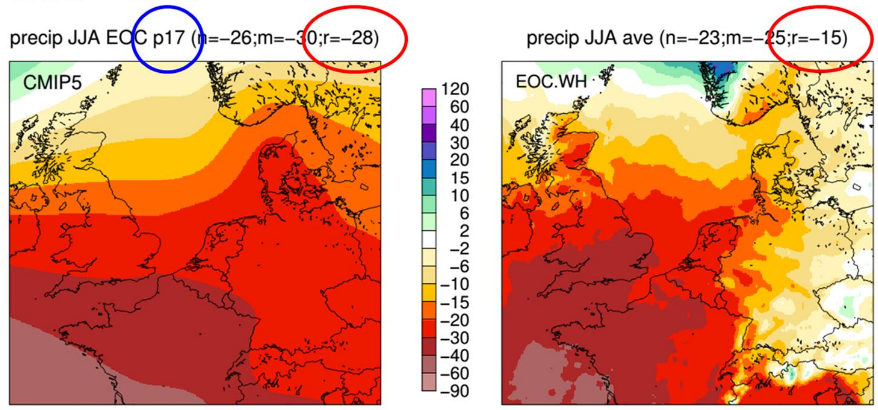
Motivation for the fifth KNMI’14 R&M scenario

EOC = 2085



$P_{2.5}$ $\mathbf{P_{10}}$ $\boldsymbol{P_{17}}$ P_{50} $\boldsymbol{P_{83}}$ $\mathbf{P_{90}}$ $P_{97.5}$

very dry ... very wet

W_H not dry enough in summer in the Rhine basin (r)

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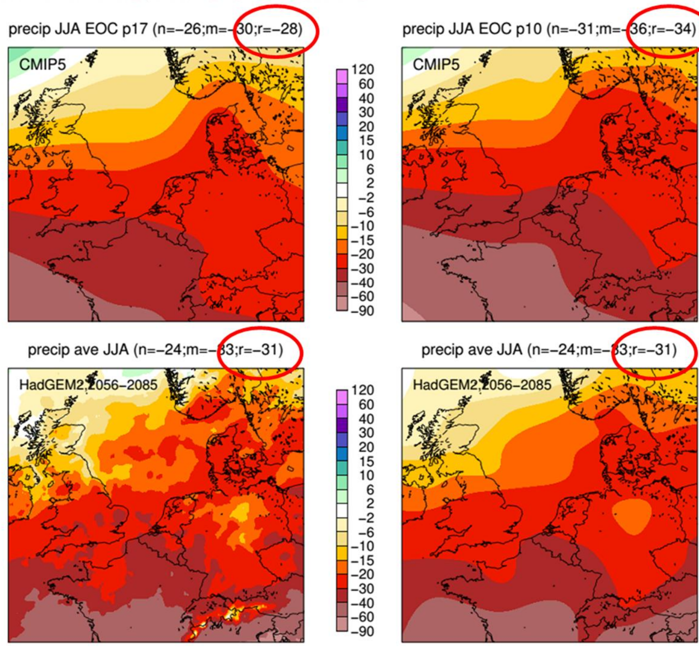
Motivation for the fifth KNMI’14 R&M scenario



6

Motivation for the fifth KNMI'14 R&M scenario

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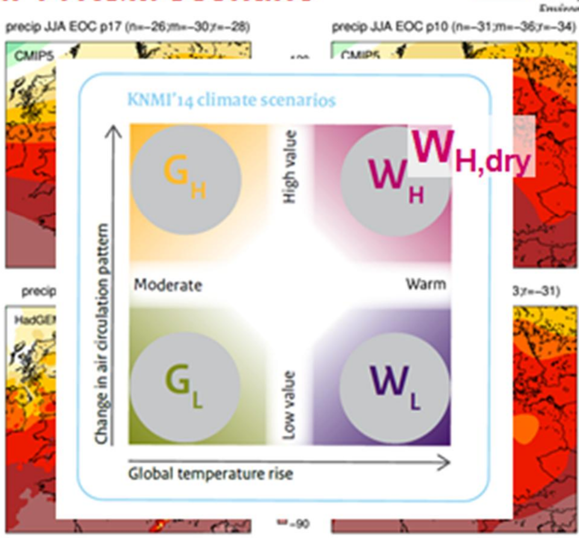

6

Advanced Delta Change method (ADC) used for CMIP5 and KNMI'14

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- Non-linear transformation of precipitation
- $P^* = aP^b$ for $P \le P_{90}$
  $P^* = aP_{90}^b + E^F/E^C\,(P - P_{90})$ for $P > P_{90}$
  with $E = \text{avg}(P - P_{90})$
  E^F/E^C avoids unrealistic large P^* if $b > 1$ and,
  E is closely related to the slope of extreme-value plot of precipitation and E^F/E^C thus to the future change in this slope
- Transformation based on 5-day precipitation sums
- The three parameters a, b and E^F/E^C calculated separately for each grid cell and each calendar month.

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Advanced Delta Change method (ADC)

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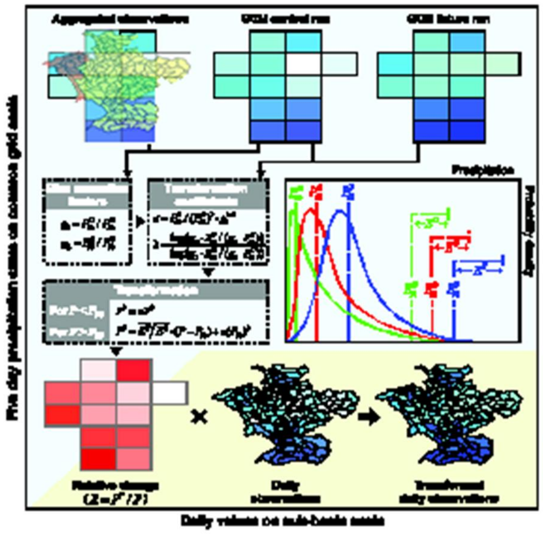

van Pelt et al., 2012

8

Temperature transformation

used for CMIP5 and KNMI'14

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- Hydrological modelling with HBV requires also temperature
- Linear temperature transformation that is performed on a daily temporal scale
- Transformation is based on monthly means and std. dev. of observed, control and future temperatures:

$$T^* = \frac{\sigma^{F}}{\sigma^{C}}(T-\overline{T}^{O})+\overline{T}^{O}+\overline{T}^{F}-\overline{T}^{C}$$

Historical reference times series for the Rhine that are transformed according to the scenarios
using the ADC method

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

- Precipitation:
  1951 – 2006 Hyras gridded data aggregated to the 134 HBV-Rhine sub-basins

- Temperature:
  1951 – 2006 E-OBS gridded data aggregated to the 134 HBV-Rhine sub-basins

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Scenario results for the Rhine discharge at Lobith

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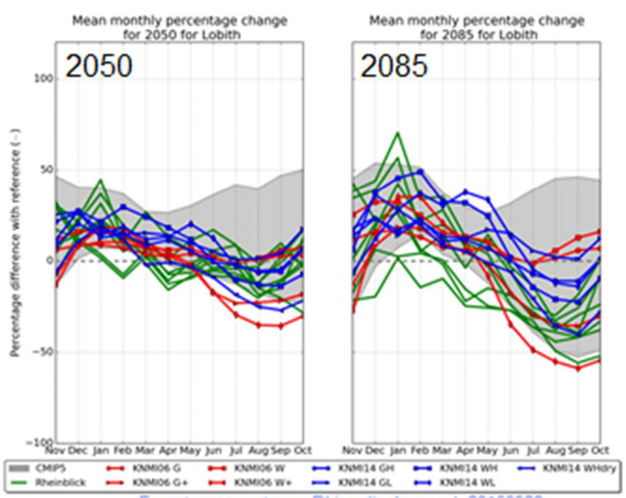

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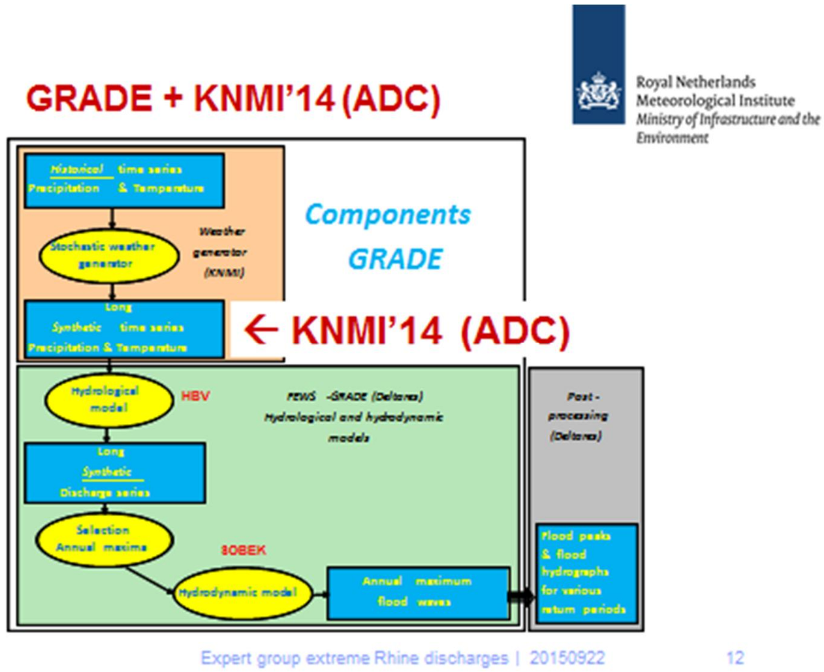
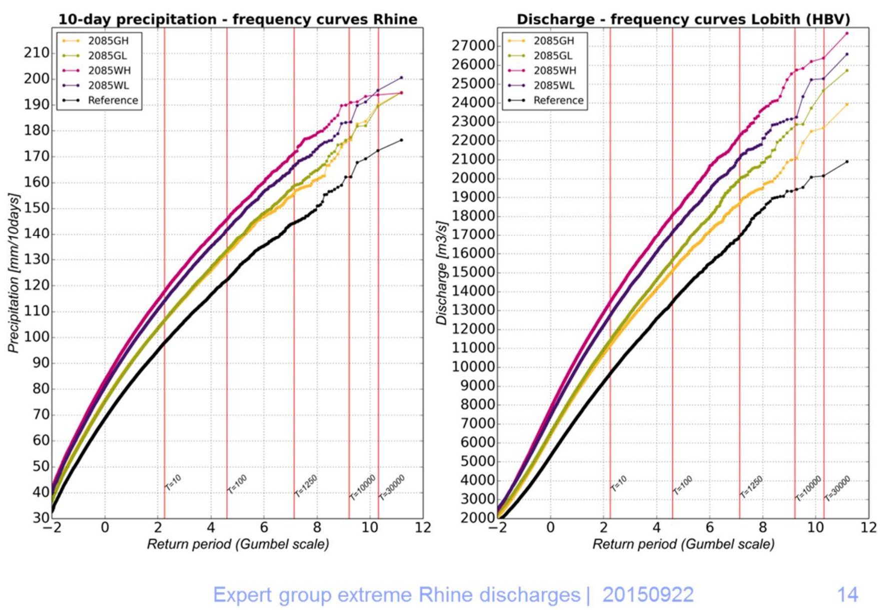
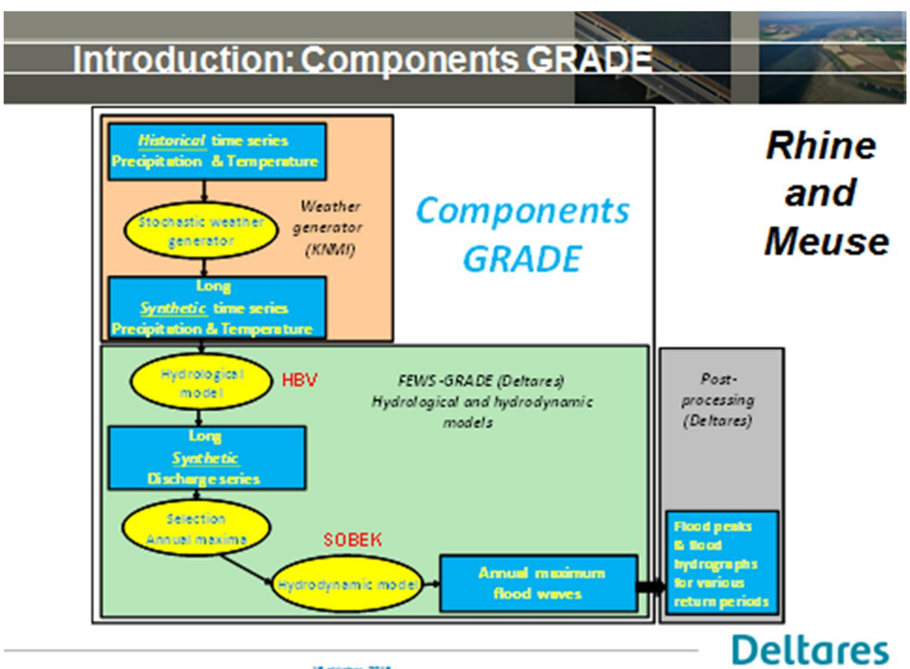


