Quantifying uncertainties in the discharge distribution at the Pannerdense Kop

MSc-thesis in Civil Engineering and Management

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March 2020

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Cover picture:

Aerial view of the Pannerdense Kop (Van Houdt, 2007).

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Master thesis Civil Engineering and Management

University of Twente

Faculty of Engineering Technology

Department of Water Engineering and Management

March 2020

Enschede

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Preface

This master thesis forms the conclusion of my Master in Civil Engineering and Management. The thesis was carried out at the Department of Water Engineering and Management at the University of Twente.

I would like to thank the graduation committee for their supervision and feedback throughout this research. Secondly, I would like to thank Matthijs for the weekly feedback sessions and the suggestions to improve the research. Thirdly, I would like to thank Jord and Suzanne for their critical views to increase the academic level and the scientific writing of the thesis. Furthermore, I would like to thank the graduation committee for cowriting the RiverFlow 2020 and NCR days conference papers. Finally, I would like to thank all the experts that participated in this research.

I hope you find this report informative and I hope that you enjoy reading it.

Sander Steenblik

Enschede, March 2020

Summary

The discharge distribution forms a crucial aspect in the flood protection of the rivers. The discharge distribution determines the water levels downstream while the water levels determine again the discharge distribution at the bifurcation point (Gensen et al., 2020). This is a complex interaction and it is important to understand the uncertainties within the discharge distribution for flood protection. This study aims to determine the effects of the uncertainties in the discharge distribution at the Pannerdense Kop for a 16,000 m^3/s flood wave using expert elicitation.

First of all, six different sources of uncertainty in the discharge distribution have been identified: (1) wind, (2) geometry, (3) roughness of the main channel, (4) roughness of the floodplain, (5) failure of the primary defence and (6) regulation structure Pannerden. During expert interviews, the different sources have been quantified as the 90% confidence interval and it was checked whether the identified list of uncertainties is complete. Firstly, wind can cause set-up close to the Pannerdense Kop. This set-up can possibly cause a change in the discharge distribution. The experts quantified this source of uncertainty as small with 30 m^3/s. Secondly, the uncertainty in the geometry is caused by erosion and sedimentation of the river bed just before and during the flood wave. Furthermore, there is the possibility that a plaster layer close to the Pannerdense Kop can erode. The erosion and failure of levees perpendicular to the flow direction can cause a shift in the discharge distribution as well. The uncertainty in the geometry was quantified as 221 m^3/s. Thirdly, there is uncertainty in the roughness of the main channel because of the formation or flattening of bed forms during the flood wave. This is the largest source of uncertainty according to the experts and was quantified as 249 m^3/s. Fourthly, the uncertainty in the roughness of the floodplain was quantified as large as well with 236 m^3/s. Fifthly, the uncertainty in the failure of the primary defence was quantified as small with 12 m^3/s. Finally, there is uncertainty in the functioning of the regulation structure Pannerden because it is based on a model study. Furthermore, there is the possibility that the regulation structure fails during a flood wave event. The experts quantified this source of uncertainty as 95 m^3/s.

Secondly, a total amount of uncertainty in the discharge distribution at the Pannerdense Kop was obtained by combining the expert opinions. The probability distributions for the discharge distribution of the experts were combined to compute a total weighted probability distribution for the discharge distribution at the Pannerdense Kop. The width of the 90% confidence interval of this weighted probability distribution is equal to 571 m^3/s.

Finally, the weighted probability distribution of the discharge distribution has been implemented in a Sobek 1-D model study for the river Waal. The discharge of the Waal was varied using a monte carlo analysis in which the weighted probability distribution of the discharge distribution was used. The width of the 90% confidence interval for the water levels at Nijmegenhaven and Tiel are equal to 29.1cm and at Zaltbommel 26.4cm.

For future research it is recommended to extent the number of experts interviewed. Furthermore, a group discussion can be added in which the experts have to reach a consensus about the individual sources of uncertainty and the total amount of uncertainty in the discharge distribution. The model study can be extended by using the full river system of the Dutch river Rhine. The river is a self-regulating system and therefore a more accurate quantification of the uncertainty in the water level is obtained. Finally, it is recommended for Rijkswaterstaat to incorporate the uncertainties in the discharge distribution into the assessment of flood risk and future planning of river engineering works.

Table of contents

1. Introduction

The discharge distribution at bifurcation points is a crucial aspect in the flood protection of rivers. The water levels downstream of a bifurcation point are determined by the amount of discharge flowing into the branch while the discharge distribution is in turn being determined by the water levels of the downstream branch. (Gensen et al., 2020). A steeper water surface slope of the downstream branch conveys a larger portion of discharge compared to a shallower water surface slope (Thomas et al., 2011). The water surface slope in a branch is mainly determined by the geometry, hydraulic roughness and the slope of the riverbed (Schielen et al., 2008). The interaction between the discharge distribution and the water levels of the downstream branch makes the discharge distribution a crucial factor in the flood risk assessment of the river.

In the Netherlands, a new risk-based flood policy has been adopted in January 2017. The new flood policy is based on the risk of flooding instead of assessing the dikes on just one single water level (De Waal, 2016). When using a probabilistic framework, it is important to include uncertainties as well because uncertainties influence the probability of flooding. This means that uncertainties are explicitly included in the new flood protection policy. Therefore, the uncertainties in the discharge distribution are crucial because of the interaction with the water levels.

The most important sources of uncertainty for water level predictions in a single branch are the upstream discharge and the main channel roughness (Warmink et al., 2011). The uncertainty in the upstream discharge of a branch is caused by the discharge distribution at the bifurcation point and the estimation of the return periods of high discharges. The uncertainty in the discharge distribution is caused by several factors (Ogink, 2006; Ten Brinke, 2013). According to earlier studies, the main sources of uncertainty are the uncertainty in the main channel roughness due to formation of bedforms (Paarlberg et al., 2010), the floodplain roughness (Straatsma & Huthoff, 2011), regulation structures (Ten Brinke, 2013) and the stability of the bifurcation point (Kleinhans et al., 2013).

The current knowledge we have is insufficient. Over time there have been changes in the river system by means of the Room for the River projects and possibly new insights have been obtained about the uncertainties resulting in new values. Because of the new probabilistic approach of the flood risk assessment it is also crucial to incorporate a probabilistic approach of the discharge distribution by including the different sources of uncertainty. Therefore, a revision of all the sources of uncertainty is required to get a better understanding of the uncertainty in the discharge distribution over the Dutch Rhine branches.

The study area of this research focusses on the first major bifurcation point of the river Rhine after entering the Netherlands. This bifurcation point is the Pannerdense Kop where the Rijn splits into the Waal and the Pannerdensch Kanaal. An overview of the study is shown in Figure 1. The Waal is the largest branch and is roughly 80km long. The Pannerdensch Kanaal is 6km long and bifurcates at the IJsselkop into the Nederrijn and the IJssel. The discharge distribution at the Pannerdense Kop is roughly 2/3 towards the Waal and 1/3 towards the Pannerdensch Kanaal in design conditions (Schielen et al., 2008).

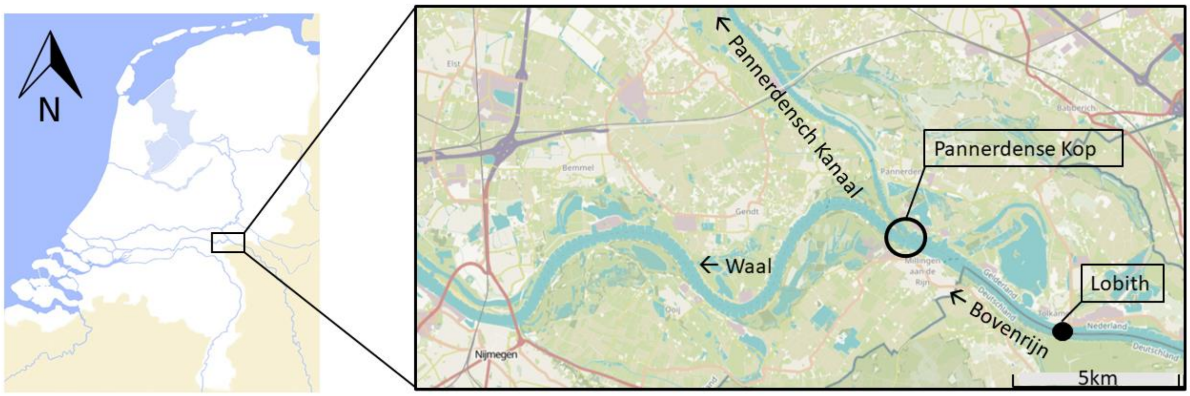

Figure 1: Schematisation of the study area. Adapted from Steenblik et al. (2020).

This study aims to identify and quantify the sources of uncertainty that have a significant influence on the discharge distribution of the Pannerdense Kop during a 16,000 m^3/s flood wave at Lobith by using expert elicitation. The Pannerdense Kop is used in this research because it is the largest bifurcation in the Netherlands and therefore plays a crucial role in the discharge distribution over the downstream branches of the Rhine river. For the quantification of the uncertainties a 16,000 m^3/s flood wave at Lobith is used. This flood wave is the old-norm for the flood protection in the Netherlands. The experts interviewed have experience with this flood wave and will therefore be able to give a reliable quantification of the uncertainty within the discharge distribution. Expert elicitation is used in this research because it has shown to be a useful method when there is scarce or inconsistent data available (Sebok et al., 2016; Van der Sluijs et al, 2005; Warmink et al., 2011).

The objective of this research is:

'To determine the effects of the uncertainties within the discharge distribution at the Pannerdense Kop during a flood wave of 16,000 m^3/s using expert elicitation.''

The following research questions are formulated:

RQ1: Which sources influence the discharge distribution at the bifurcation points?

RQ2: How large are the identified sources of uncertainty for the discharge distribution at the Pannerdense Kop?

RQ3: What is the total amount of uncertainty in the discharge distribution at the Pannerdense Kop?

RQ4: How large is the effect of the uncertainty in the discharge distribution on the water levels in the Waal?

Outline

The methodology of the research is described in Chapter 2. The results are given in Chapter 3 and the overarching discussion and conclusion can be found in Chapter 4 and Chapter 5 respectively. The Acknowledgements are presented in Chapter 6.

2. Methodology

The research firstly aims to identify all the different sources of uncertainty contributing to the uncertainty in the discharge distribution of the Pannerdense Kop (2.1). This is done using a literature review and experts are able to add any sources of uncertainty during the interviews. Secondly, these sources of uncertainties are quantified individually during the interview. For the interviews, the experts are selected (2.2.1), the interviews are prepared (2.2.2), the interviews are conducted (2.2.3) and the results are aggregated (2.2.4). In the final step, the results of the expert opinion study are used in a model study to determine the uncertainty in the water levels (2.3). An overview of the methodology is shown in Figure 2.

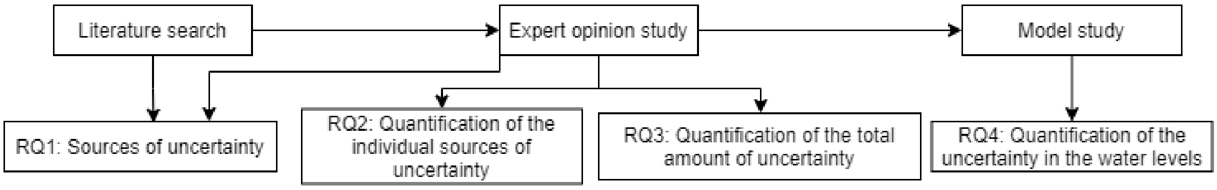

Figure 2: Flowchart of the methodology

2.1 RQ1: Sources of uncertainty

As a preparation for this Master-thesis a literature review was done (Steenblik , 2019). In this literature review, an identification of the uncertainties in the discharge distribution over the Dutch river Rhine branches has been made. The identified sources of uncertainties in the literature review are also used in this research. The list of the identified sources and the used literature is shown in Table 1. A few sources are denoted with an asterisk. These sources did not say anything about the uncertainty in the discharge distribution but quantified the uncertainty in the water levels instead. These sources are still useful in this research because of the interaction between the water levels and the discharge distribution (Gensen et al., 2020). The list as shown in Table 1 is expected to cover the most important uncertainties that are present within the discharge distribution at a bifurcation point. Sources of uncertainty like ice jams on the rivers have been excluded from the table because the chance of occurrence is very small and decreases because of climate change and the use of cooling water in industries next to the Rhine (Van der Wal, 2011). The interviews only have a limited duration of about one hour and therefore it is important to focus on the sources of uncertainty that are expected to be significant. During the interviews, the experts are asked whether they agree with the list of uncertainties that has been identified. If they think that some sources of uncertainty are missing, they can add these to the list. This is done to ensure that the list is complete and that the list reflects the expert opinion best.

