Hydraulic impact of a real time control barrier at the bifurcation points in the Rhine branches in the Netherlands

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ABSTRACT: Without flood defences much of the Netherlands would be flooded (by the sea or the river) on a regular basis. Along the full length of the river Rhine and along parts of the river Meuse protection against river flooding is needed. This protection is provided by flood defences (mainly dikes). The river Rhine has in the Netherlands two bifurcation points, the Pannerdensche Kop and de IJssel Kop. There are at this moment no regulators at these points and the distribution of the discharge is a result of natural processes. The safety against flooding downstream these bifurcation points is highly dependent on the result of the discharge distribution. In the design of the flood defences there is, according to design guidelines, assumed that the discharge distribution over the branches is completely certain. However the discharge distribution at the design frequency is never observed so the uncertainty is considerable. This uncertainty that is unaccounted for in the design of the river dikes increases the failure probability. In this paper we will present a study of a real time control barrier at the two bifurcation points, using a one-dimensional hydraulic model. The objective of these barriers is to reduce the deviations of the distribution and therewith the uncertainty. It is shown that for some of the disturbances of the water distribution a control barrier might be helpful, but it cannot be shown to be effective for all cases. The results also depend on the control criteria (for example the average disturbance of water levels along one of the branches or the maximum disturbance) and on the control objective (concentrate the discharge on one of the branches where damage of flooding is lower than the other branches, or minimize the disturbance on all branches as much as possible).

1 INTRODUCTION

Without flood defences areas along the Rhine would be flooded during periods of high discharges. The crest level of the flood defences has such a level that a certain amount of water (design discharge) is drained off without inundation.

The design discharge is never observed and the impact of different natural processes (for example local or downstream hydraulic roughness, the discharge distribution near a river bifurcation point) on the water level is difficult to predict during floods. This means that there are uncertainties involved which may result, during relatively high discharge, in different water levels than expected. So in reality it is possible that a flood will occur when the design discharge is not reached.

The water level at the river branches downstream of the bifurcation points is heavily dependent on the distribution of the discharge. To give an idea: a small deviation (few percents) in the discharge distribution causes a couple of decimetres deviation in the (design) water level.

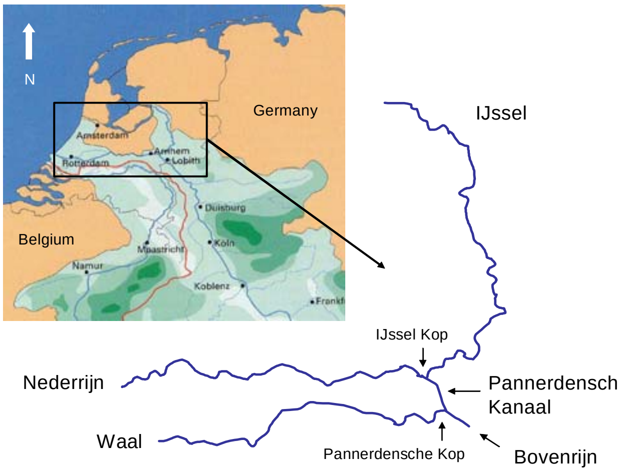

Figure 1. Location of the Rhine branches with respect to the Netherlands.

The Rhine has in the Netherlands two bifurcations points: the Pannerdensche Kop and the IJssel Kop. At the Pannerdensche Kop, 5 kilometres downstream of Lobith (at the border with Germany), the water of the Bovenrijn is distributed over the Waal and the Pannerdensch Kanaal. The Pannerdensch Kanaal splits at the IJssel Kop in the Nederrijn and the IJssel. The Pannerdensch Kanaal, connecting the bifurcations points, is about 12 kilometres long.

2 OBJECTIVE

The study is carried out to investigate if a real time regulator at the bifurcation points in the Rhine is able to contribute to a reduction in the probability of flooding.

3 UNCERTAINTIES

The degree of reduction of the probability of flooding (figure 2) depends on the extent in which the uncertainties in the design process of river dikes can be reduced (3.1) and on the extent of the uncertainties in the control system which is introduced by a real time control barrier (3.2).