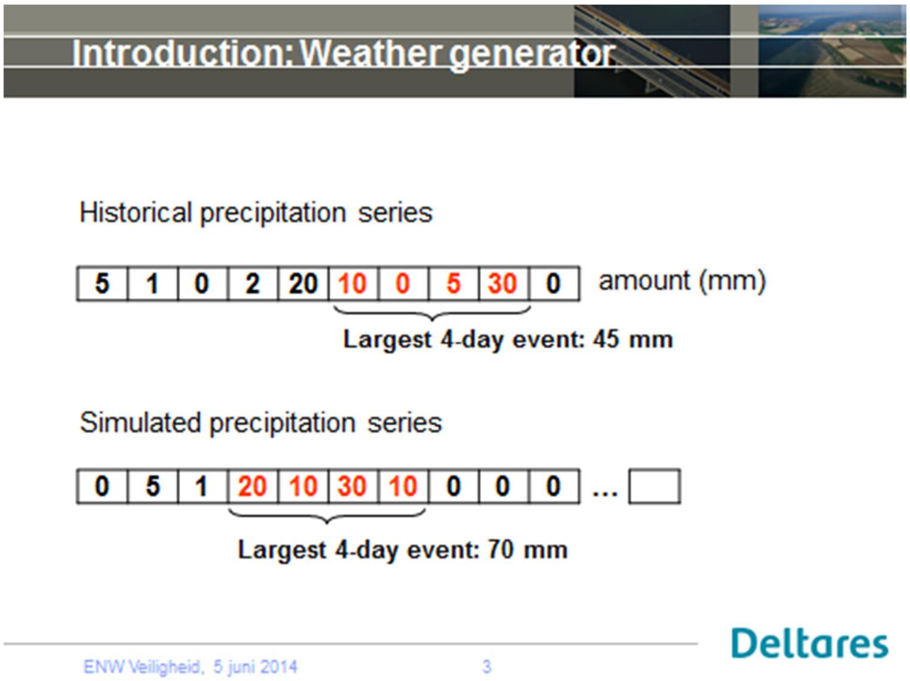
KNMI'14 scenario results for extreme discharges at Lobith

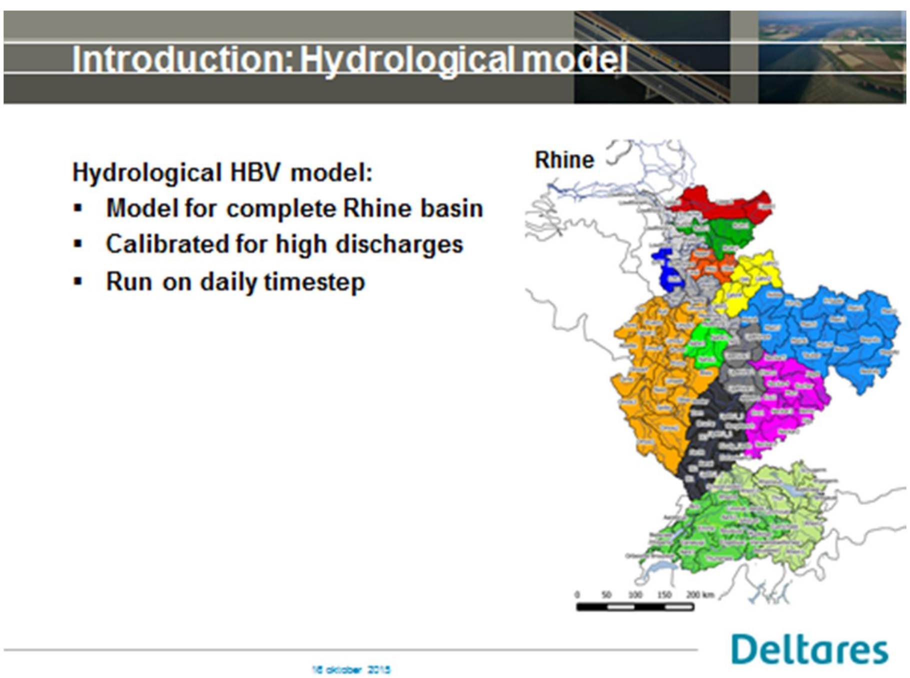
Note, $W_{H,dry}$ not relevant here



D Slides about hydrological perspective (GRADE)



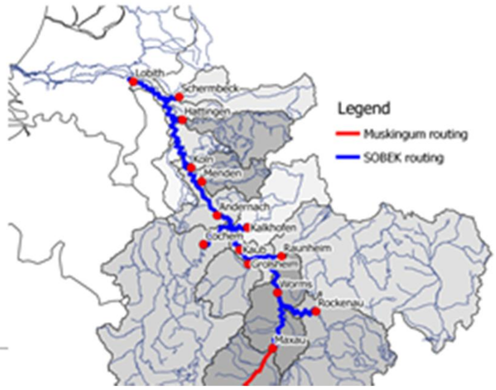

Introduction: Weather generator
Historical precipitation series
5 1 0 2 20 10 0 5 30 0
amount (mm)
Largest 4-day event: 45 mm
Simulated precipitation series
0 5 1 20 10 30 10 0 0 0 ...
Largest 4-day event: 70 mm
ENW Veiligheid, 5 juni 2014
3
Deltares


Introduction: Hydrological model
Hydrological HBV model:
▪ Model for complete Rhine basin
▪ Calibrated for high discharges
▪ Run on daily timestep
Rhine
0 50 100 150 200 km
Deltares

Introduction: Hydrodynamic models

1D Sobek-RE model:

- **2 models for the Rhine**
  - ➢ **with upstream flooding in DE**
  - ➢ **without upstream flooding in DE**
- **From Maxau to Lobith**



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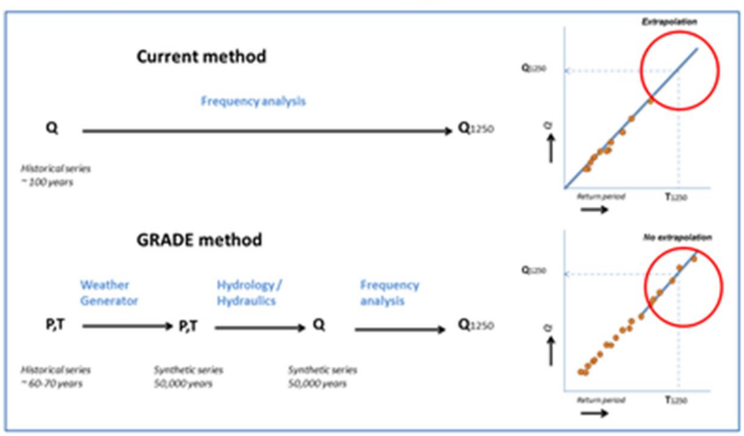
Introduction

- **Generator of Rainfall and Discharge Extremes**



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GRADE calculations

1) **Generate** long (50,000 years) P, T (and PET) series
   - *Current climate*
   - *Future climate (KNMI'14)*
2) Run **hydrological** model (HBV)
3) **Select** annual maxima from HBV series

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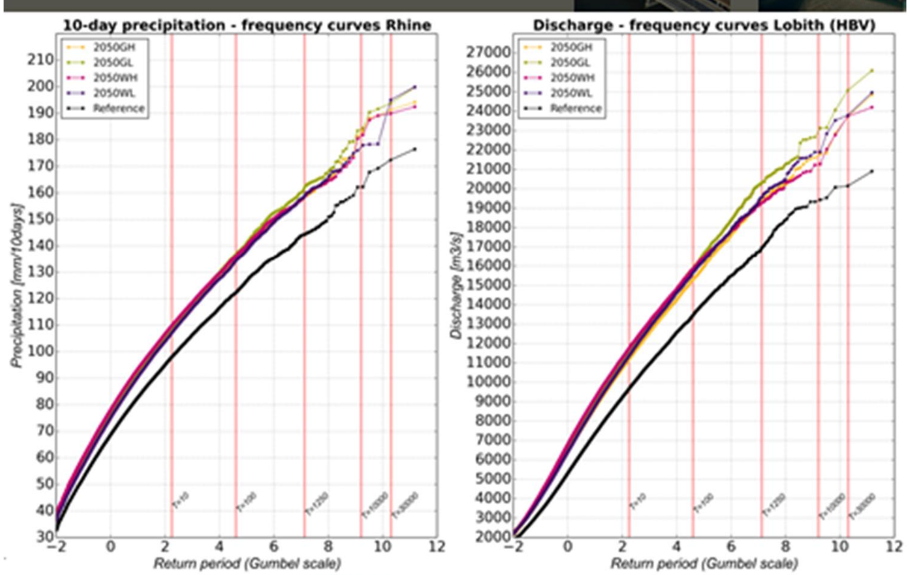
Implications of KNMI'14 scenarios: HBV



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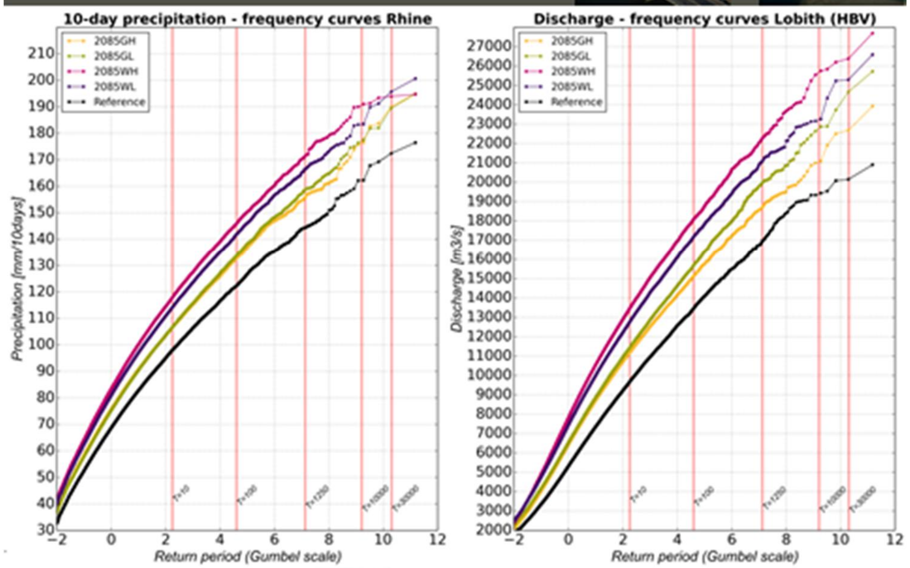
Implications of KNMI'14 scenarios: HBV