Table 1: Literature found in the literature search to answer research question 1. Sources indicated with an asterisk focused at the water levels instead of the discharge distribution.*

Source of uncertainty	**Reference(s)**
Wind	Ogink (2006)
Geometry	Kleinhans (2003) Paarlberg et al. (2010) Schropp (2002)
Roughness of the main channel	Bozzi et al. (2015)* Frings & Kleinhans (2008) Gensen et al. (2020) Hulscher et al. (2017)* Paarlberg et al. (2010) Pappenberger et al. (2008)* Warmink et al. (2013a)*
Roughness of the flood plain	Straatsma & Huthoff (2011) Warmink et al. (2011)* Warmink et al. (2013b)*
Failure of primary defence	Bomers et al. (2019)
Regulation structures	Ten Brinke (2013)

2.2 RQ2&3: Expert elicitation

The uncertainties in the discharge distribution are quantified using expert elicitation. Firstly, the experts are selected for the interviews (2.2.1). Next, the interviews are prepared (2.2.2) and conducted (2.2.3). Finally, the interviews are aggregated, and the results are obtained (2.2.4).

2.2.1 Expert selection

The first step in an expert opinion study is to select the experts for the interviews. It is important that this is done carefully because the results of expert opinion studies are sensitive to the selection of the experts (Warmink et al., 2011). Firstly, different research institutes, companies and the governmental body responsible for the maintenance of the Dutch river Rhine branches were contacted. It is important that experts are selected that can give an estimation of the uncertainties present within the discharge distribution of the river Rhine branches. Therefore, the companies contacted were asked whether they have employees with expertise in the discharge distribution over the Dutch river Rhine branches. Expert opinion studies are often prone to different biases like anchoring bias and availability bias (De Little et al., 2018). The anchoring bias occurs when experts weigh their judgement towards conventional biases and the motivational bias occurs when an expert response is based on particular context, experience or personal beliefs. By choosing experts from different companies it is tried to find experts with different backgrounds. This is done to minimise the effect of bias on the results. The effect of expert bias is discussed further in the discussion section 4.1.

2.2.2 Interview preparation

The experts selected for the interviews in the previous step need to be prepared with the required information for the interviews. A document is sent to the experts as preparation and this document can be found in Appendix 1. The aim of the document is to inform the experts about how the quantification is done and how the interview is structured. An Excel-sheet is used as a tool during the interview for the quantification of the different sources of uncertainty. The experts also see their quantification of the uncertainty by means of visualising the probability distribution as shown in Figure 3. The visualisation is done during the interview. When the expert quantifies an uncertainty, this number is filled in the Excel-sheet. The expert can then adjust the quantification until the expert is satisfied with the result. This is done to ensure that the expert gives a quantification which is reliable visually as well.

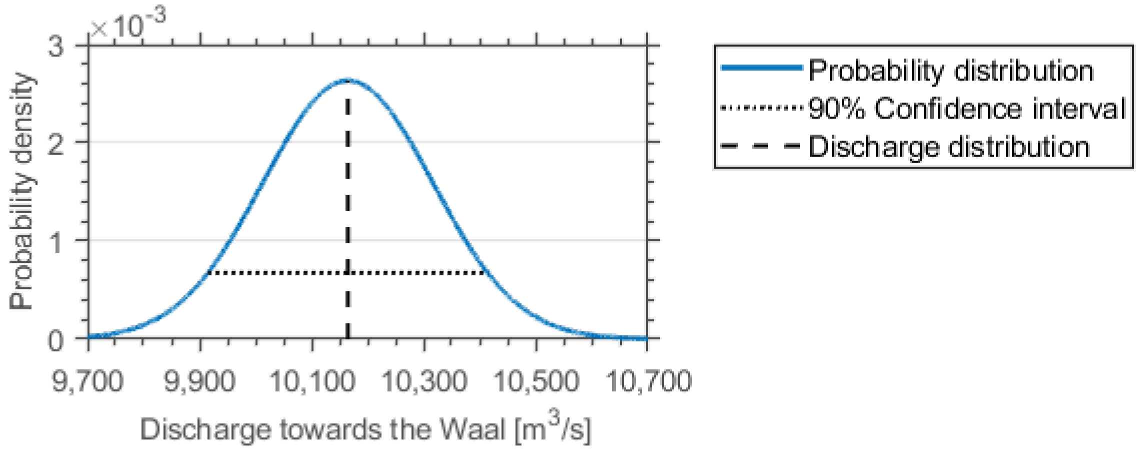

Figure 3: Example visualisation of the tool

In Figure 3, the dashed vertical line is the mean of the discharge distribution during a 16,000 m^3/s flood wave at Lobith towards the Waal. Around this mean, the uncertainty bandwidth of the discharge distribution is quantified. The mean of the discharge distribution is determined by the expert during the interview (2.2.3). The blue line in Figure 3 is the normal distribution that is plotted using the 90% confidence interval that is quantified by the expert. The 90% confidence is the horizontal dotted line. In a normal distribution, the 90% confidence is equal to $2*1.64\sigma$ (Walck, 2007). The normal distribution is used in the tool because there is no reason to believe that the distribution should be larger or smaller towards one side of the mean. It is possible that an expert indicates that they believe that a probability distribution different than the normal distribution is more reliable. This is not incorporated in the tool used during the interview, but it will be aggregated after the interview. The 90% confidence interval is used because it is commonly used in this field of research and therefore the experts will be able to give a more reliable quantification of the uncertainties (Tan et al., 2010).

2.2.3 The interview

The aim of the interview is to verify the identified sources of uncertainty and to get a quantification of the individual sources of uncertainty and the total uncertainty. For this purpose, the interview has been divided in three different parts as shown in Figure 4. The three different parts are further explained on the next page. A list of all the interview questions can be found in Appendix 2.

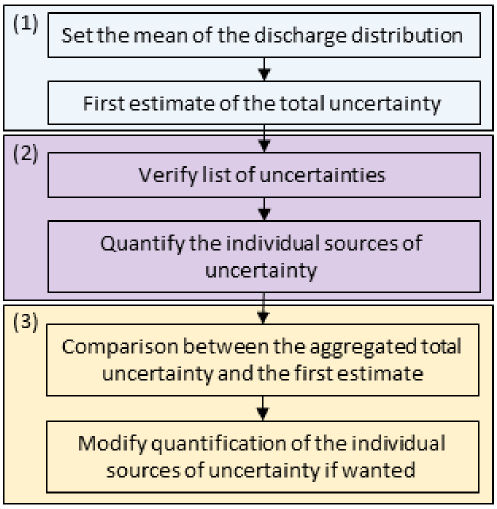

Figure 4: Methodological overview of the interview

The first part of the interview started by asking the expert what the discharge distribution at the Pannerdense Kop will be during a 16,000 m^3/s flood wave at Lobith by quantifying the amount of discharge towards the Waal. Next, the expert is asked to give a first estimate of the total uncertainty around this discharge distribution. This first estimation is compared to the sum of the estimates of the sources, to assess the internal coherence of the expert's opinion later on in the interview.

In the second part of the interview the experts quantified all the individual sources of uncertainty. The expert is asked whether they agree if the list with sources of uncertainty sent to them in the preparation document are the most important ones or if some sources of uncertainty are missing. This is done for the verification of the sources of uncertainty. If the expert does not agree to the list, the extra source(s) of uncertainty is added to the list. Next, the expert is asked to quantify the sources of uncertainty conform the 90% confidence interval and the normal distribution. When quantifying the effect of the uncertainty the expert is also asked to incorporate and comment on the chance of occurrence in the given quantification. It is possible for the expert to deviate from the normal distribution if they believe that for example a source of uncertainty only increases the discharge towards the Waal.

In the third and final part of the interview the total amount of uncertainty is quantified. All the quantified individual sources of uncertainty from the second part of the interview are added up to determine the total amount of uncertainty. The method for this is explained in the aggregation method (2.2.4). The quantified total amount of uncertainty by adding up all the individual sources can now be compared to the first estimate of the total uncertainty quantified in the first part of the interview. The expert is asked to comment on the difference if there are any and if the expert would like to make any changes to the quantification of the individual sources of uncertainty because they might have made an under- or overestimation. By doing this, it is ensured that the expert gives a quantification that they support, and think is reliable. Furthermore, the experts are asked whether the amount of uncertainty is also applicable for a 18,000 m^3/s flood wave at Lobith because of the probabilistic framework used in flood risk assessment.

2.2.4 Aggregation method

To be able to weight the different expert opinions, the experts need to be weighted accordingly. During the interview, the experts are asked to give themselves a weight on a scale of 1-5 based on how they rate their ability to give reliable quantifications of the uncertainty compared to colleagues in the water engineering field. The assigning of the weights also creates a bias which is further discussed in the discussion section 4.1.

Firstly, the individual sources of uncertainty are weighted according to the weights that have been assigned to the experts. The output of this step is a list of all the sources of uncertainty and their averaged 90% confidence interval. This is used for the importance assessment to see which of the sources of uncertainty contribute most to the total amount of uncertainty and it answers research question 2 as well.

Secondly, the probability distribution of the total amount of uncertainty needs to be obtained for all the experts by adding up all the individual sources of uncertainty. The sources of uncertainty can be added up assuming that they are independent from eachother. When they are independent, they can be added by taking the square root of the sum of the standard deviations squared (Ogink, 2006). Now, the probability distributions of the total amount of uncertainty of all the experts need to be combined to find a total weighted probability distribution of the discharge distribution towards the Waal. This is done by random sampling. In this sampling, each expert's probability distribution gets assigned the weight of the corresponding expert. For 10,000 runs, a probability distribution of an expert is selected according to their weights and a value for the discharge towards the Waal is sampled from the selected probability distribution. From this newly created dataset, a probability distribution is determined. The output of this step is the total amount of uncertainty and answers research question 3. The results after aggregation are also send to the experts for rectification. The experts are asked if their quantification given during the interview is interpreted properly and if they would like to make any changes to the quantification of the individual sources of uncertainty. This is done to make sure that the results are conform the expert opinion. All the experts replied to the rectification with the confirmation that their quantifications are interpreted correctly.

2.3 RQ4: Uncertainty in the water levels

The aim of the model study is to translate the uncertainty in the discharge distribution to an uncertainty in the water levels. Uncertainty is often expressed in an uncertainty in water levels in river engineering studies. As was visible in the methodology of research question 1, there is a reasonable amount of literature available about the uncertainty in the water levels. This literature has been marked with an asterisk in Table 1. When translating the uncertainty in the discharge distribution to an uncertainty in the water level, the results can be compared to this literature and it can be seen if they are coherent or not.

The weighted probability distribution of the total uncertainty obtained during the expert opinion study can now be used for a model study. For this model study, a Sobek 1D model of the Dutch river Rhine branches is used. The version of the Sobek model used is: sobek-rijn-j16_5-v1. Rijkswaterstaat uses this model for water management and operational purposes. The model uses a staggered grid for calculating the water levels (RWS-WVL & Deltares, 2017). The practical implication of this is that the water levels and the flow velocities are not solved at the same location. The model solves the one-dimensional Saint-Venant equations (Deltares, 2020). The distance between two calculation points for the water levels is on average 500 meters. For each calculation point a schematisation of the river profile is defined with corresponding hydraulic roughness. The model has been calibrated by first calibrating the water levels of the river branches, Waal, Nederrijn-Lek, IJssel and Bovenrijn and Pannerdensch Kanaal separately (RWS-WVL & Deltares, 2017). For the final phase of the calibration, the upstream discharge has been set as the boundary condition of the model. After the calibration of the water levels, the river branches have been added in the final model and the discharge distribution has been adjusted to meet the policy discharge distribution.