3.1 *Uncertainties in design process of river dikes*

In the design of the height and strength of a river dike many uncertainties have to be taken into account. Examples are natural processes such as the river discharge waves (height and shape), wind (speed and direction), local or downstream hydraulic roughness and the discharge distribution near the river bifurcation points. The current flood defence design practise along the major rivers in the Netherlands is to include only the natural variability of the discharge in assessing the exceedance frequency. Other sources of uncertainty which can cause flooding such as the roughness of the riverbed or the discharge distribution at the bifurcation points are not explicitly accounted for. However the discharge distribution at the design frequency (which is 1/1250 per year) is never observed so the uncertainty is considerable. This uncertainty, which is not accounted in the design of the river dikes, increases the flooding probability. A real time barrier is possibly an appropriate instrument to reduce the deviations of the distribution and therewith the uncertainty.

3.2 *Uncertainties in control system*

The main uncertainties with respect to the impact of a real time control system at the bifurcations points are:

1. uncertainties with respect to regulate the discharge distribution;
2. uncertainties with respect to technical failure of the control barrier;
3. uncertainties in measurements.

ad 1) Regulating the discharge distribution means an intervention in the water system during floods. This can be done automatically or manually. Uncertainties are involved in each method: technical malfunction, electricity failure, human failure (tiredness, lack of knowledge or experience), etc.

ad 2) Failure or collapse of the control barrier means that the control barrier is not able to serve its purpose anymore. For example a ship collides with the control barrier.

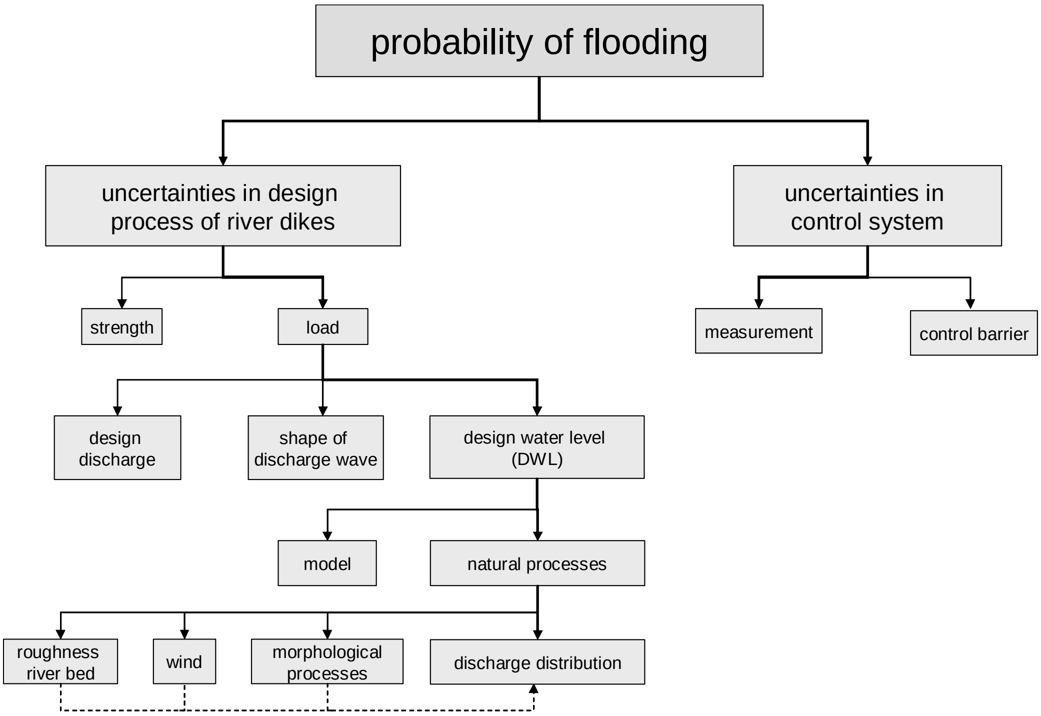

Figure 2. Schematic overview of uncertainties.

ad 3) For a proper use of a control barrier at the bifurcation points in the Rhine measurement are necessary, for example water levels or discharges. An extra uncertainty is introduced when a control barrier is used at the bifurcation points in the Rhine: wrong control because of a measurement error. We have done an analysis of measurement errors in discharges and water levels. The uncertainty in a discharge measurement is relatively large: the uncertainty in the discharge distribution (1-2% of the discharge before the bifurcation points) is smaller than the uncertainty in a discharge measurement (5% of the measured discharge). The uncertainty in a water level measurement is, however, much smaller (0.1% of the measured water level). Therefore, we recommend to use measured water levels for the real time control of the control barrier.