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GRADE calculations

1) Generate long (50,000 years) P, T (and PET) series
   - *Current climate*
   - *Future climate (KNMI'14)*
2) Run hydrological model (HBV)
3) Select annual maxima from HBV series
4) **Run hydrodynamic model (SOBEK) for selected peaks**
5) **Select annual maxima from SOBEK series**
6) **Calculate distribution of extreme discharges**

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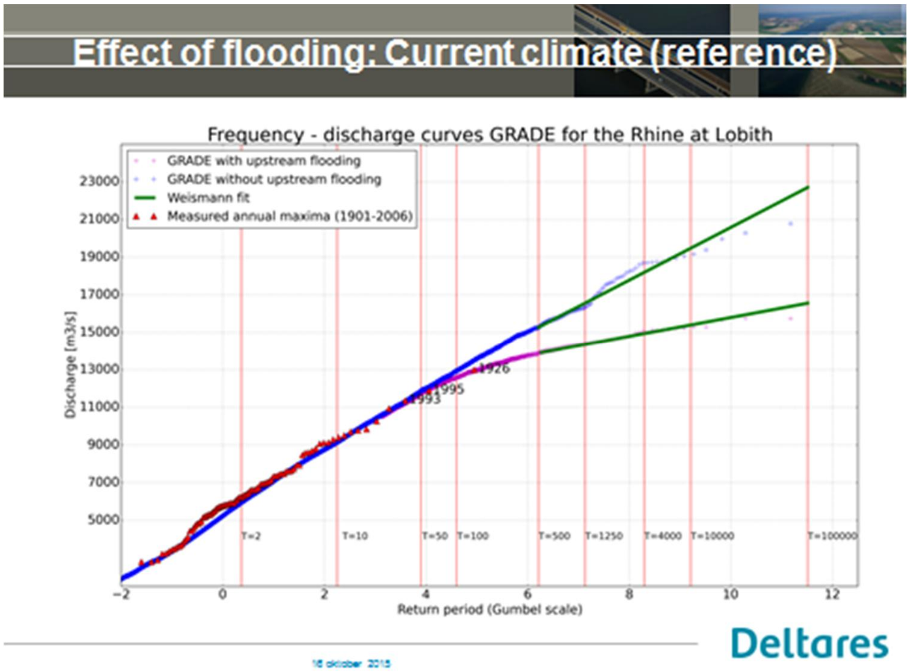
Effect of flooding: Current climate (reference)
Frequency - discharge curves GRADE for the Rhine at Lobith
GRADE with upstream flooding
GRADE without upstream flooding
Weismann fit
Measured annual maxima (1901-2006)
Discharge [m3/s]
Return period (Gumbel scale)
T=2
T=10
T=50
T=100
T=500
T=1250
T=4000
T=10000
T=100000
1926
1995
1993
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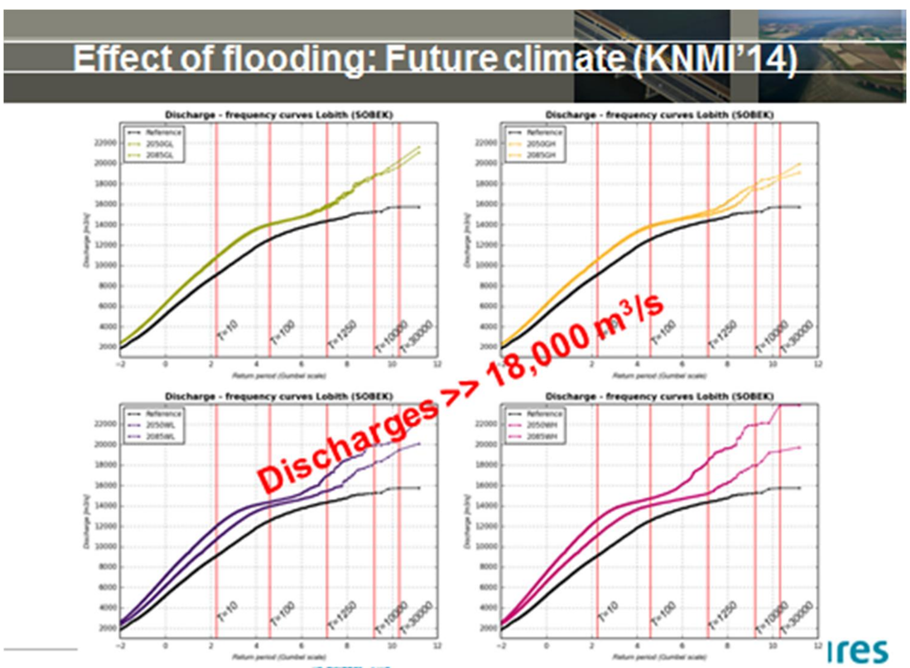
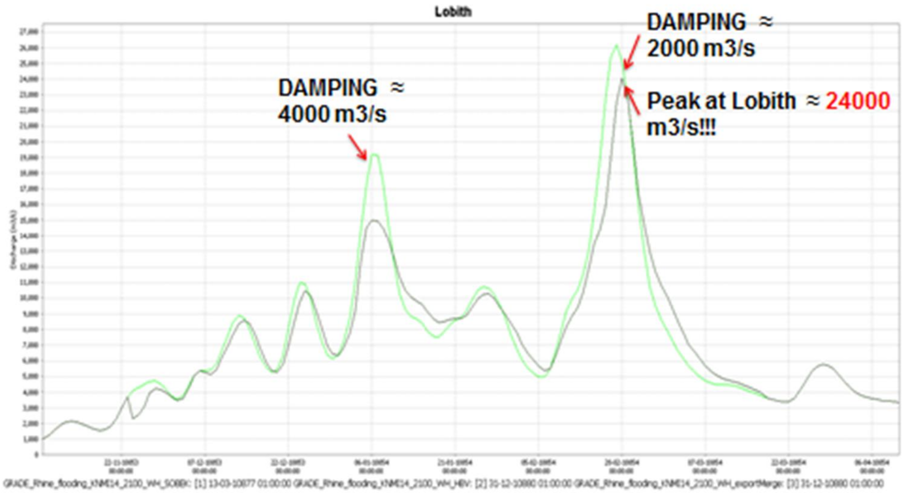

Effect of flooding: Future climate (KNMI'14)
Discharge - frequency curves Lobith (SOBEK)
Discharges >> 18,000 m³/s

Effect of flooding: Peak damping



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Effect of flooding: Peak damping

- Flood volume very large
- Flooded areas "full" before the peak arrives
- Flooded areas not completely empty between two peaks
- 1D model with:
  - Pre-defined locations
  - Pre-defined areas
  - Pre-defined volume
- Other shortcoming of the model…

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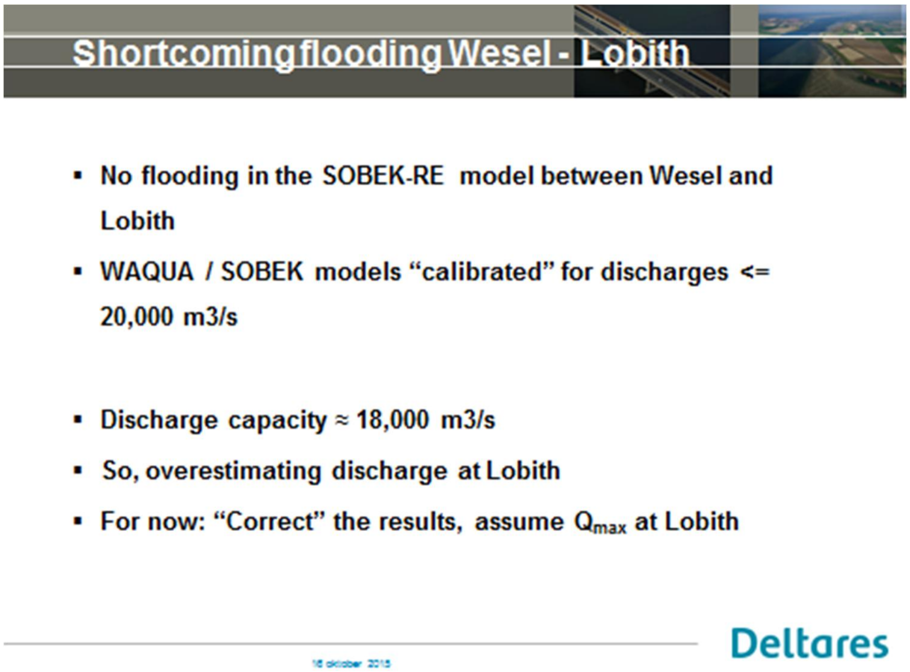
Shortcoming flooding Wesel - Lobith
▪ No flooding in the SOBEK-RE model between Wesel and Lobith
▪ WAQUA / SOBEK models “calibrated” for discharges <= 20,000 m3/s
▪ Discharge capacity ≈ 18,000 m3/s
▪ So, overestimating discharge at Lobith
▪ For now: “Correct” the results, assume Q_{max} at Lobith
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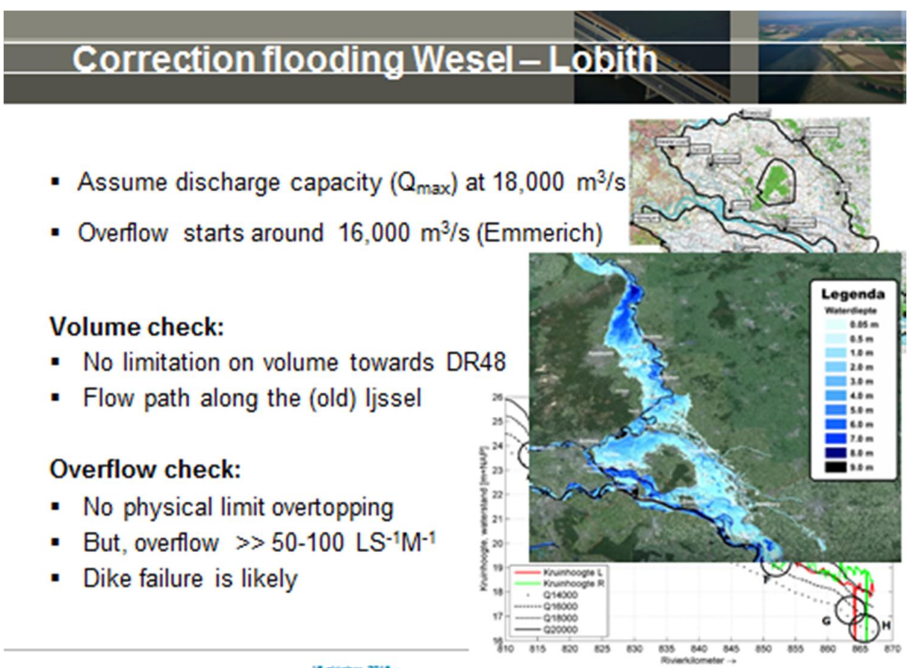
Correction flooding Wesel – Lobith
▪ Assume discharge capacity (Q_{max}) at 18,000 m^3/s
▪ Overflow starts around 16,000 m^3/s (Emmerich)
Volume check:
▪ No limitation on volume towards DR48
▪ Flow path along the (old) Ijssel
Overflow check:
▪ No physical limit overtopping
▪ But, overflow >> 50-100 $LS^{-1}M^{-1}$
▪ Dike failure is likely
Legenda
Waterdiepte
Kruinhoogte L
Kruinhoogte R
Q14000
Q16000
Q18000
Q20000
Rivierkilometer
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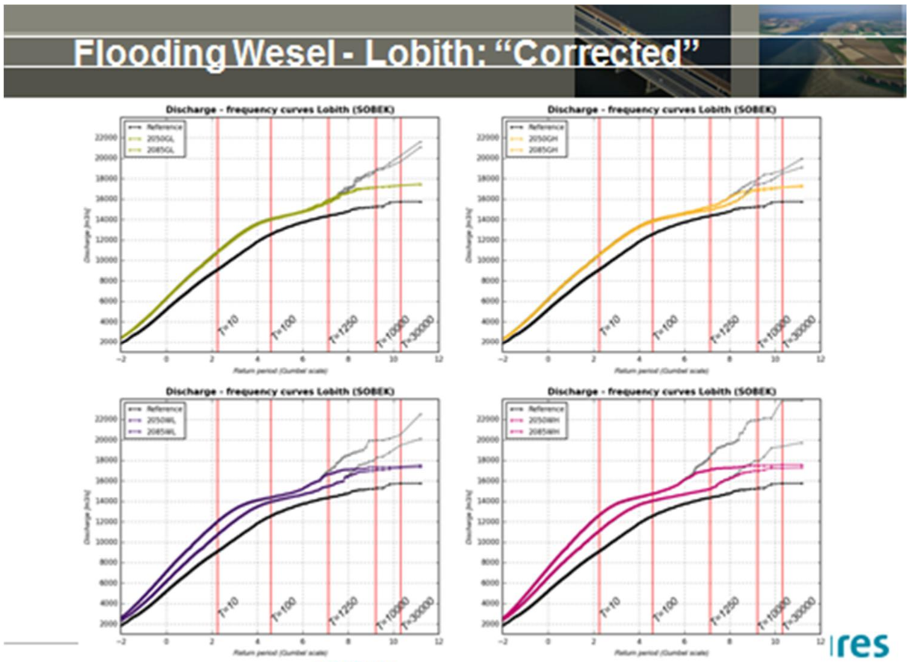