The calibrated model is used for the study and is reduced to the river Waal. Upstream in the model there is a small section that has an aberrant hydraulic roughness to adjust for the discharge distribution in the calibration of the model. The effects of this section can be neglected because it does not influence the water levels downstream. The downstream boundary condition of the model is the water level at Hardinxveld and is set at 0.5 m+ NAP. The upstream boundary conditions of the model are the discharge towards the Waal at the Pannerdense Kop. 10,000 values for the discharge towards the Waal are randomly sampled from the weighted probability distribution. The sampled discharges are used as the input discharge for the Waal at the Pannerdense Kop. It is important to consider that the water levels are influenced by the downstream boundary of the model. The water levels are influenced by this fixed boundary condition of the model because of the backwater curve. The effects of the backwater curve are visible up to Zaltbommel (Warmink et al., 2013b), this means that the uncertainty in the results from the boundary conditions up to Zaltbommel are underestimated and unreliable. Therefore, the water levels at Nijmegenhaven, Tiel and Zaltbommel are used as output. The effect of the downstream boundary condition at Hardinxveld is also analysed by setting the boundary conditions to 1 m +NAP instead of the 0.5 m +NAP in the calibrated model. An overview of the three locations used for the analysis and the results is shown in Figure 5. The water levels that are used as the output are the water levels obtained after running the model with a stationary discharge sampled from the probability distribution for 7 days. It is visible that the water levels of the Waal have reached an equilibrium state after this time period. From the output of the water levels, a probability distribution is determined to assess the effects of the uncertainty in the discharge distribution on the uncertainty in the water levels.

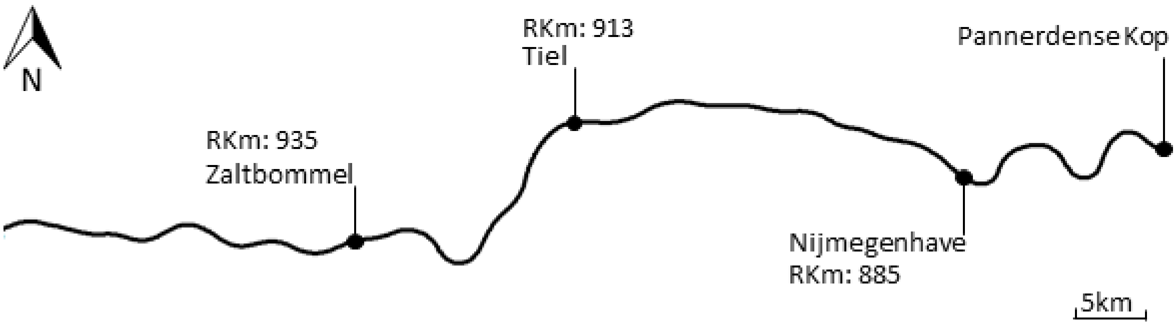

Figure 5: Overview of the locations used for the Sobek output with corresponding name and river kilometre

3. Results

In this chapter the results of the research questions are presented. Firstly, the individual sources of uncertainty in the discharge distribution are identified and described in section 3.1. Secondly, the individual sources of uncertainty are quantified in section 3.2 and the total amount of uncertainty is quantified in section 3.3. Finally, the results of the model study are presented in section 3.4.

3.1 RQ1: Sources of uncertainty

Wind

The first source of uncertainty is the effect of wind on the discharge distribution. When wind speeds of above 25 m/s (severe storm) are measured, there is a significant influence on the discharge distribution (Ogink, 2006). Wind speeds of above 25 m/s only have a probability of 1/1000 years in the Netherlands which means that it is very unlikely that this will coincide together with a flood wave (Ogink, 2006). The effect of wind on the Pannerdense Kop is largest with South-Western wind because then more water is directed towards the Pannerdensch Kanaal because of set-up in the Waal. When there is North-Eastern wind, the opposite occurs and the discharge towards the Waal is increased because of set-up in the Pannerdensch Kanaal.

Geometry

The uncertainty in the geometry during a flood wave is caused by different factors. Firstly, large scale erosion is a source of uncertainty for the discharge distribution. Large scale erosion can occur when the bifurcation point is unstable (Kleinhans, 2013). It is highly uncertain how the river bed is going to respond to minor changes in the discharge distribution. There is a risk that the Pannerdensch Kanaal erodes during a flood wave (Schropp, 2002). This introduces the risk of a bifurcation point being instable. The length of the flood wave can also influence the amount of erosion. When the flood wave is longer, the effects of erosion are increased. Furthermore, it was mentioned during the interviews by four of the experts that the erosion of a plaster layer can have a significant effect on the discharge distribution. A plaster layer is a layer of coarse sediments that serves as a firm layer in the river bed. When a plaster layer erodes close to the Pannerdense Kop, the branch where the plaster layer erodes attracts more discharge. This can be accelerated when a layer of fine sediment is reached what increases the amount of erosion. A cross-section of the Bovenrijn close to the Pannerdense Kop is shown in Figure 6. It is visible that the top layer of the river bed is covered with gravel with a thickness of around 90cm. This is also visible in the branches of the Waal and the Pannerdensch Kanaal (Frings & Kleinhans, 2001). Below the layer of the gravel, a layer of sand is present which is the layer that is prone to accelerating the erosion when this layer is reached. There is a difference in the median grain size of the Waal and the Pannerdensch Kanaal, respectively, 2.8mm and 6.1mm (Frings & Kleinhans, 2001). This can also be explained by the amount of sand that is present in the gravel layer of both branches. In the Waal this is on average 46% and in the Pannerdensch Kanaal 26% on average (Frings & Kleinhans, 2001). This shows that the Pannerdensch Kanaal is coarser compared to the Waal.

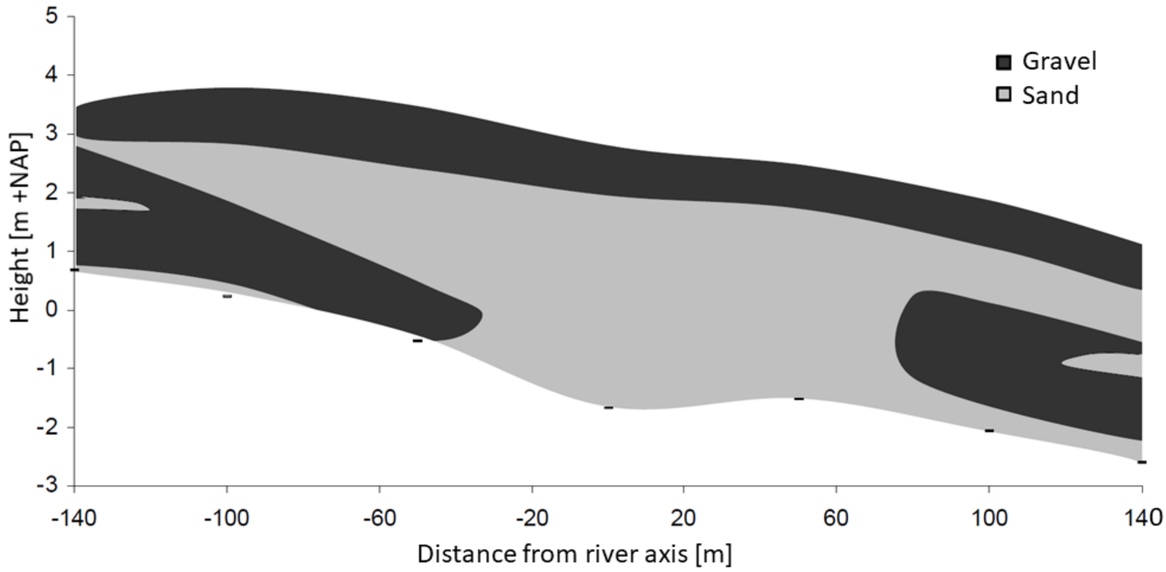

Figure 6: Geological cross section of the Bovenrijn at river kilometre 866.9 (Frings & Kleinhans, 2002)

Secondly, during the interviews it was mentioned by four of the experts that the failure of levees in the floodplain downstream of the Pannerdense Kop can have a significant effect on the discharge distribution. Especially the levees that are perpendicular to the flow direction have a significant effect when there is failure or severe erosion. In Figure 7, erosion of a levee close to the IJsselkop is shown. This erosion occurred in 2018 when a discharge of 8,500-9,000 m^3/s at Lobith was measured. When a 16,000 m^3/s flood wave will occur, it can be expected that the effects of erosion and possible failure of the levees is larger. In Figure 8 an overview of the important levees around the Pannerdense Kop is shown.

Finally, it was also mentioned by one of the experts that sedimentation can occur in side channels and in the area in between the groynes. When this occurs in a branch, the branch attracts less discharge because of the sedimentation and thus decreasing the flow profile of the branch.

Figure 7: Erosion of a levee in between Bakenhof and Meinerswijk close to the IJsselkop (Rozier, 2018a)

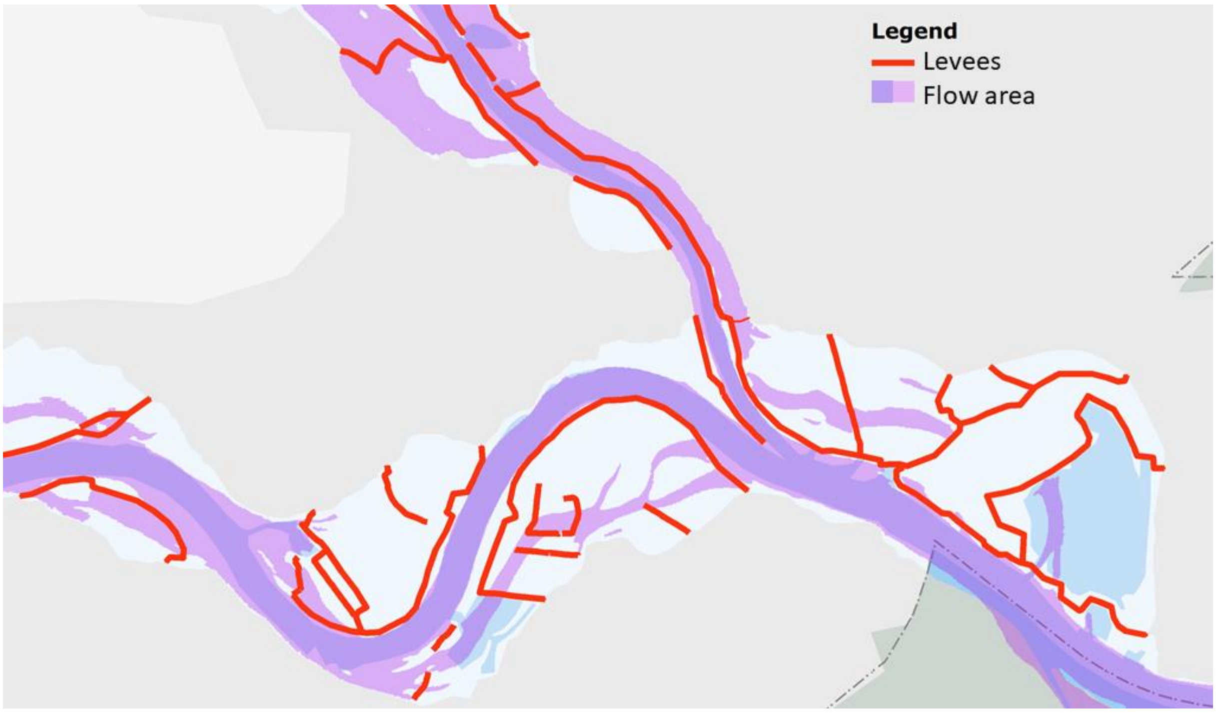

Figure 8: Overview of the levees close to the Pannerdense Kop. Adapted from Rozier (2018b).

Roughness of the main channel

The roughness of the main channel has shown to be an important source of uncertainty for the water levels of a branch in several rivers. For the Po river in Italy (Bozzi et al., 2015) and the Alzette river in Luxembourg (Pappenberger et al., 2008), the roughness of the main channel turned out to be a crucial source of uncertainty for determining the water levels. In lowland, sand bed rivers, the roughness of the main channel is dominated by the formation of bedforms before and during the flood wave (Paarlberg et al., 2010). There is a large variation in bedforms and their sizes and thus the roughness of the main channel (Frings & Kleinhans, 2008). It was found that for relatively short flood waves there is an increased discharge towards the Pannerdensch Kanaal (Paarlberg et al., 2010). This is caused by the relatively low roughness of the Pannerdensch Kanaal. During a relatively short flood wave, the bedforms are smaller compared to a long flood wave. This means that for a flood wave with a longer duration the uncertainty in the discharge distribution is smaller because the difference in the relative roughness between the Waal and the Pannerdensch Kanaal is smaller compared to a shorter flood wave (Paarlberg et al., 2010). It is also possible that bedforms flatten out because of the high flow velocities that can occur during a flood wave (Hulscher et al., 2017). When the bedforms flatten out in a branch, this branch attracts less discharge because of the decreased hydraulic roughness. In hydrodynamic models the roughness of the main channel is a significant source of uncertainty (Warmink et al., 2013a). For the Waal river a significant amount of uncertainty was found in the design water level due to the uncertainty in the bed form roughness (Warmink et al., 2013a). This also influences the discharge distribution of the Pannerdense Kop because the discharge distribution is determined by the water level of the downstream branches (Gensen et al., 2020). The uncertainty in the discharge distribution due to the hydraulic roughness is dependent on the correlation of the branches. When the branches are not correlated, the hydraulic roughness of one branch shows different behaviour than the other branch. This causes a change in the relative roughness and the discharge towards the branch with a lower hydraulic roughness is increased.