4 DESIGN

Many types of “disturbances” of discharges at the bifurcation points are possible. These disturbances result in a deviation of the expected (design) – discharge. We have chosen to study the impact of a real time control barrier by considering five case studies. In each case study it is investigated whether a control barrier is effective at the bifurcation points in the Rhine, and the water system of the Rhine is disturbed in a different way (4.1). In this section we discuss also the different control objectives (4.2) and control criteria (4.3).

4.1 *Disturbances*

Disturbances play a key role in deviations in the discharge distribution.

Schropp (2003) has applied in total 10 types of disturbances in the water system of the Rhine, and the impact on discharges is given in Table 1. The following three types of disturbances have the highest impact:

- variation of the hydraulic roughness;
- morphological changes in the vicinity of the bifurcation points;
- wind effects.

The impact of wind effects is smaller but it is a disturbance that can occur suddenly during flood.

With these three types of disturbances five case studies are carried out: two case studies with variation of the hydraulic roughness (higher hydraulic roughness at the upper and the lower part of the Waal), two case studies with wind effects (wind field 11 days and 1 day before passing discharge peak) and one case study with morphological changes in the vicinity of the bifurcation points.

The following five “disturbance” case studies have been investigated:

1. increase of roughness of river bed (with 5%) in the first/upstream part (47 kilometres) of the Waal;
2. increase of roughness of river bed (with 5%) in the second/downstream part (47 kilometres) of the Waal;
3. increase in wind speed (12 m/s), starting 11 days before the maximal water level, and it can be forecasted;
4. increase in wind speed (12 m/s), starting 1 day before the maximum water level, and it can not be forecasted;
5. morphological processes (sand dunes), which result in increase of bed levels and increase of water levels.

Table 1. Summery discharge effects (source: Schropp, 2002).

disturbances	**Waal**		**Nederrijn**		**IJssel**	
	min. (m^3/s)	**max. (m^3/s)**	**min. (m^3/s)**	**max. (m^3/s)**	**min. (m^3/s)**	**max. (m^3/s)**
wind	-41	+20	-19	+10	-25	+52
drainage	-3	+3	-3	+3	-5	+5
shape of discharge wave	-5	+9	-44	+14	-55	+20
morphological processes	-168	-28	+20	+133	+8	+35
water reservoirs	-63	+73	-38	+33	-35	+30
failure of quays and weirs	-64	+16	-36	+33	-7	+46
river geometry	-44	+44	-36	+36	-45	+45
hydraulic roughness summer bed	-75	+75	-75	+75	-75	+75
hydraulic roughness winter bed	-116	+139	-72	+87	-67	+55
model parameters	-32	+35	-12	+10	-20	+21
TOTAL	**-611**	**+386**	**-315**	**+434**	**-326**	**+384**

4.2 *Control objectives*

The disturbances cause higher water levels than expect at certain locations at the Rhine branches during floods. This negative impact (`the pain`) can be divided over the Rhine branches in different ways by regulating the discharge distribution.

In this study two control objectives are formulated; their feasibility is tested:

- dividing the negative impacts equally over the Rhine branches;
- concentrating the negative impacts on one Rhine branch.

It is clear that the first objective is the best as long as we are able to prevent a flood in the total system. However, if there is a flood we will prefer that the flood will happen in only one of the Rhine branches, and not in all the branches. It is difficult to change the control objectives during a high water period, and therefore we will present the results of both control objectives. The decision maker has to choose which objective is to be preferred.

4.3 *Control criteria*

In the Netherlands we have a measurement system along the river to measure the water levels (MSW = Monitoring System Water, managed by the Ministry of Transport, Public Works and Water Management). Several MSW-survey stations along the river Rhine are used to control the discharge distribution (figure 3).