Final remarks

- Assumptions need to be validated (!)
- Assuming flooding between Wesel and Lobith might have huge consequences for Ijssel delta

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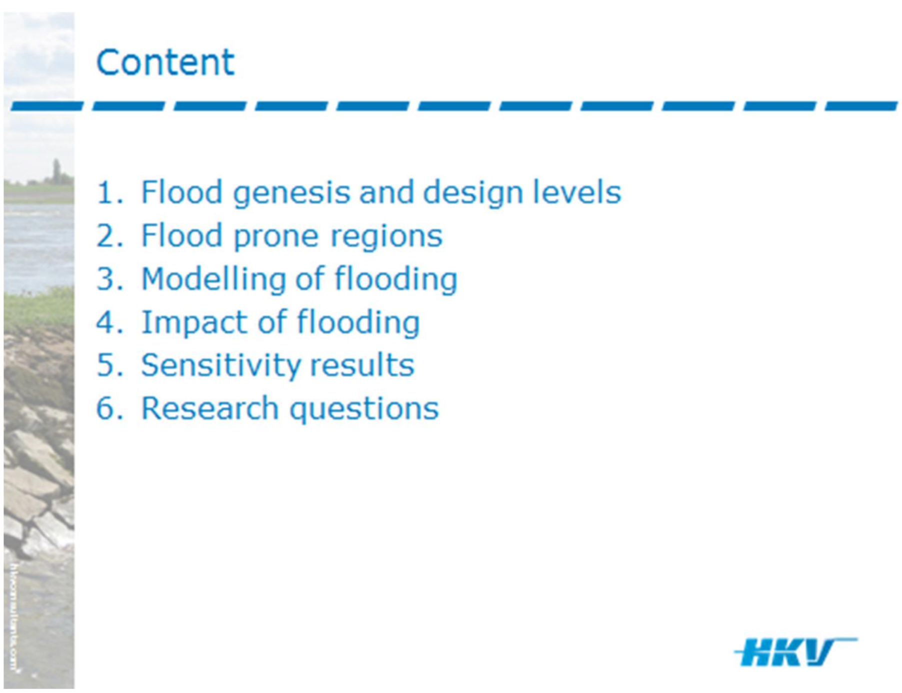
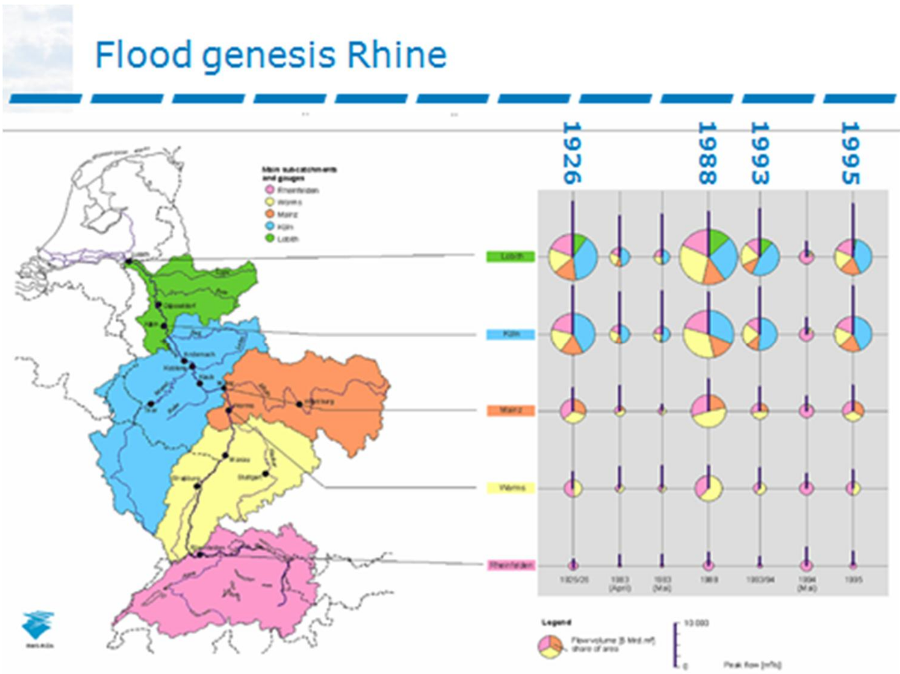
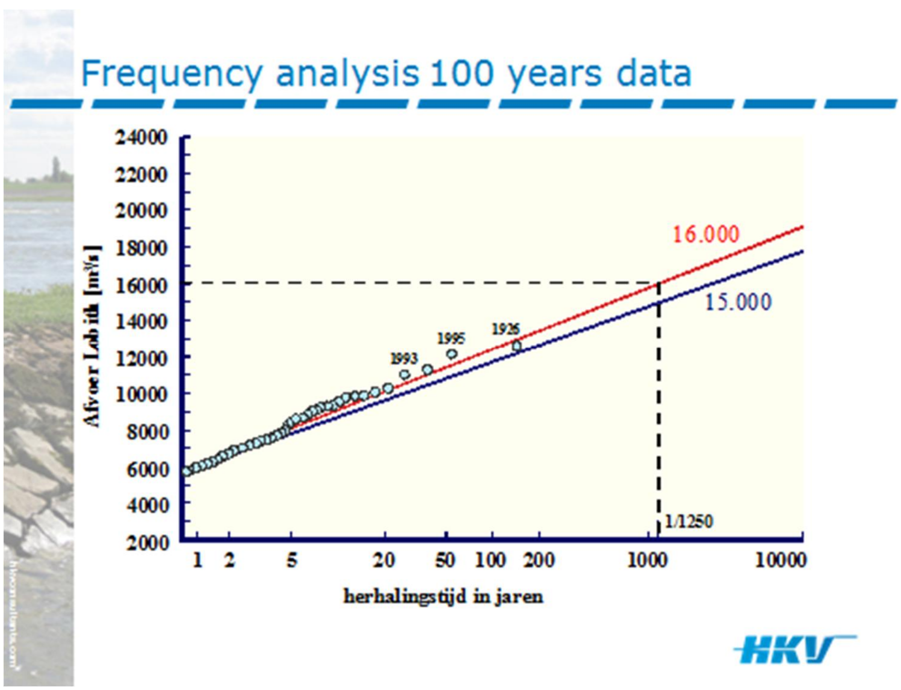
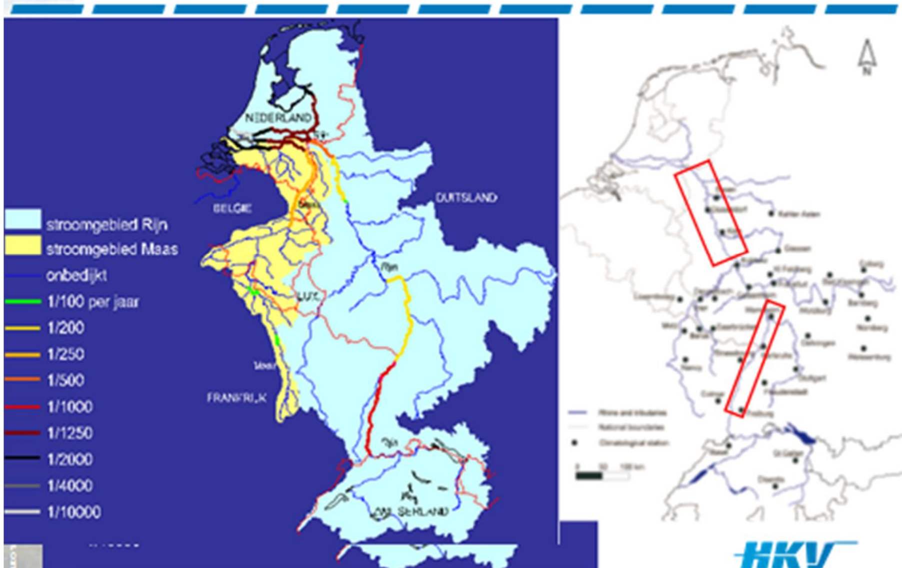
E Slides about hydrodynamic perspective




Flood genesis Rhine
1926
1988
1993
1995


Frequency analysis 100 years data
24000
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
Afvoer Lobith [m³/s]
16.000
15.000
1993
1995
1926
1/1250
1 2 5 20 50 100 200 1000 10000
herhalingstijd in jaren
HKV

Protection levels and flood areas



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Flood areas Niederrhein

Modelling

- Niederrhein study 2004*
  Provinz Gelderland Delft-FLS
  RWS-RIZA SOBEK (tuned on Delft-FLS)
  Dikes 2002 and 2012
- WAQUA-model Niederrhein
  RWS-RIZA, 2007-2008

* (Grenzüberschreitende Auswirkungen von extremem Hochwasser am Niederrhein)