Roughness of the floodplain

The vegetation is the main contributor to the roughness of the floodplain and also the most significant source of uncertainty in the roughness of the floodplain (Warmink et al., 2013b; Straatsma & Huthoff, 2011). Firstly, there are measurement errors in the actual vegetation that is on the floodplain (Warmink et al., 2011). Secondly, the measured vegetation needs to be implemented into a model and this gives schematisation and discretisation errors. This creates uncertainty in the aggregated roughness of the floodplain. Furthermore, there is a seasonal variability of the vegetation in the floodplain area. The roughness of the vegetation can differ significantly between the seasons of autumn and winter. These months are the most important ones because the flood seasons lasts from November to March (Warmink et al., 2013b). For the roughness of the floodplain the same is valid as for the roughness of the main channel. The roughness of the branches needs to be uncorrelated to be able to create a significant uncertainty in the discharge distribution.

Failure of the primary defence

The failure of the primary defence lowers the water levels in the branch where a dike breach occurs. The lowering of the water levels in this branch can cause a change in the discharge distribution by directing more discharge towards the branch where the dike breach occurred. Furthermore, upstream failure of the primary defence can change the discharge distribution as well (Bomers et al., 2019). For the Dutch Rhine river, the old IJssel Valley can convey a significant amount of discharge when there is a breach upstream of the Pannerdense Kop reducing the actual discharge that reaches the Pannerdense Kop. Furthermore, three of the experts also mentioned that the failure of the primary defence is more likely to happen in Germany as was shown in Bomers et al. (2019). Therefore, these experts said that we should not take into account the uncertainty in the failure of primary defence downstream of the Pannerdense Kop.

Regulation structure Pannerden

Regulation structure Pannerden has been built on the Eastern floodplain of the Pannerdensch Kanaal and is shown in Figure 9. The regulation structure is built to steer discharge to ensure that the design discharge distribution is met at the Pannerdense Kop. The regulation structure has a steering margin of 480 m^3/s (Ten Brinke, 2013). With the closure of the entire regulation structure, 480 m^3/s is steered towards the Waal. The regulation structure is evaluated every year and the beams are placed before the start of each autumn because the structure is semi-dynamic. There is uncertainty in the functioning of the regulation structure because it is based on a model study. Furthermore, it was also mentioned by one expert that we should consider failure of the regulation structure. If some of the beams in the structure will break, there is an increased discharge towards the Pannerdensch Kanaal.

Figure 9: Regulation structure Pannerden (Rijkswaterstaat, 2016)

Overview

An overview of the identified uncertainties is shown in Table 2. This are the sources that were presented to the experts and they were asked whether this list is complete and if some sources of uncertainty are missing. All experts agreed that the list is complete but not all experts agreed about the uncertainty within the geometry. Four of the experts mentioned a significant change in the discharge distribution due to large scale erosion of a plaster layer. Furthermore, four of the experts mentioned the failure of levees downstream of the Pannerdense Kop. Finally, one of the experts mentioned the sedimentation of side channels as a source of uncertainty within the geometry. Since all the experts were able to add uncertainties to the list it is expected that the list as shown in Table 2 captures the sources of uncertainty in the discharge distribution at the Pannerdense Kop.

Table 2: Overview of the identified uncertainties with an assigned Uncertainty ID

Uncertainty ID	Description
1	Wind
2	Geometry
3	Roughness of the main channel
4	Roughness of the floodplain
5	Failure of the primary defence
6	Regulation structure Pannerden

3.2 RQ2: Quantification of the individual sources of uncertainty

During the interviews, the individual sources of uncertainty have been quantified by the experts. The sources of uncertainty have been weighted according to the expert weights which are given in Table 3. The weights of the experts are given on a scale of 1-5.

Table 3: Expert weights

Expert	Weight
1	2
2	4
3	3
4	3
5	3.5
6	2.5
7	4

With the assigned weights from Table 3 the quantifications of the experts are weighted and presented in Table 4. The experts quantified all sources of uncertainty. The uncertainties are indicated with numbers which are described in Table 2. The values in Table 4 are also presented visually in Figure 10.

Table 4: The quantification of the individual sources of uncertainties and the weighted average (U=uncertainty, E=expert). Numbers are given as the 90% confidence in m³/s.

	U1	U2	U3	U4	U5	U6
E1	40	500	100	300	0	100
E2	20	447	400	200	10	200
E3	10	100	400	400	?*	50
E4	50	300	300	250	0	40
E5	30	128	150	150	40	100
E6	50	90	300	400	0	25
E7	20	50	80**	80	0	103***
Average	30	221	249	236	12	95

*Expert could not quantify this source of uncertainty but said that the source should not be neglected.
**This uncertainty is larger towards the Pannerdensch Kanaal. Expert agreed that the average of the normal distribution around this uncertainty should be set 30 m³/s larger towards the Pannerdensch Kanaal.
***This uncertainty exists out of a bandwidth of 25m³/s uncertainty around the discharge distribution and the uncertainty in case of failure of the regulation structure of 100 m³/s only towards the Pannerdensch Kanaal.

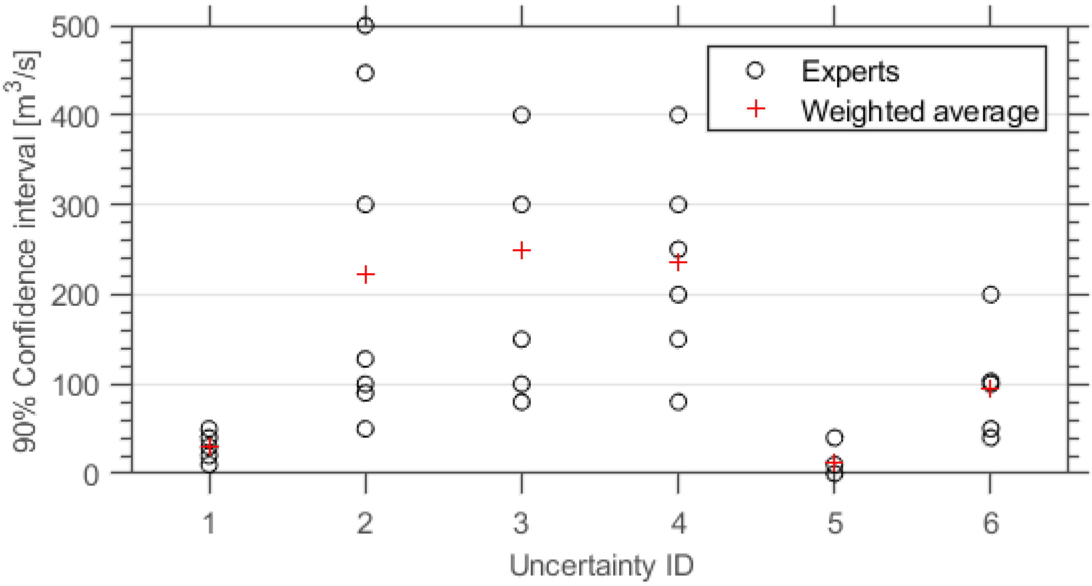

Figure 10: Quantitative results of the expert opinions for the individual sources of uncertainty as shown in Table 4. The numbers on the horizontal axis refer to the Uncertainty ID's in Table 2.

The six different uncertainties have been quantified by the experts and clear differences between the uncertainties are visible in Figure 10. The uncertainties in the geometry (2), roughness of the main channel (3) and the roughness of the flood plain (4) were quantified as largest. While the uncertainties in the wind (1) and the failure of the primary defence (5) were quantified as being relatively small. The uncertainty in the regulation structure Pannerden (6) was quantified as medium. The quantification of the different sources of uncertainty is further explained below.

Wind

The uncertainty of the wind was quantified relatively small with a width of the 90% confidence interval of 30 m³/s. The experts said that the chance that wind speeds and directions required for significant set up close to the bifurcation point coincide with a flood wave is negligible. This is coherent to the findings in Ogink (2006) in which a 90% confidence interval of 55 m³/s was found for the uncertainty in the wind.

Geometry

The uncertainty in the geometry was quantified as 221 m^3/s. However, there is a large spread in the quantifications given by the experts, ranging from 50 m^3/s to 500 m^3/s. This range can be explained by two different factors in the geometry, namely, the erosion of plaster layers and the erosion and failure of levees perpendicular to the flow direction. Not all the experts mentioned the erosion of plaster layers and have therefore likely not included it in their quantification. Two of the experts that did mention it did not believe it would have a significant effect on the discharge distribution because only local erosion would occur which would not lead to a significant change in the discharge distribution. The other two experts that did quantify the erosion of plaster layers as significantly large said that a layer of thin sediments can be reached and that the erosion effects are accelerated. This acceleration of the effects can lead to large changes in the discharge distribution. The erosion and possible failure of levees perpendicular to the flow direction close to the Pannerdense Kop was mentioned by four of the experts. For this uncertainty, three of the experts said that this would have a significant effect on the discharge distribution because of the increased flow velocities in the floodplain area. In the report of Ogink (2006) the failure of levees was quantified with the 90% confidence interval as 80 m^3/s. The three experts that said that the failure of levees is a significant source quantified the uncertainty between 100-200 m^3/s. This is a significant difference compared to the report of Ogink (2006).

Roughness of the main channel

The uncertainty in the roughness of the main channel was quantified as 249 m^3/s, thereby on average being the largest source of uncertainty in the discharge distribution. However, also a large spread between the experts is observed. All experts agreed that the formation of the bedforms during a flood wave and also possible flattening of the bedforms is highly uncertain. However, a distinction between two different groups in the expert opinions can be made. The experts quantifying the uncertainty between 80 m^3/s and 150 m^3/s clearly estimate the effects significantly smaller compared to the group quantifying it between 300 m^3/s and 400 m^3/s. This difference can be explained by the expert's opinion on the correlation between the roughness of the branches. The group of experts quantifying it rather low expect that when the roughness is under- or overestimated, it will be the same for both branches. This means that the relative roughness between the two branches does not change a lot which does not lead to a significant change in the discharge distribution. The group quantifying the roughness rather large did believe in the possibility that the roughness of a branch will show different behaviour compared to the other branch.

Roughness of the flood plain

The uncertainty in the roughness of the floodplain was quantified as 236 m^3/s. The experts agreed that the uncertainty of the floodplain roughness is large. However, three of the experts mentioned that Rijkswaterstaat has adopted a new mowing strategy in which they have a stricter regime of cutting the vegetation on the floodplains. This reduces the effect of the seasonal variability. For the roughness of the floodplain there are also two different groups of experts in which one group quantifies the uncertainty in the discharge distribution as low because the floodplain roughness of the branches are correlated, and the other group quantifies it as large because the floodplain roughness of the branches are uncorrelated.

Failure of the primary defence

The effect of the failure of the primary defence was quantified as small by two experts and even quantified as zero by four of the experts, obtaining a weighted average of 12 m^3/s. One of the experts did not quantify the source because the expert said not to have enough knowledge about the probability of failure and the eventual effects. Furthermore, it was said by some of the experts that it is more probable that the primary defence in Germany fails which would induce that the actual 16,000 m^3/s would not reach the Netherlands via the main river.

Regulation structure

The uncertainty in discharge distribution caused by the regulation structure Pannerden was quantified rather small with 90 m^3/s. It was quantified rather small because the regulation structure has a steering capacity of 480 m^3/s. This means that the model uncertainty would not be significantly large compared to the other sources of uncertainty. Two of the experts mentioned a probable failure of the structure. This would happen when some of the concrete weirs break out or when the full structure would fail. When this would happen, a more significant effect in the discharge distribution would be observed with an increased discharge towards the Pannerdensch Kanaal.

3.3 RQ3: Quantification of the total amount of uncertainty

The total amount of uncertainty is quantified in the first part of the interview when the experts give their first estimate and secondly, in the last part of the interview when all the individual sources of uncertainty are aggregated. The quantification of both is shown in Table 5 per expert.