We do not include MSW stations upstream the bifurcation points, because the water levels at these points are influenced by the control barrier. Comparing the water levels at the MSW-survey stations with the reference water levels may provide information how the discharge distribution should be regulated.

The following control criteria are defined:

- "maximum": the *maximum* disturbance of water levels along one of the branches is minimized;
- "average": the *average* disturbance of water levels along one of the branches is minimized;
- "first": the disturbance at the *first* MSW-survey station of the branches is minimized (downstream the bifurcation point).

5 REAL TIME CONTROL BARRIER AT THE TWO BIFURCATION POINTS

A one–dimensional hydraulic model of the Rhine branches is used. This model is implemented in the Sobek system [Veen, 2002]. With the Rhine branches model it is possible to calculate the water levels on the river, taking into account all sorts of irregularities in the river, under the influence of a river discharge wave.

In order to estimate the effectiveness of a real time control barrier at the bifurcation points, the Rhine branches model is extended with an automatic control system (see figure 4). This control system is implemented in Matlab.

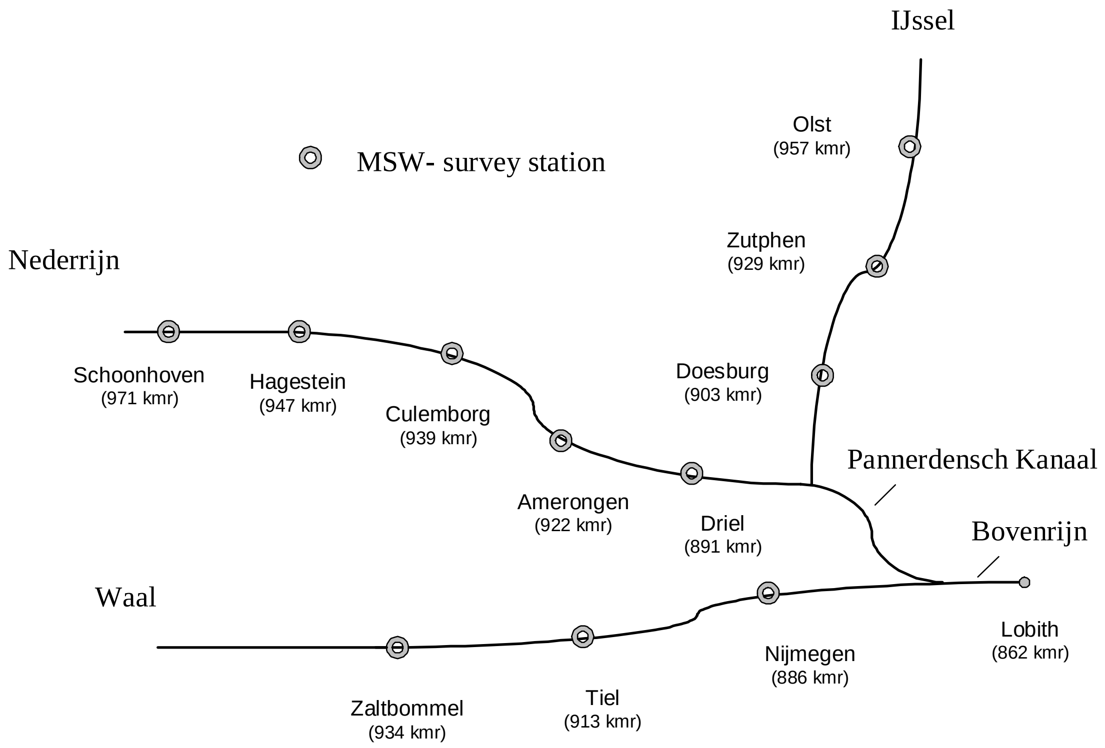

Figure 3. Overview of the 11 MSW-survey stations at the Rhine branches.

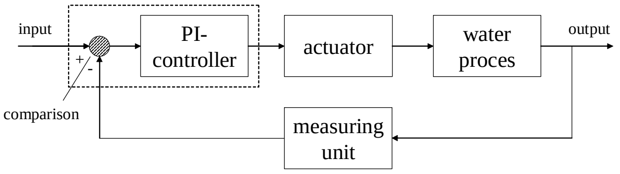

Figure 4. Automatic control system.