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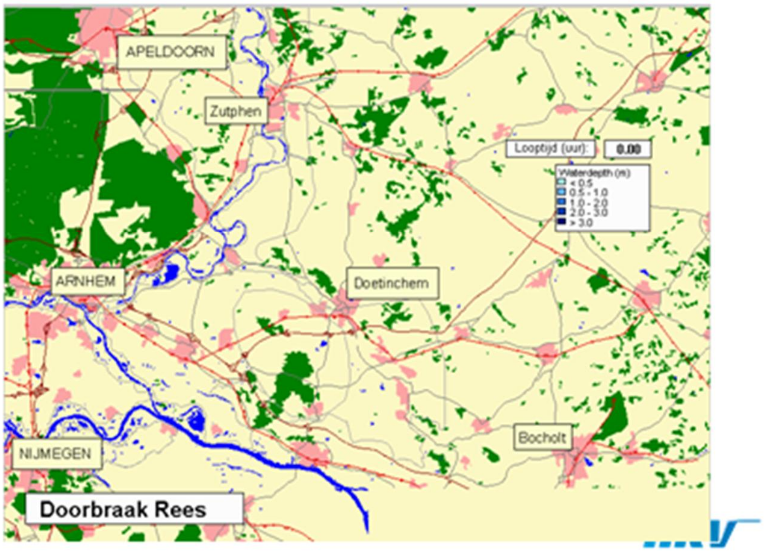
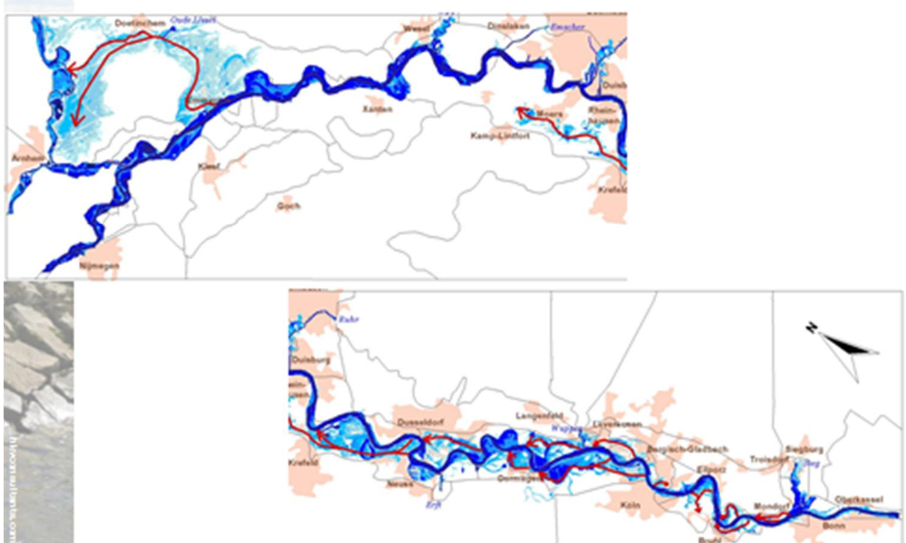
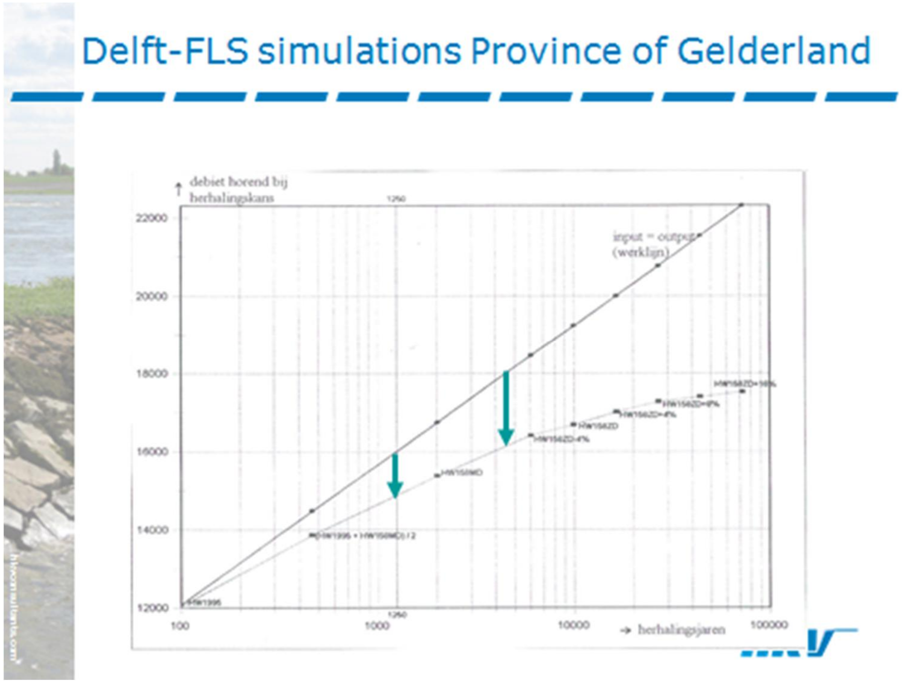
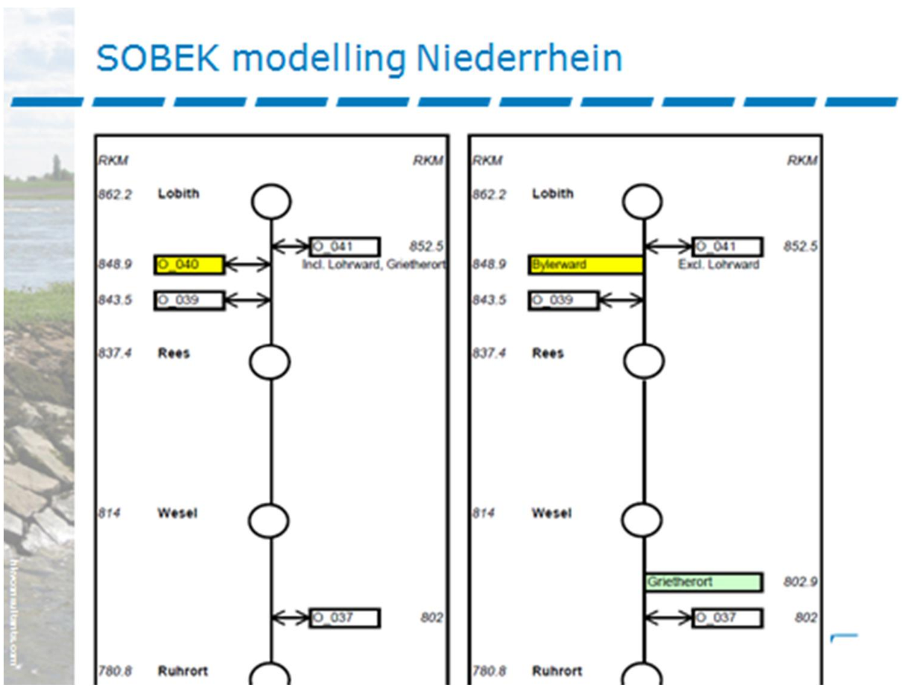
Flood areas Niederrhein



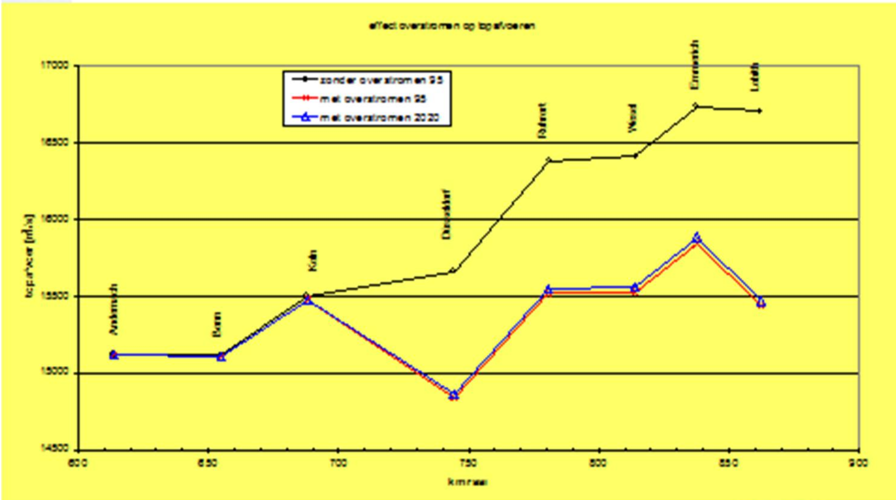
Delft-FLS modelling Niederrhein




Delft-FLS simulations Province of Gelderland
debiet horend bij herhalingskans
22000
20000
18000
16000
14000
12000
100
1000
1250
10000
100000
herhalingsjaren
input = output (werklijn)
HW1995
HW1568D
HW1562D
HW1562D-4%
HW1562D=4%
HW1562D=8%
HW1562D=16%


SOBEK modelling Niederrhein
RKM
862.2 Lobith
O_041 852.5
848.9 O_040
Incl. Lohrward, Grietherort
843.5 O_039
837.4 Rees
814 Wesel
O_037 802
780.8 Ruhrort
RKM
862.2 Lobith
O_041 852.5
848.9 Bylerward
Excl. Lohrward
843.5 O_039
837.4 Rees
814 Wesel
Grietherort 802.9
O_037 802
780.8 Ruhrort

Niederrhein study Impact on Qmax Lobith



Niederrhein study Impact on Q & Qmax Lobith

Scheitelabfluss bei Lobith

Abflussganglinie BfG	1995_O	1995_M	Differenz
MET95	11958	11940	18
HW457	12628	12518	110
HW841	13500	13291	208
HW846	13760	13521	238
HW329	13862	13665	197
HW719	14867	14318	549
HW036	15685	14459	1225
HW158	16283	14873	1410
HW824	16708	15437	1270

Abfluss Andernach
Abfluss Lobith, Szenario 1995_O
Abfluss Lobith, Szenario 1995_M

Niederrhein study Impact Qmax Lobith (2020)

Scheitelabfluss bei Lobith

Abflussganglinie BfG	2020_O	2020_M	Differenz
MET95	11958	11958	0
HW457	12631	12630	2
HW841	13497	13466	32
HW846	13766	13610	157
HW329	13852	13827	25
HW719	14873	14693	179
HW036	15695	14910	785
HW158	16326	14807	1519
HW824	16706	15412	1294