Table 5: Quantification of the total amount of uncertainty as the 90% confidence interval per expert

Expert	First estimate [m^3/s]	Individual sources [m^3/s]
1	1,000	601
2	1,000	664
3	1,000	577
4	500	497
5	200	272
6	500	511
7	800	162
Average	711	453

It is visible that the first estimate is for 5 of the 7 experts larger than the total amount of uncertainty when adding up all the individual sources. The first estimate of all the experts is plotted in Figure 14. It is visible that not all the experts quantified the same mean for the discharge distribution. Four of the experts set the discharge distribution as 10,165 m^3/s, which is equal to the policy discharge distribution. Three of the experts quantified the discharge distribution to be larger towards the Waal because of the erosion that is seen in the Waal over the past couple of years. This trend in the erosion is visible in Figure 11, where the average bed level of the Waal is plotted over the past couple of years. Comparing this to the trends in the bed level of the Pannerdensch Kanaal as shown in Figure 12, it is visible that the trend in the erosion is smaller. The trend in the erosion is also visible in the discharge distribution at the Pannerdense Kop over the past couple of years. In Figure 13, the discharge of the Bovenrijn is plotted against the discharge of the Pannerdensch Kanaal. It is visible that a there has been a shift of less discharge going to the Pannerdensch Kanaal of up to 200 m^3/s for upper Rhine discharges of 2000 m^3/s.

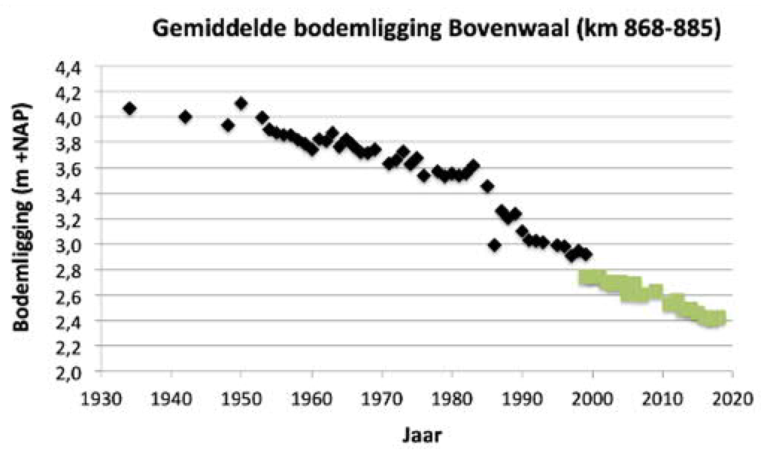

Figure 11: Average bed level height Upper-Waal (RKm 868-885). Adapted from Schropp (2019).

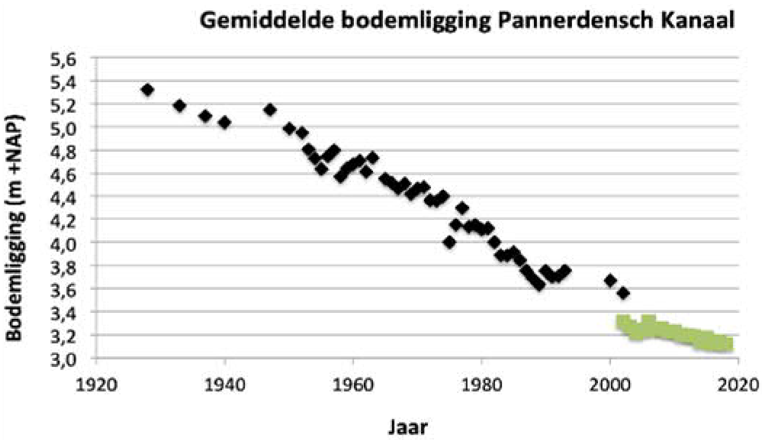

Figure 12: Average bed level height Pannerdensch Kanaal. Adapted from Schropp (2019).

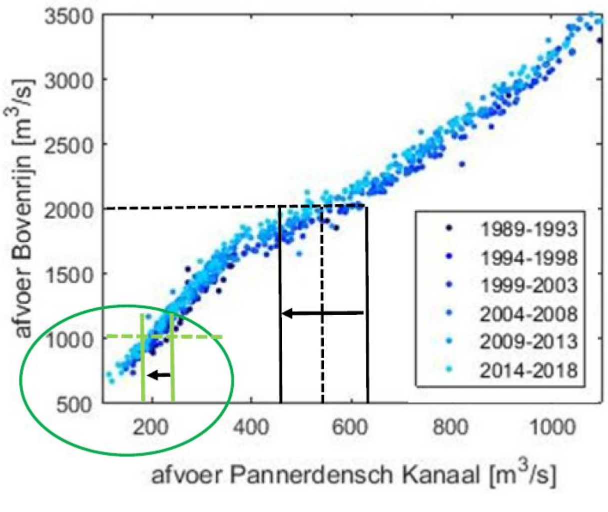

Figure 13: Discharge of the Bovenrijn vs. discharge of the Pannerdensch Kanaal (Tönis, 2019)

The plot of the total uncertainty found by all the experts when adding up all the individual sources of uncertainty is shown in Figure 15. It is visible that for expert 7, the mode of the probability distribution shifted towards the left. This can be explained by the uncertainty in the roughness of the main channel and the regulation structure. The expert expected that the uncertainty in the roughness of the main channel would have a larger effect of increased discharge towards the Pannerdensch Kanaal. Secondly, the regulation structure has an effect of increased discharge towards the Pannerdensch Kanaal when the structure fails. When the experts were asked which of the two quantifications represent the uncertainty best, they all responded that the second estimation when the individual sources are added up represents the total uncertainty best. This probability distribution is assumed to be best because this probability distribution is obtained by splitting up all the individual sources of uncertainty and therefore giving a more accurate quantification.

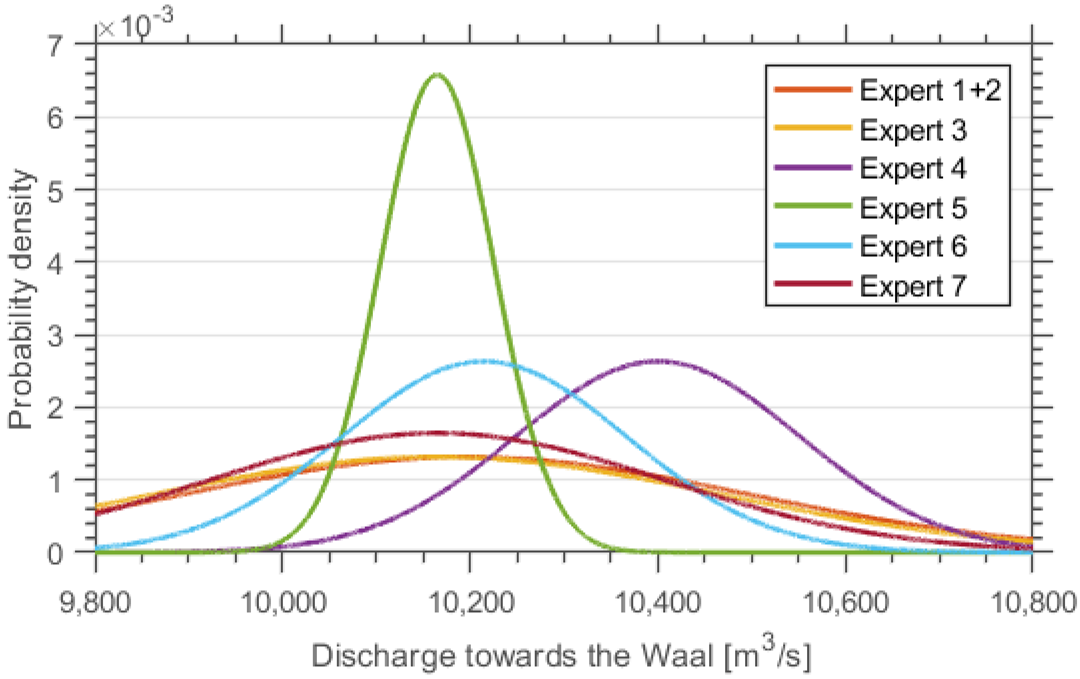

Figure 14: The first estimate of the total amount of uncertainty by all the experts

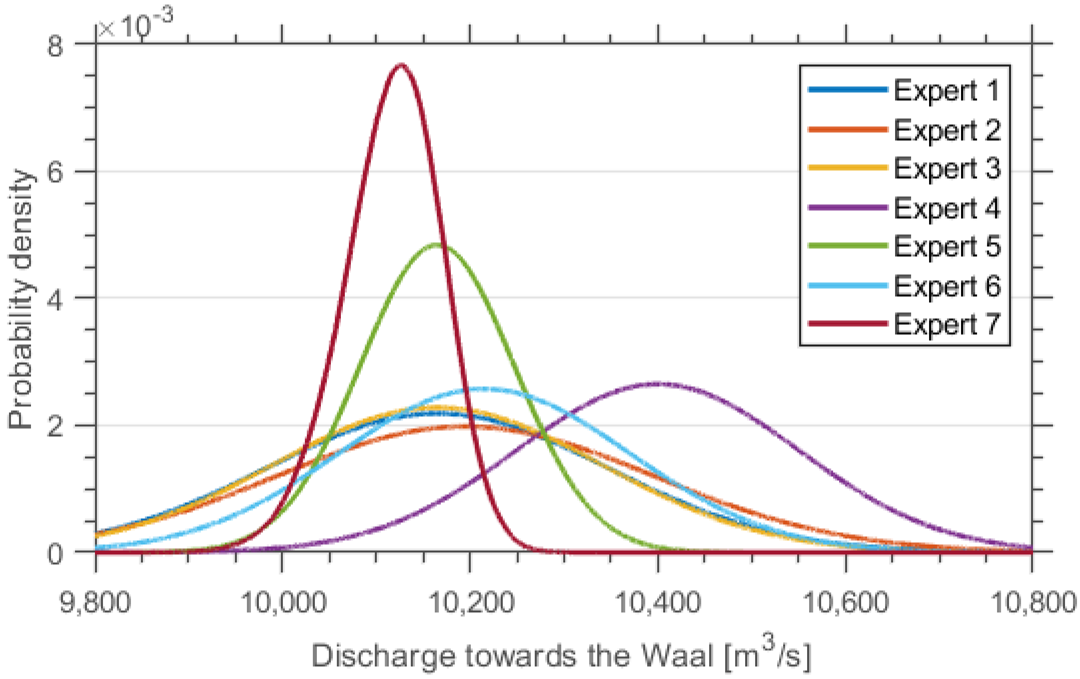

Figure 15: The total uncertainty after adding up all the individual sources by all the experts

A weighted probability distribution is obtained by using the weights assigned to the experts as given in Table 3. By using random sampling, a weighted probability distribution of the total uncertainty is obtained. The weighted probability distribution of both the first estimate and the total uncertainty after aggregating the individual sources of uncertainty is plotted in Figure 16. It is visible that the 90% confidence interval ranges between 9,784 m^3/s and 10,609 m^3/s. This gives a width of the 90%

confidence interval of 825 m³/s. The mode of the probability distribution of the aggregated individual sources of uncertainty is equal to 10,110 m³/s. That means that there has been a small shift towards the left side compared to the policy discharge distribution that is equal to 10,165 m³/s. This shift can be explained by expert 7, who has a relatively high weight and quantified a probability distribution with a heavy left tail, which means that there is a higher probability of less discharge going to the Waal. The 90% confidence interval ranges between 9,940 m³/s and 10,511 m³/s. Furthermore, it is visible that the weighted probability distribution has a relatively heavy right-tail. This right-tail is caused by the experts that quantified the discharge distribution larger towards the Waal than the policy discharge distribution of 10,165 m³/s. A width of 571 m³/s for the 90% confidence interval was found. This also shows the effect of assessing the individual sources of uncertainty compared to the first estimate of the total uncertainty. The first estimate was quantified significantly larger. All the experts said that the total uncertainty after aggregating the individual sources of uncertainty represents the uncertainty in the discharge distribution best.