Measurements are necessary to regulate the discharge distribution at the bifurcations points in the Rhine. To calculate the way of intervention some logical or arithmetical operations are necessary.

The “controller” is the apparatus that is capable to translate measurements signals to an intervention in the water system of the Rhine. In control engineering standard controllers have been developed for a wide range of applications. A well-known and simple controller is the PI-controller, which stands for **P**roportional **I**ntegral. A PI-controller is used in this research to regulate the discharge distribution.

The “actuator” is a unit that reacts upon signals from the PI-controller. The actuator provides the motive power for the control-structure. There are many types of structures possible. Examples are a simple weir, an extra side channel or a barrier. In the hydraulic model we schematised a simple weir (see figure 5) on the river branches downstream of the bifurcation points to regulate the discharge distribution.

In spite of the highly simplified representation of the actuator the representation is satisfactory to assess the feasibility of the objectives of a real time control barrier.

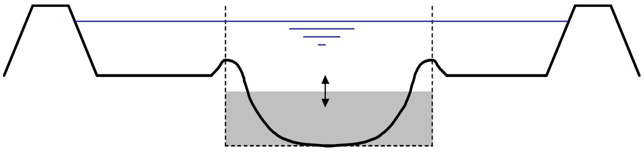

Figure 5. Simple weir

6 IMPACT OF A CONTROL REGULATOR AT THE BIFURCATION POINTS OF THE RHINE

Disturbances which have a negative influence on the water level during periods of high discharges are applied in the study. Negative means here that due to the disturbances the water level at the Rhine branches will exceed above the Design Water Levels. On the basis of the formulated objectives the discharge distribution is regulated in such a way that at one or more Rhine branches the deviation in the water level is reduced. Comparing the deviation in water levels with and without regulating the discharge distribution a concept is obtained of the impact (effectiveness) of a control regulator at the bifurcation points in the Rhine. In figure 6 it is illustrated how the impact of a control barrier is calculated.