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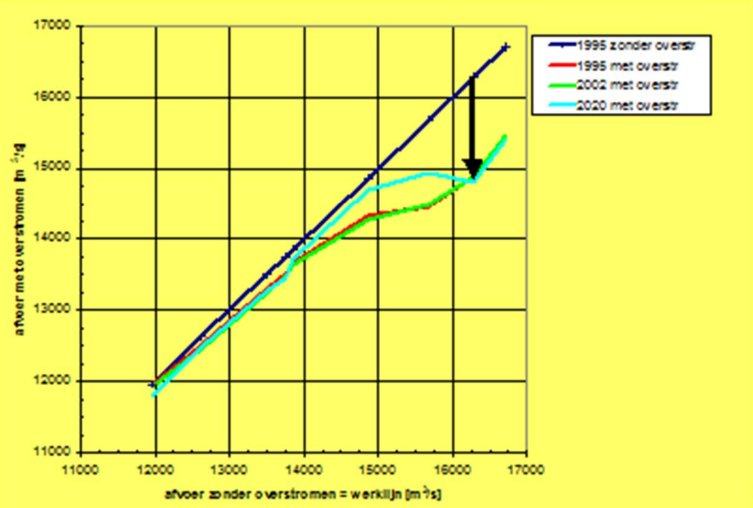
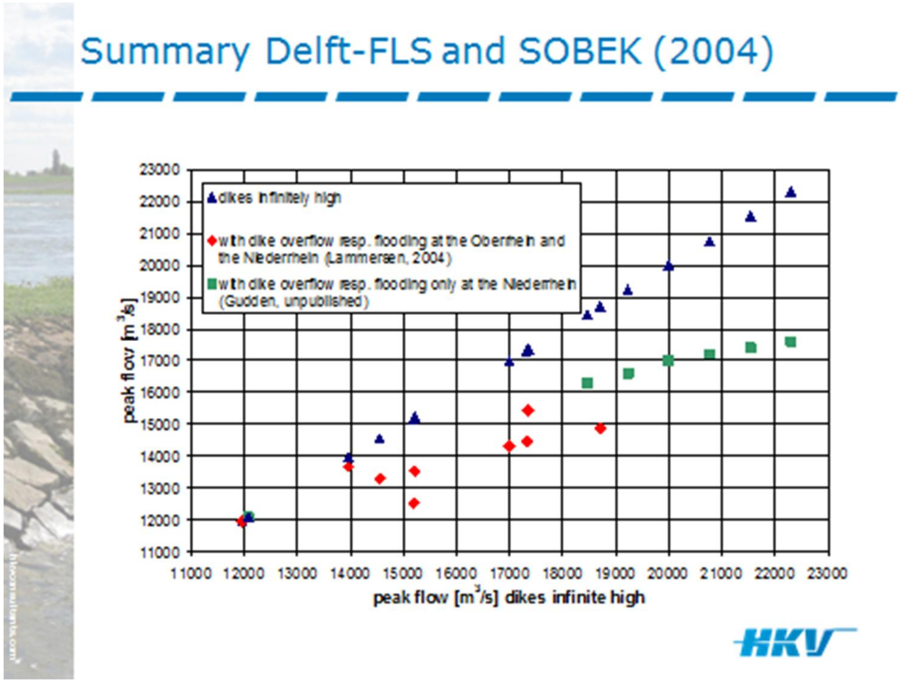
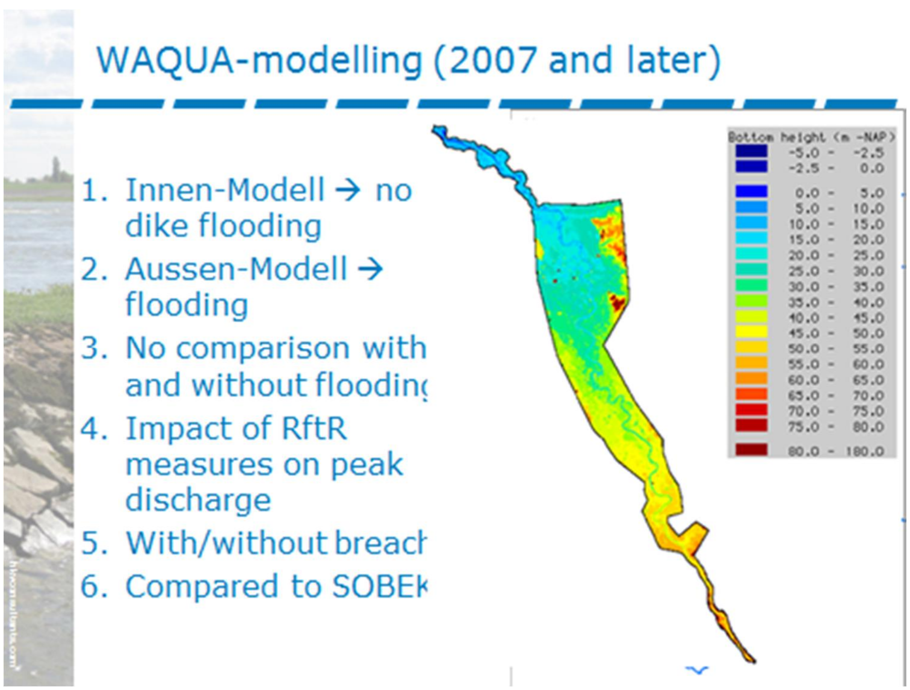
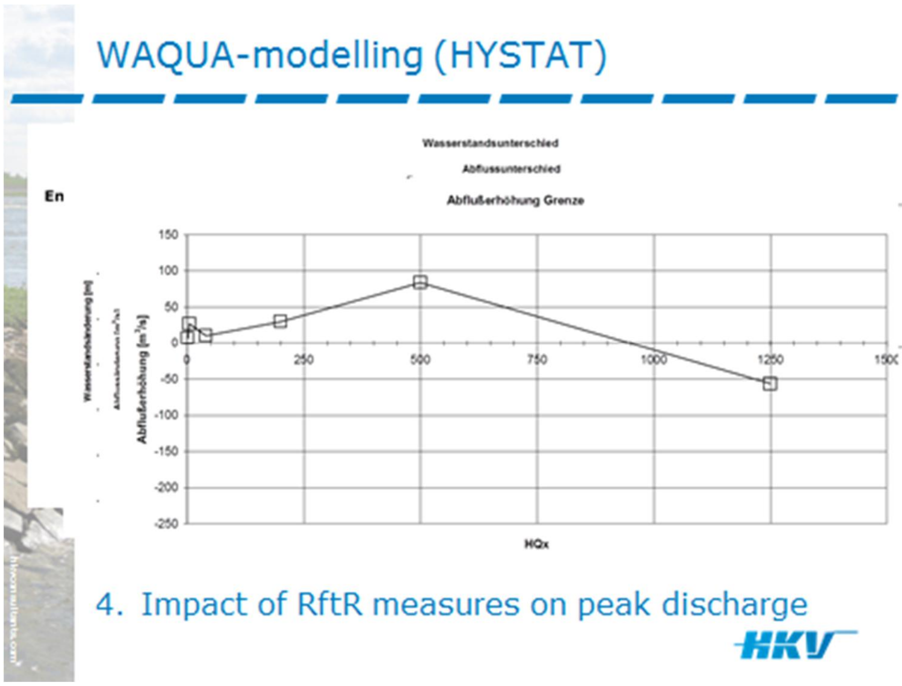
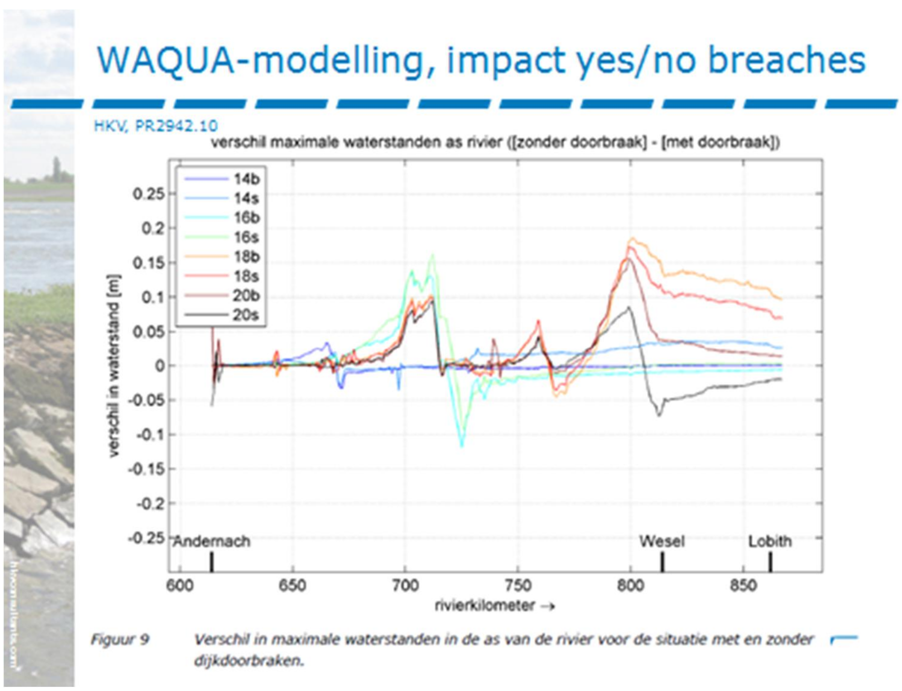
Niederrhein study Impact frequency Lobith

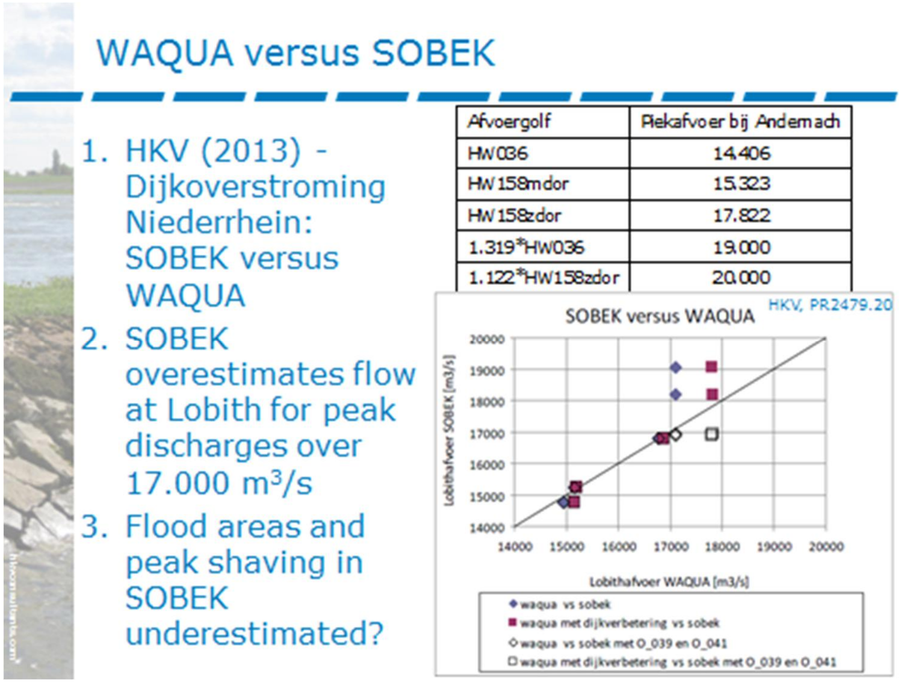



Summary Delft-FLS and SOBEK (2004)
dikes infinitely high
with dike overflow resp. flooding at the Oberrhein and the Niederrhein (Lammersen, 2004)
with dike overflow resp. flooding only at the Niederrhein (Gudden, unpublished)
peak flow [m³/s]
peak flow [m³/s] dikes infinite high
11000 12000 13000 14000 15000 16000 17000 18000 19000 20000 21000 22000 23000
HKV

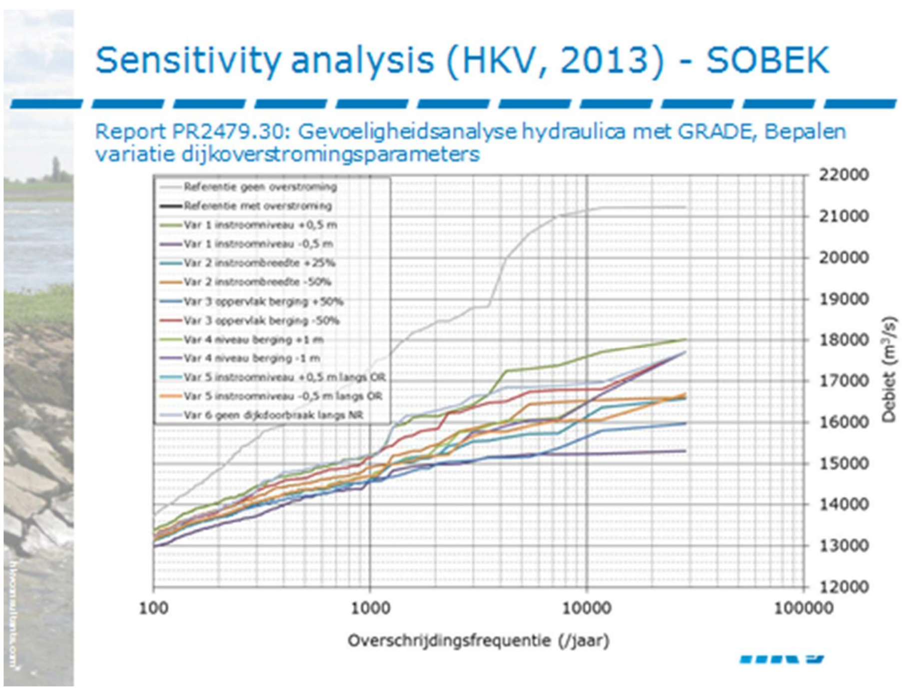

WAQUA-modelling (2007 and later)
1. Innen-Modell → no dike flooding
2. Aussen-Modell → flooding
3. No comparison with and without flooding
4. Impact of RftR measures on peak discharge
5. With/without breach
6. Compared to SOBEK
Bottom height (m -NAP)
-5.0 - -2.5
-2.5 - 0.0
0.0 - 5.0
5.0 - 10.0
10.0 - 15.0
15.0 - 20.0
20.0 - 25.0
25.0 - 30.0
30.0 - 35.0
35.0 - 40.0
40.0 - 45.0
45.0 - 50.0
50.0 - 55.0
55.0 - 60.0
60.0 - 65.0
65.0 - 70.0
70.0 - 75.0
75.0 - 80.0
80.0 - 180.0


WAQUA-modelling (HYSTAT)
Wasserstandsunterschied
Abflussunterschied
Abflußerhöhung Grenze
En
Abflußerhöhung [m³/s]
150
100
50
0
-50
-100
-150
-200
-250
0
250
500
750
1000
1250
HQx
4. Impact of RftR measures on peak discharge
HKV


WAQUA-modelling, impact yes/no breaches
HKV, PR2942.10
verschil maximale waterstanden as rivier ([zonder doorbraak] - [met doorbraak])
14b
14s
16b
16s
18b
18s
20b
20s
verschil in waterstand [m]
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
Andernach
Wesel
Lobith
600
650
700
750
800
850
rivierkilometer →
Figuur 9 Verschil in maximale waterstanden in de as van de rivier voor de situatie met en zonder dijkdoorbraken.