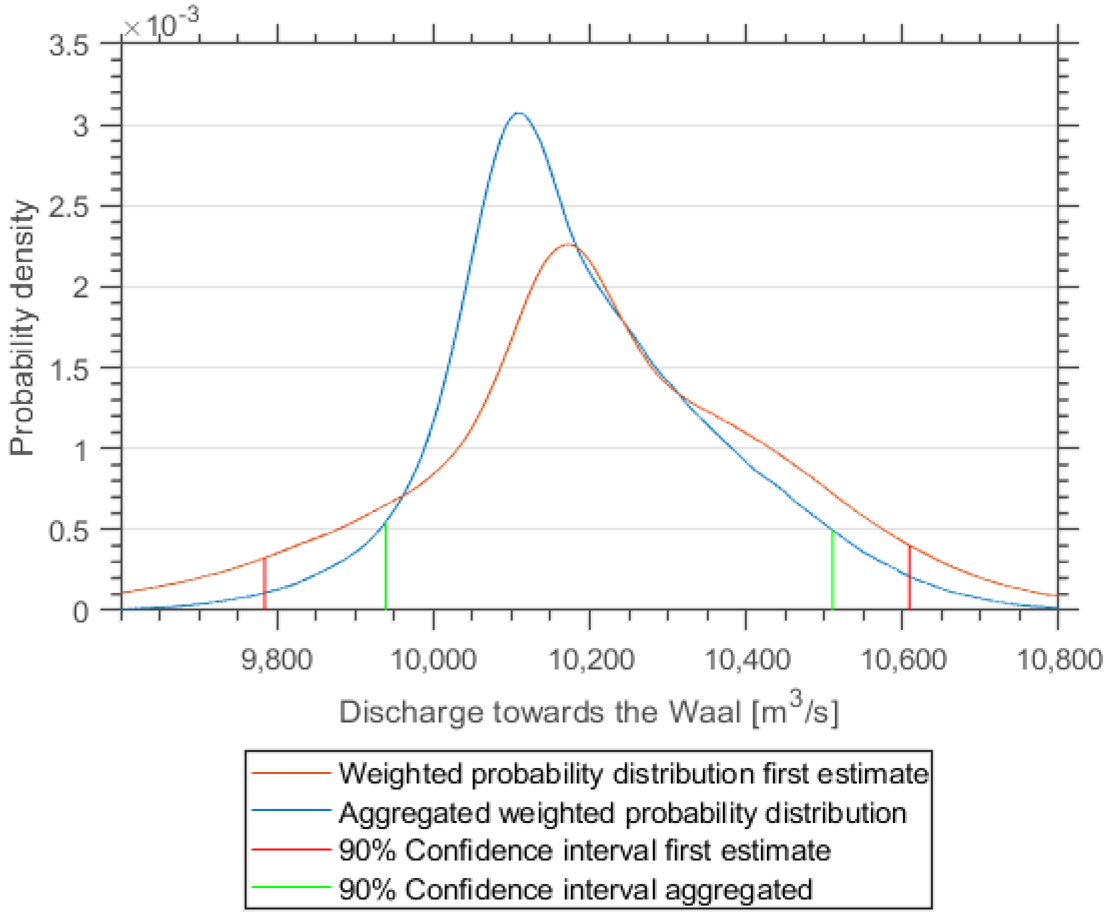

Figure 16: Weighted probability distribution of all the expert opinions

3.4 RQ4: Uncertainty in the water levels

Firstly, the effect of the boundary condition at Hardinxveld has been studied. Under normal conditions the boundary at Hardinxveld is set at 0.5 m+ NAP. To analyse the effects of this boundary conditions, the Sobek model was run with the design discharge and a boundary condition at Hardinxveld of 1 m +NAP. These results were compared to the initial situation and the results are shown in Figure 17. It is visible that the effects of the boundary conditions are negligible at Nijmegen and Tiel and at Zaltbommel the effects of the backwater curve are minor in the range of 1cm.

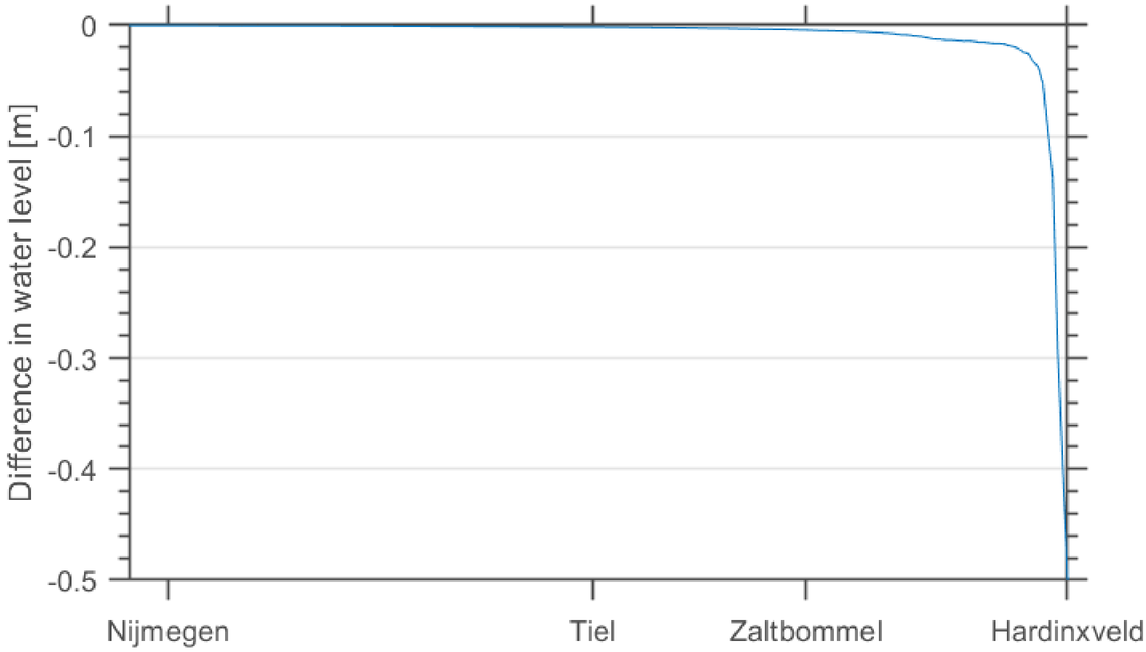

Figure 17: Difference in the water level for a boundary condition of 0.5 m +NAP and 1 m +NAP at Hardinxveld

The aggregated weighted probability distribution as shown in Figure 16 has been used as the input for the Sobek study of the Waal. The results of the runs are plotted in Figure 18. It is visible that the shape of the weighted probability distribution of the discharge distribution is also visible in the plot for the probability distribution of the water levels. This means that the left bound of the 90% confidence interval is relatively close to the mode compared to the right bound of the 90% confidence interval. The 90% confidence interval for the locations of Nijmegenhaven, Tiel and Zaltbommel are respectively, 29.1cm, 29.1cm and 26.4cm. These results are coherent to the findings of Hendriken (2018) who found an uncertainty in the water level of the Waal of 24-30cm. In this study an uncertainty in the discharge distribution at the Pannerdense Kop has been implemented by applying a 90% confidence interval of 500 m^3/s for a 16,000 m^3/s flood wave.

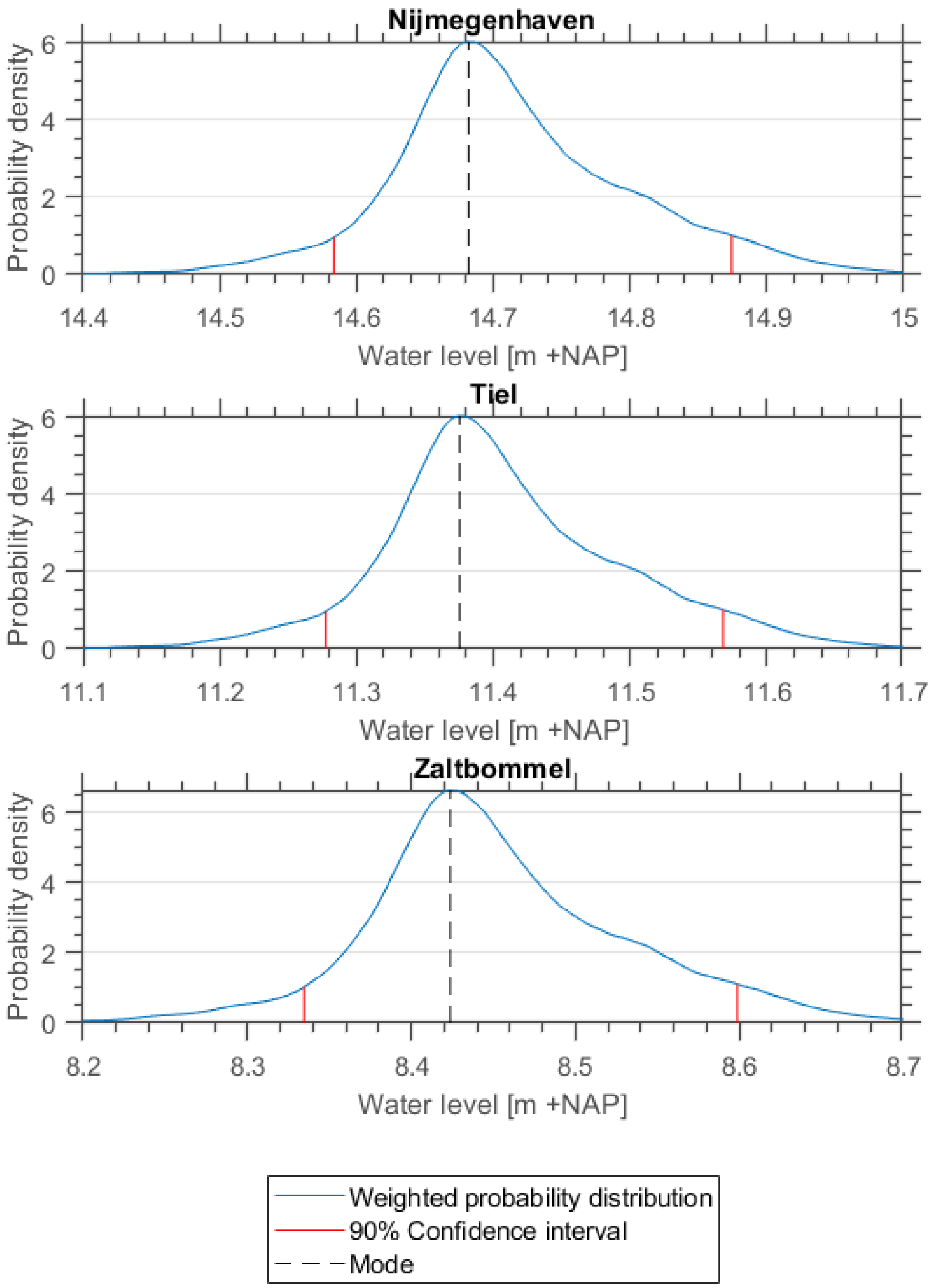

Figure 18: Modelled uncertainty in the water levels

4. Discussion

4.1 Expert bias

Expert opinion studies are often prone to cognitive and motivational biases because they are based on subjective judgement (De Little et al., 2018). The sources of bias that have probably been important in this research are the anchoring bias, availability bias, overconfidence bias and the motivational bias.

The anchoring bias occurs when an expert weighs their opinion towards a conventional value. It was noticed during the interviews that some of the experts referred to the reports of Ogink (2006) and Ten Brinke (2013). This creates the bias that some of the experts might have weighted their opinion towards the values of these reports. Therefore, also the availability bias plays a role in this research because the experts might give too much weight to the available information. Furthermore, small studies and unpublished memos were part of some of the expert's responses. Not all of the experts mentioned the possible failure of the levees close to the Pannerdense Kop. Effect studies about the failure of levees were still being conducted while doing the interviews and this might also explain why it was not mentioned by all the experts because these effect studies are not available yet.

The third bias of overconfidence occurs when an expert is too confident about their ability to make a quantitative judgement. The experts were asked to give themselves a weight on a scale of 1-5 on how they rate their ability to quantify the uncertainties. This possibly influenced the weights assigned to the experts because an expert might have been overconfident and therefore give themselves a too high weight. However, an expert can also be underconfident and underestimate their ability of making a quantitative judgement. It was also noticed during the interviews that the possible failure of the primary defence was quantified as low. None of the experts did really believe it would be realistic that there would be a dike breach. This can also be overconfidence because some of the dikes in the study area do not meet the norms of the flood-risk policy.

Finally, the motivational bias occurs when experts make their judgement depending on particular context, personal beliefs or experiences. This possibly was important during the interview because each of the expert have their own field of research. Some of the experts were therefore specialised in one or a few of the sources of uncertainty. This can result in experts giving large quantifications to the sources of uncertainty that they are specialised in.

To further investigate the effect of expert bias on the results, three newly computed probability distributions have been plotted in Figure 19. Firstly, a weighted probability distribution of the discharge distribution has been made by excluding expert 4. This expert quantified the discharge distribution towards the Waal considerably larger compared to the other experts (see Figure 15). When excluding this expert, a width of 502 m^3/s for the 90% confidence interval is found for the discharge distribution. Secondly, expert 7 stands out by quantifying the probability distribution with a skewness towards the Pannerdensch Kanaal. When excluding this expert, a width of 609 m^3/s for the 90% confidence interval is found. Finally, there is a bias in the weighting of the experts because the experts weight themselves and this can create under- or overconfidence. To analyse this effect, all the experts were given an equal weight and the probability distribution is determined again. For this probability distribution, a width of 580 m^3/s for the 90% confidence interval is found. It shows that there is some effect of the expert bias, but no significantly large changes are observed. This means that the assigning of the weights did not have a significant effect on the results in this research.

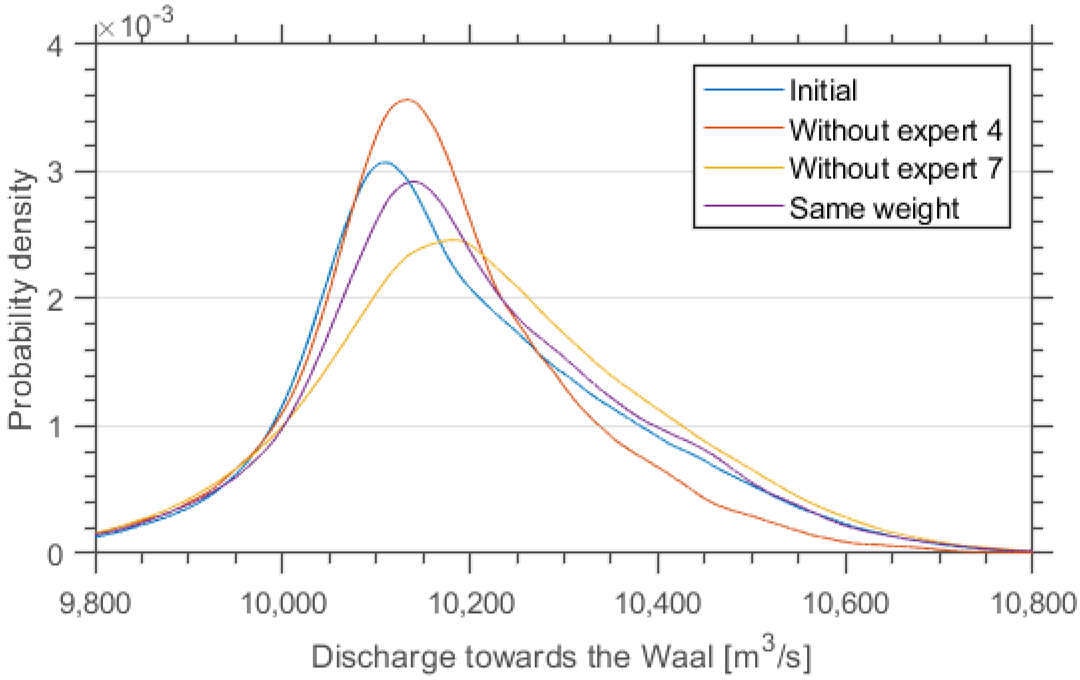

Figure 19: Probability distributions of the discharge towards the Waal for the analysis of expert bias

Table 6: Quantitative results in m^3/s of the probability distributions plotted in Figure 19.

	Mode	Left bound	Right bound	90% confidence interval
Initial	10,110	9,939	10,511	571
Without expert 4	10,133	9,927	10,429	502
Without expert 7	10,175	9,922	10,531	609
All experts same weight	10,144	9,933	10,513	580

It is also visible in the results that for only two of the experts, the first estimate is in the same range as the total uncertainty in the discharge distribution after aggregating the individual sources of uncertainty. Five of the experts quantified their first estimate significantly larger compared to the aggregated amount of uncertainty. This possibly could mean that the experts did not have enough understanding about the statistical mechanism that is behind the aggregation method of the individual sources of uncertainty. This possibly could have led to an underestimation of the total uncertainty in the discharge distribution. However, that the experts are provided with an explanation of the aggregation method before the interviews.

4.2 Method of expert elicitation

In this research, seven experts have been interviewed all individually. It is visible that there is a large spread in the quantifications made by the experts. In expert opinion studies it is also an option to have group discussions to obtain a quantitative result (Sebok et al, 2016). It has been shown that group discussions have added value because experts may be exposed to many different opinions raising several issues that single individuals did not originally take into account (Sebok et al., 2016). Furthermore, the group discussions reduce the effect of expert bias explained above. During a discussion it is the aim to reach a consensus between the experts about the uncertainties within the discharge distribution. It would be an added value to the research to see if the experts can reach a consensus about the large spread in the qualifications made. The number of experts being interviewed is also a point of interest. This number could be enlarged because of the large spread in the quantifications. By enlarging the number of experts interviewed, it is possible to get a better understanding of the spread in the results. However, it should be noticed that it can be difficult to find enough experts because the field of research on uncertainties in the discharge distribution is very specific.

4.3 Applicability on 18,000 m^3/s

The newly adopted flood-risk policy in 2017, requires assessment of the dikes on a probability distribution of the water levels. This means that the dikes can also be assessed on a flood wave of 18,000 m^3/s at Lobith. During the interviews with the experts, they were asked how the uncertainty in the discharge distribution would differ for a 18,000 m^3/s flood wave. It was found that the experts generally agreed that the uncertainty would be larger with around 100-200 m^3/s. This extra amount of uncertainty is caused by the fact that the flow velocities increase a bit compared to the 16,000 m^3/s. This increases the chances of erosion of the river bed close to the Pannerdense Kop. Furthermore, the probability of failure of levees close to the Pannerdense Kop increases as well. For the bedforms and the main channel roughness the probability that bedforms flatten out increase according to the experts. However, it was also mentioned by two of the experts that the chance of failure of the primary defence increases. It gets more likely that a primary defence in Germany fails and that the flood wave of 18,000 m^3/s does not reach the Netherlands via the main river. From this we can conclude that the uncertainty for a 18,000 m^3/s will be a bit larger but that it is comparable to the uncertainty found in this research.

4.4 Significance of the uncertainty

The experts were also asked whether the quantified amount of uncertainty in the discharge distribution is significant or not. The experts quantifying the amount of rather small, 272 m^3/s and 162 m^3/s respectively, said that this amount of uncertainty is acceptable. The other experts were a bit more sceptical and generally agreed that their quantified amount of uncertainty is indeed significant for the discharge distribution of the Pannerdense Kop. Consider, for example, the Room for the River projects, these projects had targets which needed to be met on the scale of centimetres accurately. When taking the uncertainty in the discharge distribution, this will have an effect of far more than a few centimetres and therefore is significant. Furthermore, the regulation structures both built on the Pannerdense Kop and the IJsselkop are semi-dynamic. This means that the structures cannot be adjusted when the flood wave is passing. This means that we cannot adjust for changes in the discharge distribution resulting from the uncertainty in it. Therefore, the uncertainty in the discharge distribution is something to take into account as significant.

4.5 Comparison with previous research

Previously conducted research from Ogink (2006) and Ten Brinke (2013) obtained an uncertainty in the discharge distribution of around 500 m^3/s as the width of the 90% confidence interval. This is comparable to the 571 m^3/s obtained in this research. For the individual sources of uncertainty, it is visible that the roughness of the main channel and the roughness of the floodplain are the sources contributing most to the total amount of uncertainty. This was also concluded in the researches of Ogink (2006) and Ten Brinke (2013). However, in this research it is concluded that the roughness of the main channel is the largest source of uncertainty while in the other research (Ogink, 2006; Ten Brinke, 2013) it was concluded that the roughness of the floodplain largest. The differences in the quantification are not significant. It was noticed during the interviews that the experts did not agree about the effects of the failure of levees and the erosion of plaster layers. The failure of levees was found to be a small source of uncertainty in previously conducted research (Ogink, 2006; Ten Brinke, 2013). According to four of the experts, the failure of levees close to the Pannerdense Kop can have a significant effect on the discharge distribution. The effects of failure are studied in more detail while writing this thesis. The erosion of plaster layers already was found to be a significant source of uncertainty (Ogink, 2006; Ten Brinke, 2013) and still is a significant source of uncertainty according to four of the experts.

More recent studies about the uncertainty in the discharge distribution found a width for the 95% confidence interval of 908 m^3/s and 992 m^3/s (Twijnstra, 2020). In this research the uncertainty in the rating curves of the Dutch river Rhine branches was quantified. In this research a 95% confidence interval was used which means that the width of the interval is larger compared to a 90% confidence interval. Next, Gensen et al. (2020) studied the effects of the uncertainty in the main channel roughness on the discharge distribution. In this research, extreme scenarios for the main channel roughness were used and an uncertainty in the discharge distribution at the Pannerdense Kop of around 1,000 m^3/s was found. These results are larger compared to the total amount of uncertainty found in this research.

4.6 Model study

To assess the effects of the uncertainty in the discharge distribution on the water levels, a model study has been done. The results of this study should be seen as a worst case scenario. First of all, the probability distribution of the discharge distribution takes into account the failure of the primary defence. This leads to an increased discharge towards the Waal when there is a dike breach close to the Pannerdense Kop in the Waal. However, due to the dike breach, water levels will decrease. The dike breach is not implemented in the model and therefore the water levels are overestimated. Secondly, a similar effect is seen for the hydraulic roughness. When the hydraulic roughness is larger in the Waal, the water levels rise in the Waal. Furthermore, when there is an increased discharge towards the Waal it means that the hydraulic roughness of the Waal is smaller than expected. When the hydraulic roughness is smaller, it means that the water levels are decreased as well. The hydraulic roughness is not changed in the model and is kept at its initial settings. This leads to an overestimation of the uncertainty. Also, for the other sources of uncertainty, no changes in the model have been made. This means that the water levels should be seen as a worst case scenario since they are overestimated.

To give a more accurate quantification of the uncertainty in the water levels, a more comprehensive model study should be executed. The river should be modelled as a coupled system, which means that the branches are coupled and that the discharge distribution is variable. Next, the hydraulic roughness of the main channel can be changed until the desired change in the discharge distribution at the Pannerdense Kop is visible. The desired change in the discharge distribution can for example be the right bound of the 90% confidence interval of the uncertainty in the hydraulic roughness of the main channel. The water levels observed in this case would give an appropriate value for the effect of the uncertainty in discharge distribution due to the hydraulic roughness of the main channel on the water levels. The same method could be applied to the geometry as well. Erosion of the main channel can be modelled using a similar method by lowering the bed level of the main channel close to the bifurcation point until the desired change in the discharge distribution is observed.

The uncertainty in the water levels for the Waal were found to be 29.1 cm for the locations of Nijmegenhaven and Tiel. When comparing this to other values from studies conducted about the uncertainty in the Waal, interesting differences are visible. For the roughness of the main channel of the Waal an uncertainty of 53cm was quantified by Warmink et al. (2013a). The uncertainty in the roughness of the floodplain was quantified by Straatsma et al. (2013) and Warmink et al. (2013a) as 19 cm and 34 cm respectively. In these studies, the discharge distribution was not taken into account. This could mean that the quantification of these studies can be larger when incorporating the discharge distribution. It should also be said that he quantifications already seem to be relatively large comparing it to the 29.1 cm modelled in this study which represents a worst case scenario of the total amount of uncertainty because only a single stretch was modelled. When modelling the full river system, there is an important self-regulating effect in the water levels through changes in the discharge distribution (Gensen et al., In press). Furthermore, it is also seen that for the Dutch river Rhine branches the Waal is the most important because it is the largest branch. When the roughness increases for the Waal, the discharge towards the Pannerdensch Kanaal is increased which can increase the local effects and thus also increase the range of water levels in this branch. Only small effects are seen in the water levels of the Waal when changing the roughness of the Pannerdensch Kanaal. (Gensen et al., In press).

5. Conclusions and recommendations

5.1 Conclusions

The objective of this study was to identify and quantify the uncertainties in the discharge distribution of the Pannerdense Kop for a flood wave of 16,000 m3/s and its effect on the water levels in the river Waal using expert elicitation. To meet the objective, the following research questions were addressed:

RQ1: Which sources influence the discharge distribution at the bifurcation points?