Afvoergolf	Piekafvoer bij Andernach
HW036	14.406
HW158mdor	15.323
HW158zdor	17.822
1.319*HW036	19.000
1.122*HW158zdor	20.000



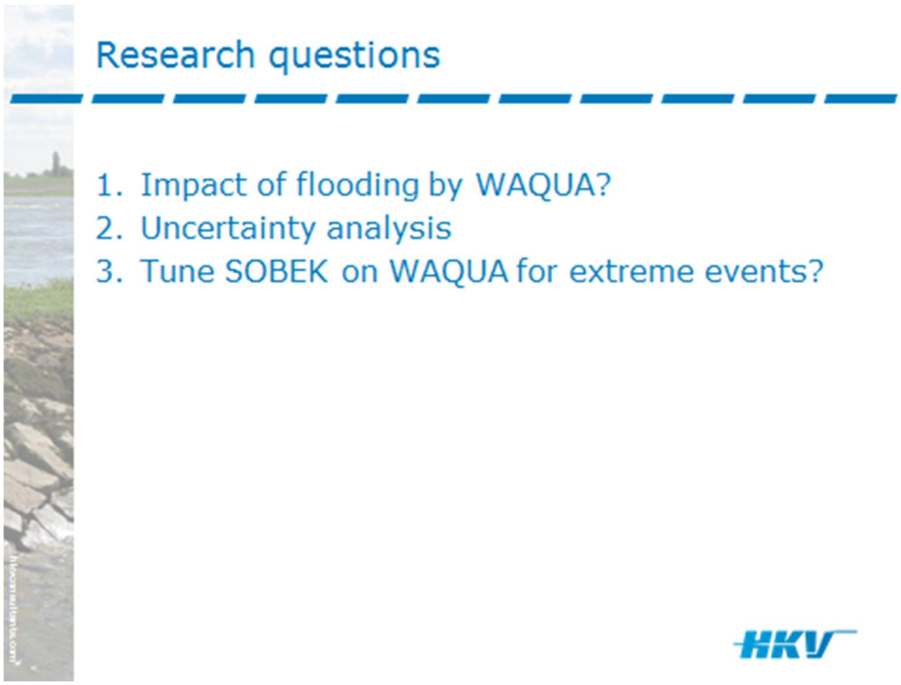
Sensitivity analysis (HKV, 2013)

PR2479.30 - Gevoeligheidsanalyse hydraulica met GRADE, Bepalen variatie dijkoverstromingsparameters

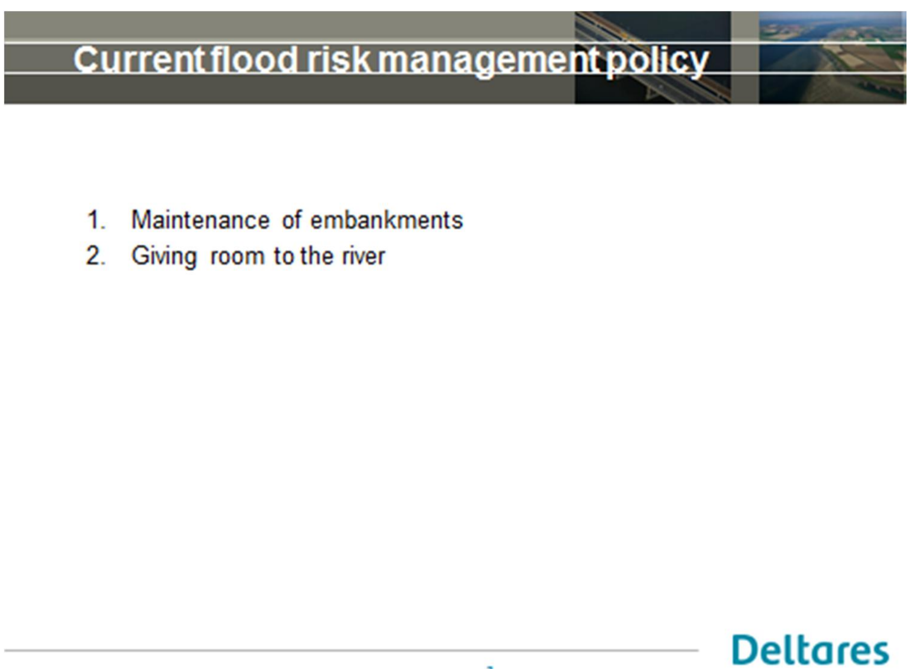
			verandering max. afvoer bij Lobith t.o.v. referentie [m³/s]
variant	Niederrhein	Oberrhein	freq. 1/1.250
1: Overstromingshoogte drempel	+0,5 m	+0,5 m	876
	-0,5 m	-0,5 m	-174
2: Overstromingsbreedte drempel	+25%	+25%	+2
	-50%	-50%	191
3: Bergend oppervlak	+50%	+50%	-317
	-50%	-50%	434
4: Bodemniveau in retentiegebieden	+1 m	+1 m	0
	-1 m	-1 m	0
5: Overstromingshoogte drempel OR	--	+0,5 m	0
	--	-0,5 m	-19
6: Dijkdoorbraak langs Niederrhein	geen	--	887

Conclusions

1. Delft-FLS, SOBEK and WAQUA modelling available. FLS not operational any more
2. WAQUA-modelling: no studies on impact yes/no flooding
3. Impact of (1) yes/no breaches; (2) height breach; (3) volume flooded area
4. Impact of flooding larger in WAQUA than in SOBEK. SOBEK underestimates flood volume for extreme discharges?
5. Flooding downstream Wesel-Lobith well modelled in SOBEK?


Research questions
1. Impact of flooding by WAQUA?
2. Uncertainty analysis
3. Tune SOBEK on WAQUA for extreme events?
HKV

F Slides about the Dutch flood standards



Present protection standards in the Netherlands

= probability of occurrence of water level that the embankment retains without significant deformation

≠ probability of flooding

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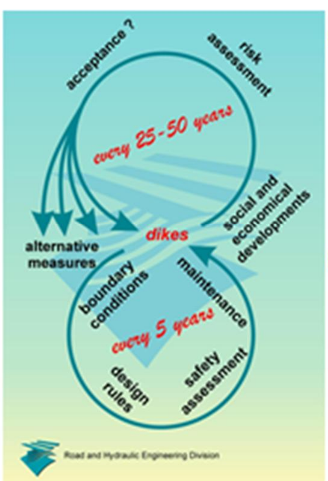
Flood Protection Law



Every 5 years:

- Determine the design water levels
- Safety assessments of embankments
- If embankments do not pass the test → strengthen them

Every 25-50 years:

- Update the protection standards

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Deltaprogramme – Flood protection standards

Risk based approach:

- Economic risk (benefit/cost-analysis)
- Individual risk (probability of getting killed during flood < 10^{-5})
- Group risk
- Risk to critical infrastructure (essential for the functioning of society and economy)

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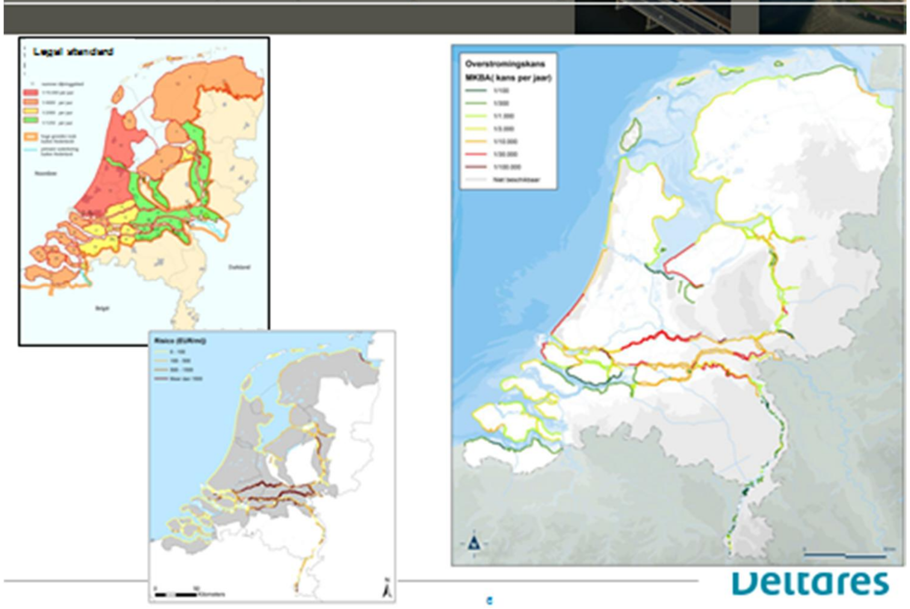
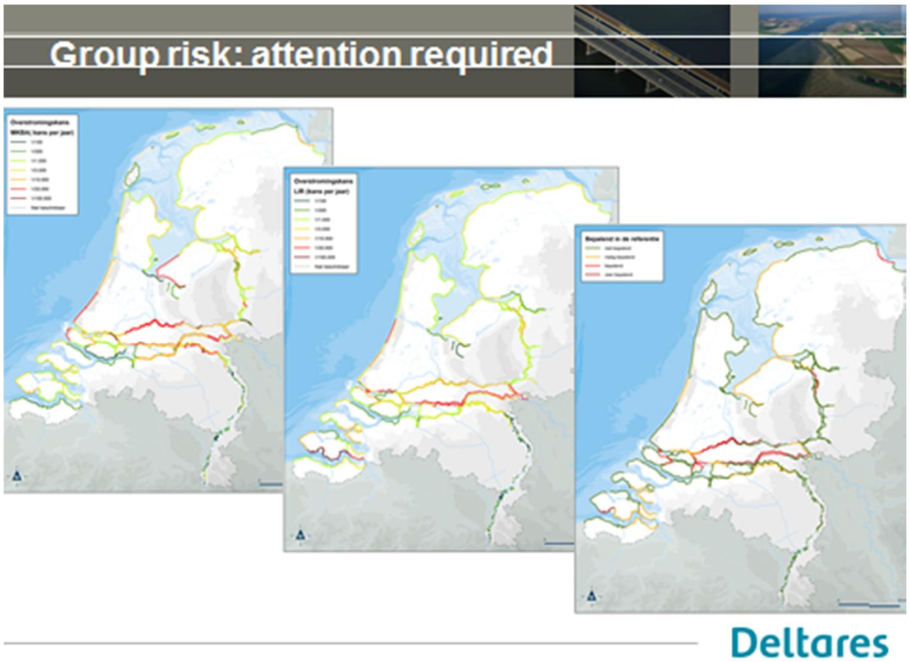
Economic optimal probability for flooding