Six different sources of uncertainty in the discharge distribution at the Pannerdense Kop have been identified: (1) wind, (2) geometry, (3) roughness of the main channel, (4) roughness of the floodplain, (5) failure of the primary defence and (6) regulations structure Pannerden. Firstly, the wind can cause set-up close to the bifurcation point and therefore cause a change in the discharge distribution. Secondly, the geometry can change the discharge distribution when erosion occurs close to the bifurcation point before or during the flood wave. Furthermore, the erosion or failure of levees perpendicular to the flow direction possibly cause a change in the discharge distribution. Thirdly, the roughness of the main channel is uncertain because it is uncertain how the bedforms will develop during the flood wave. Fourthly, the roughness in the floodplain creates uncertainty as well because of the vegetation that is the main contributor of the roughness. Fifthly, there is uncertainty in the failure of the primary defence and its possible influence on the discharge distribution. Finally, the number of weirs that need to be installed in regulation Pannerden has been determined by a model study which creates uncertainty in the actual functioning during a 16,000 m^3/s flood wave. The experts agreed that this list covers the uncertainties that contribute to the uncertainty in the discharge distribution.

RQ2: How large are the identified sources of uncertainty for the discharge distribution at the Pannerdense Kop?

In the quantification of the individual sources of uncertainty a clear distinction is visible. The geometry, roughness of the main channel and the roughness of the floodplain were quantified largest with a width of the 90% confidence intervals of 221 m^3/s, 249 m^3/s and 236 m^3/s, respectively. The uncertainties in the wind, failure of the primary defence and the regulation structure Pannerden are quantified rather small with 30 m^3/s, 12 m^3/s and 90 m^3/s, respectively.

RQ3: What is the total uncertainty of the discharge distribution at the Pannerdense Kop?

The total uncertainty in the discharge distribution at the Pannerdense Kop is equal to 572 m^3/s. The left bound of this probability distribution is equal to 9,939 m^3/s and the right bound is equal to 10,511 m^3/s. The mode of the probability distribution is equal to 10,110 m^3/s. This means that the probability distribution has a relatively heavy right-tail which is caused by the experts that set the middle of their probability distribution discharge larger towards the Waal because of the erosion patterns over the past couple of years.

RQ4: How large is the effect of the uncertainty in the discharge distribution on the water levels of the Waal?

The effect of the uncertainty in the discharge distribution was quantified for the river Waal at the locations of Nijmegenhaven, Tiel and Zaltbommel. The probability distributions of the water levels have the same shape as the probability distribution for the discharge distribution.

The width of the 90% confidence interval of the water levels was quantified for Nijmegen, Tiel and Zaltbommel as 29.1cm, 29.1cm and 26.4cm, respectively.

5.2 Recommendations

For future research it is recommended to analyse the effects of the failure of levees in more detail and incorporate this into the uncertainty in the discharge distribution. Furthermore, it is also recommended to further analyse the probability of occurrence and the effect of erosion of plaster layers close to the Pannerdense Kop. The morphological development close to the Pannerdense Kop during a flood wave are still uncertain.

To further extent the expert opinion study in this research, it is recommended to increase the number of experts being interviewed. A large spread in the quantification of the uncertainties in the geometry, roughness of the main channel and the roughness of the floodplain is visible. To further analyse these uncertainties, it would be helpful to get more expert input. Furthermore, the expert opinion study can be extended with a group discussion. This has shown to be a useful method in previous research (Sebok et al, 2016). Because of the large spread in the expert's quantifications, group discussions might give results contributing to the research. Furthermore, it is interesting to see whether the experts can reach a consensus about the amount of uncertainty in the discharge distribution.

It is also recommended to further extend the model study that was done in this research. This should be done by modelling the full river system as a coupled system. Next, the uncertainty in the discharge distribution can be modelled by making changes in the model in the hydraulic roughness or geometry for example until the desired change in the discharge distribution is reached. By doing this, the river system is modelled as a coupled system and more accurate values for the uncertainty in the water levels are obtained.

Finally, for Rijkswaterstaat it is recommended to incorporate the uncertainties in the discharge distribution into the assessment of flood risk and future planning of river engineering works. The uncertainty in the discharge distribution is important for setting the regulation structures and it can also affect the effectiveness of the river engineering works.

6. Acknowledgements

This thesis is part of the Perspectief research programme All-Risk with project number P15-21, which is (partly) financed by NWO Domain Applied and Engineering Sciences, in collaboration with the following private and public partners: Rijkswaterstaat, Deltares, STOWA, HKV consultants, Natuurmonumenten and the regional water authorities Noorderzijlvest, Vechtstromen, it Fryske Gea, HHNK.

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Appendix 1

Document sent to the experts before the interview.

Dear *name expert*,

Hereby, the information as a preparation for our appointment. The interview will exist out of three different parts. The first part is about the discharge distribution at the Pannerdense Kop during a flood wave with a peak of 16,000 m^3/s. We will quantify the discharge distribution and the uncertainty around the discharge distribution using a bandwidth. The bandwidth of the uncertainty will be explained further below.

In the second part of the interview we will discuss the induvial sources of uncertainty. The list of uncertainties that we will discuss are given below in Table 1. You are free to add any other sources of uncertainty if you think that something is missing. In this second part of the interview we will try to quantify the individual sources of uncertainty as the uncertainty in the discharge in m^3/s.

In the third and last part of the interview we will reflect on the total amount of uncertainty that we found around the discharge distribution at the Pannerdense Kop.

Table 1: Description of the uncertainties

Uncertainty	**Description**
Wind	There is uncertainty in the wind direction and the wind speeds that will occur during a flood wave and this can give a change in the discharge distribution.
Geometry	It is uncertain how the bed level will respond to the flood wave just before and during the flood wave passes.
Roughness of the main channel	Uncertainty in the roughness of the main channel is caused by the bedforms that are created during a flood wave.
Roughness of the floodplain	The vegetation is the main contributor in the roughness of the floodplain and it is uncertain how the roughness will affect the discharge distribution.
Failure of the primary defence	The failure of the primary defence downstream of the Pannerdense Kop can cause a change in the distribution and thus introducing uncertainty.
Regulation structures	The regulation structures have been adjusted using a model study and have never witnessed a 16,000 m^3/s before, introducing uncertainty.

Quantification

In the first part of the interview, the discharge distribution at the Pannerdense Kop is quantified. Furthermore, a probability density function is determined around this discharge distribution. Next, all the individual sources of uncertainty are quantified using a probability density function again around the discharge distribution. The probability density function that will be used is a normal distribution. The mentioned bandwidth mentioned in the beginning of the document that will be use dis the 90% confidence interval. This is equal to 2*1.64 the standard deviation. In Figure X, the tool is visualised that will be used during the interview. The bandwidth is also depicted in this figure as the 90% confidence interval. The discharge distribution given in the first part of the interview is also shown with the dashed line.

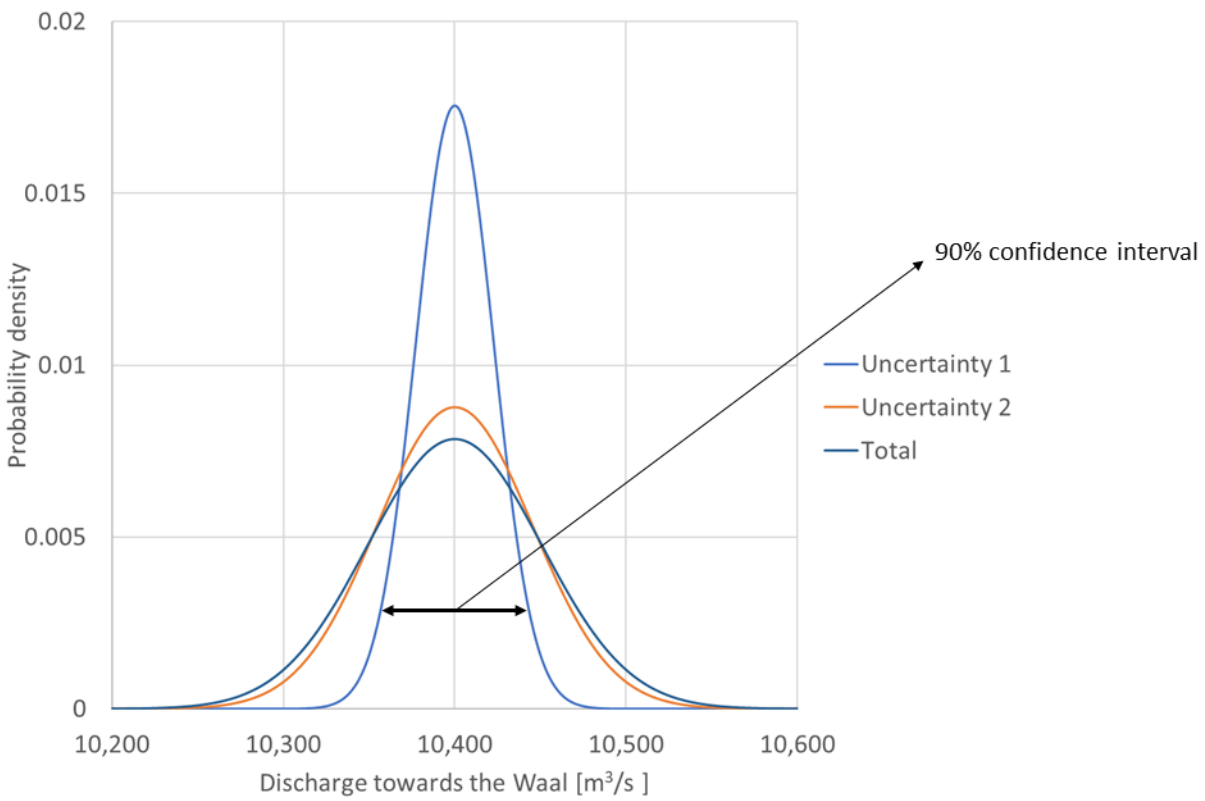

Figure X: Visualisation of the quantification of the uncertainties using the tool

Appendix 2

Interview questions

Part 1: Quantifying the discharge distribution and the uncertainty bandwidth

- What do you expect the discharge distribution to be at the Pannerdense Kop when a flood wave of 16,000 m^3/s passes by in the near future?

When the experts deviate from the policy discharge distribution:

- You give a different discharge distribution than the policy discharge distribution, why do you deviate from the policy discharge distribution?

- What is the total uncertainty bandwidth around the mentioned discharge distribution?

Part 2: Quantification of the individual sources of uncertainty

- Do you agree that the sources of uncertainty I sent you in the document before the interview are the largest sources of uncertainty? If yes, then you can add any other sources of uncertainty at the end of interview. If no, then I would like to hear from you which sources of uncertainty are missing that have a large amount of uncertainty when a discharge wave of 16,000 m^3/s passes in the near future.

- How large is the effect of the uncertainty in the wind when a flood wave of 16,000 m^3/s passes in the near future?

- How large is the effect of the uncertainty in the geometry when a flood wave of 16,000 m^3/s passes in the near future?

- How large is the effect of the uncertainty in the roughness of the main channel when a flood wave of 16,000 m^3/s passes in the near future?

- How large is the effect of the uncertainty in the roughness of the floodplain when a flood wave of 16,000 m^3/s passes in the near future?

- How large is the effect of the uncertainty in the failure of the primary defence when a flood wave of 16,000 m^3/s passes in the near future?

- How large is the effect of the uncertainty in the regulation structure Pannerden when a flood wave of 16,000 m^3/s passes in the near future?

When the expert wants to add uncertainties to the list:

- How large is the effect of the just mentioned uncertainty by you when a flood wave of 16,000 m^3/s passes in the near future?

- Can we assume that the individual sources of uncertainty are independent from eachother?

Part 3: Reflection

- How can we reflect on the total bandwidth in the uncertainty mentioned at the beginning of the interview and the just quantified total bandwidth in the uncertainty by adding up all the induvial sources of uncertainty?
    - Do the two different total bandwidths in the uncertainty match?
    - Which of the two is best?
    - Would you like to change anything?

- Is the just quantified total bandwidth in the uncertainty also applicable for a 18,000 m^3/s flood wave?

- Is the amount of uncertainty we just quantified significant and something to worry about?

- On a scale of 1-5, how do you rate your ability of quantifying the uncertainties?

- How can we decrease the amount of uncertainty in the discharge distribution? What should future research focus on?