Group risk: attention required
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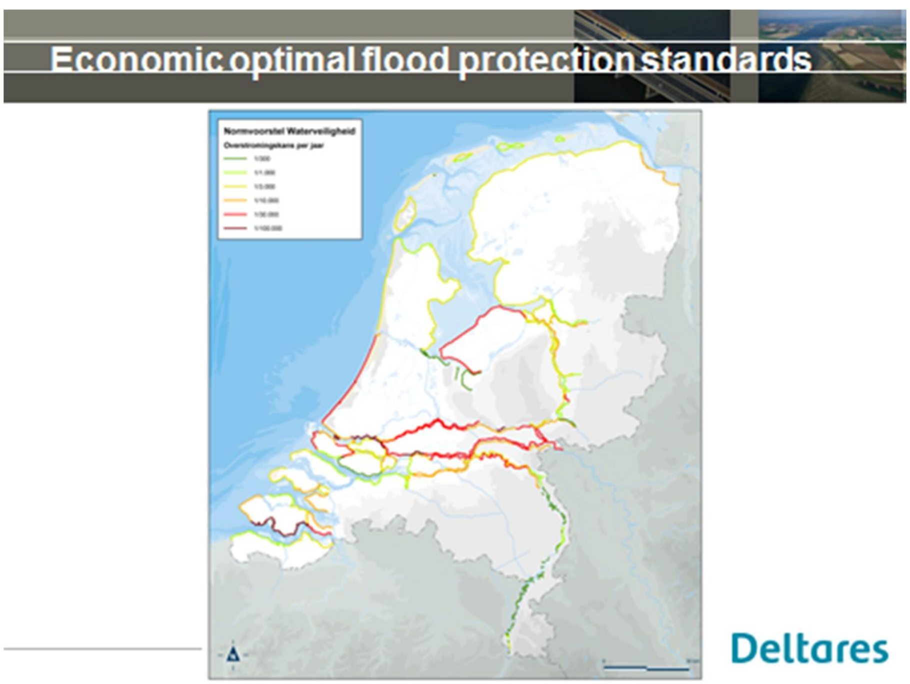
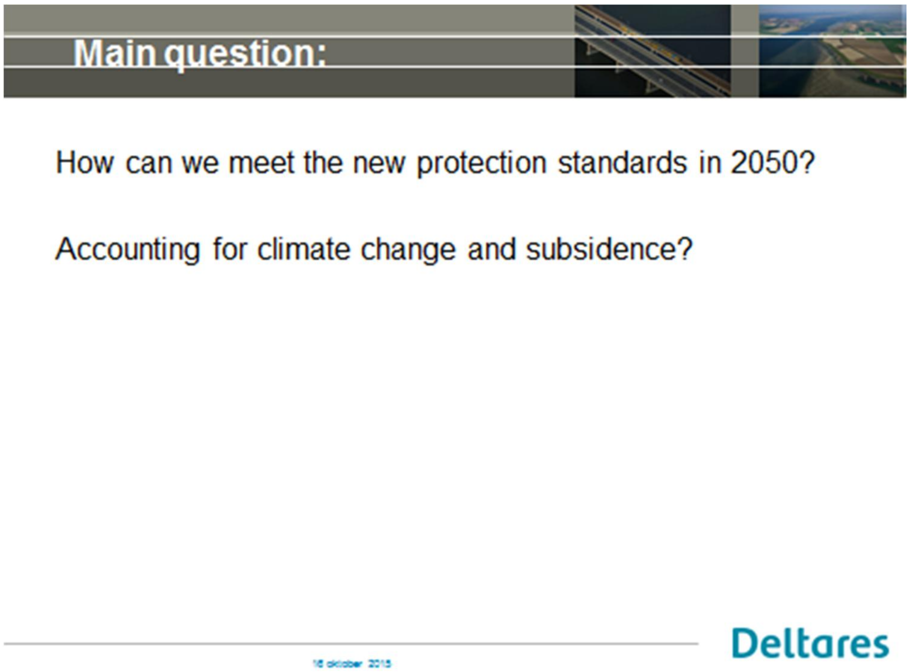

Economic optimal flood protection standards
Normvoorstel Waterveiligheid
Overstromingskans per jaar
Deltares


Main question:
How can we meet the new protection standards in 2050?
Accounting for climate change and subsidence?
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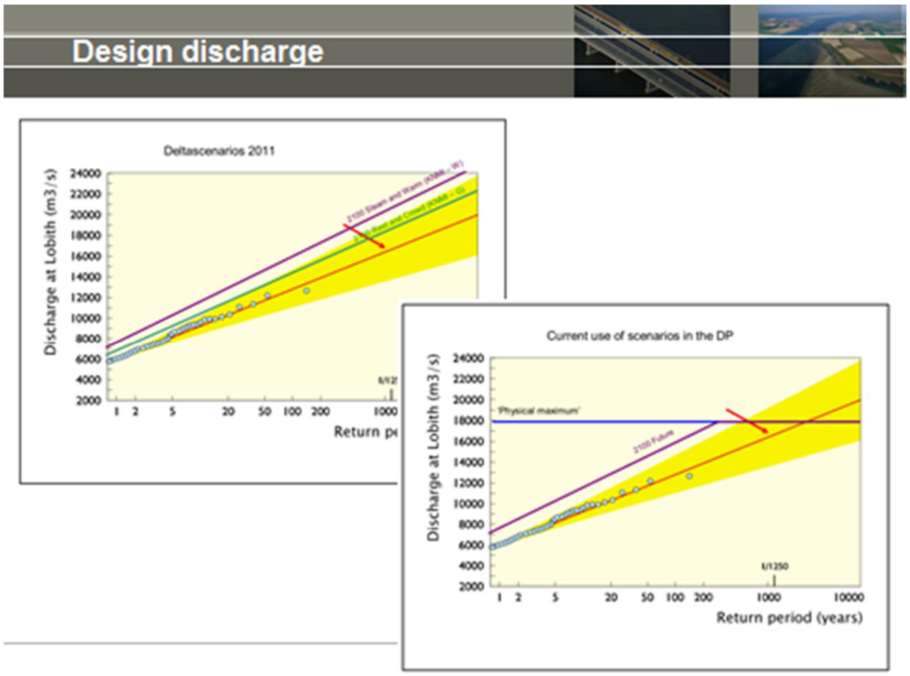
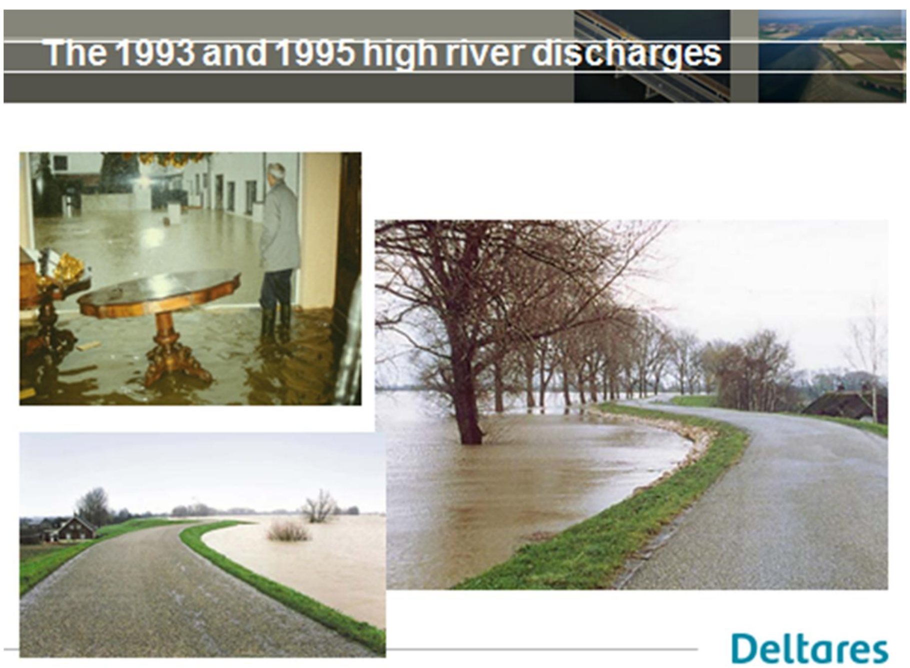
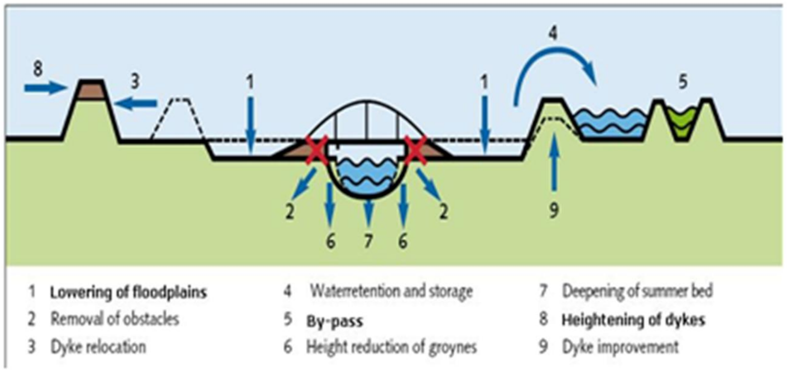
Deltaprogramme Large Rivers
Reinforcement of levees and River widening
in a
Powerful Combination


Design discharge
Deltascenarios 2011
Discharge at Lobith (m3/s)
Current use of scenarios in the DP
'Physical maximum'
2100 Future
Discharge at Lobith (m3/s)
1/1250
Return period (years)


The 1993 and 1995 high river discharges
Deltares

Preferred strategy



'Room for the river': hundreds of measures were evaluated
And: costs for dike strengthening were assessed

Problem: assessment and design instruments still under construction

- No longer 'retain without significant deformation', but 'allowed to fail with a certain probability'
- Implementation of new knowledge on failure modes (overtopping, seepage, macro stability)
- Hydraulic loadings subject of discussion

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Design discharge

- Protection standard 1:10.000 per year
- 24% of this probability related to overtopping (remaining 76% related to other failure mechanisms, like seepage, macro stability, etc.)
- Thus: failure probability for overtopping 1:40.000 per year

- In case of protection standard of 1:30.000 per year, failure probability for overtopping becomes 1:120.000 per year

- Design for period of 50 years

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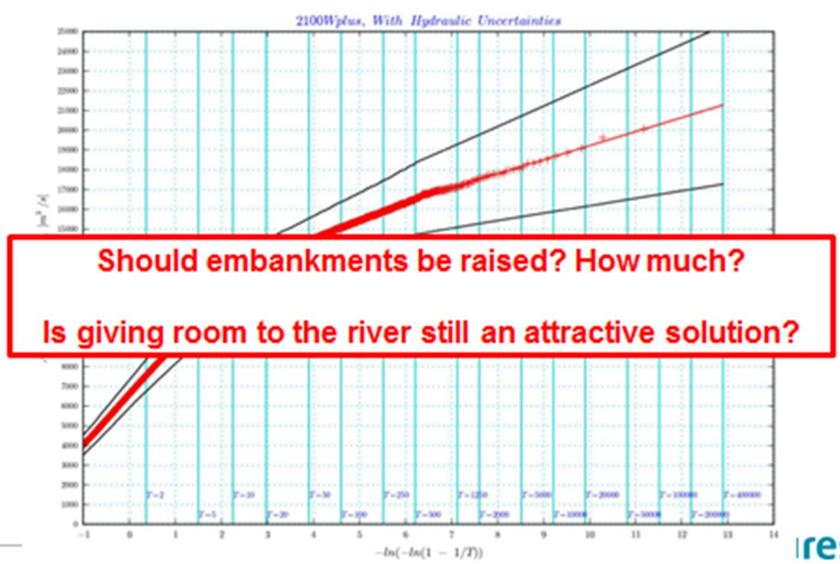
'Design discharge' in 2100



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