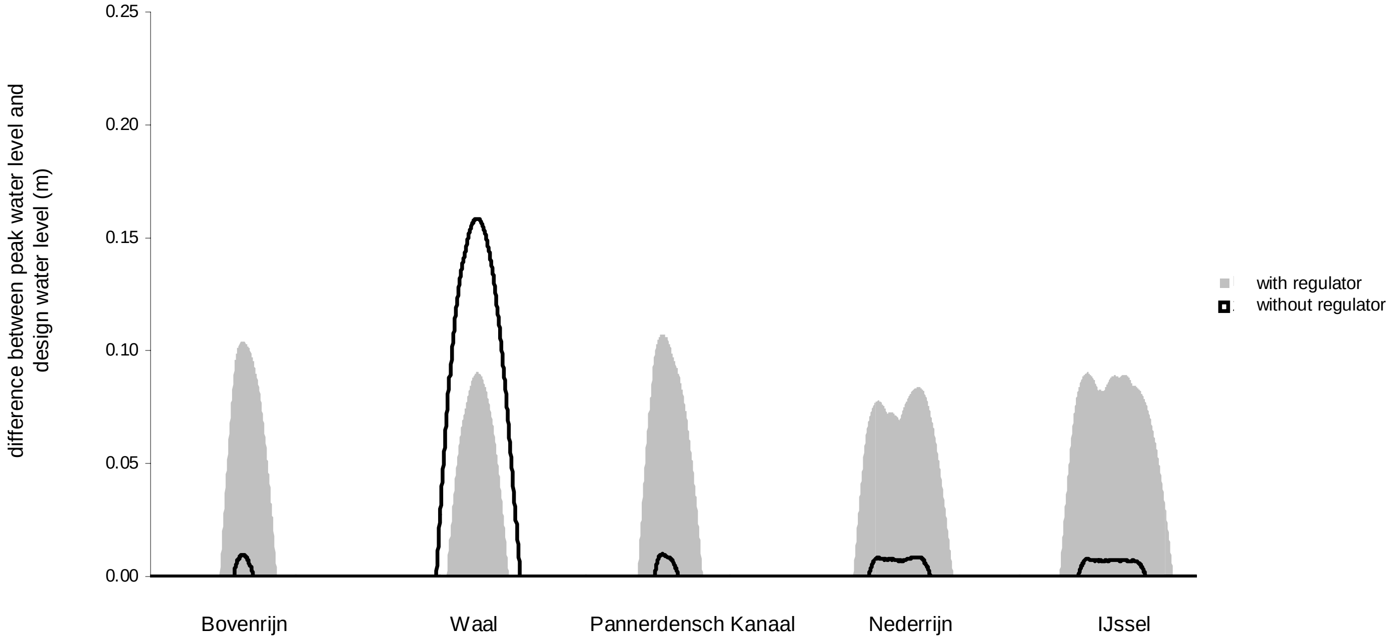

Figure 6. Disturbance (higher hydraulic roughness at the second/downstream part of the Waal), control objective (dividing the pain equally over the Rhine branches), control criterion (maximum disturbance of water levels along one of the branches)

The figure shows the deviation in the water level at the Rhine branches when the roughness of the river bed is increased at the lower/downstream part of the Waal. The results are shown for 5 branches of the Rhine in the Netherlands (see figure 1). The disturbance does result by an increase in the water level (17 centimetres) at the Waal, compared with the 'expected' design conditions. The figure presents also the deviation in the water level at the Rhine branches when the discharge distribution is regulated (dividing the "pain" equally over the Rhine branches). In this case the maximum deviation in the water level (11 centimetres) occurs at the Pannerdensch Kanaal. The deviation in the water level is reduced by 43%, but still there is an increase in the water levels compared with the expected (design) conditions. These results suggests that although a real time control barrier may improve the situation (and hence decrease the flooding probability), it may not always be possible to return to the water levels which were used in the design state. The reason is of course that the deviation of the discharge has a physical reason (for example increase of roughness in one of the branches than expected) and the control barrier cannot compensate this increase in water levels.

7 RESULTS

The main results of the research are presented in table 2, 3 and 4. More result can be found in Arnold, 2004. In the tables is shown that under certain conditions an improvement can be reached (-), but in some cases that also a deterioration may result (+). An improvement is that the water levels are decreased (compared with the situation where there is no control barrier), and a deterioration means that the water levels are increasing using a control barrier.

We present (table 2, 3 and 4) the results of all control criteria ("*maximum*", "*average*", "*first*"). It was not clear at the beginning of the research which control criterion provided the best results. From the results in the tables we can conclude that the control criterion "*maximum*" provided overall the best results.

Below the results are summarised of control criterion "*maximum*". A distinction is made between the two control objectives.

7.1 *Dividing the "pain" equally over the Rhine branches*

In two case studies the difference between peak water level and DWL at the Rhine branches are reduced (43 and 92%). The other three case studies show that the impact of a control barrier is small (3 to 8%). In three case studies an improvement is reached, two studies result in deterioration.

7.2 *Concentrating the "pain" on one Rhine branch*

The difference between peak water level and DWL are strongly reduced at the other Rhine branches by regulating the discharge distribution (10 to 100%). In all the case studies an improvement is obtained.

Table 2. Effectiveness of a control barrier at the bifurcation points of the Rhine using the control criterion: the *maximum* disturbance of water levels along one of the branches is minimized.

case studies		**control objectives**	
		dividing the "pain" equally over the Rhine branches	**concentrating the "pain" on a Rhine branch**
		(%)	**(%)**
1.	higher roughness of river bed (first part Waal)	+3	-61
2.	higher roughness of river bed (second part Waal)	-43	-88
3.	wind (11 days before DWL)	+6	-97
4.	wind (1 day before DWL)	-8	-10
5.	morphological processes	-92	-100

Table 3. Effectiveness of a control barrier at the bifurcation points of the Rhine using the control criterion: the *average* disturbance of water levels along one of the branches is minimized.

case studies		**control objectives**	
		dividing the "pain" equally over the Rhine branches (%)	**concentrating the "pain" on a Rhine branch (%)**
1.	higher roughness of river bed (first part Waal)	+53	+28
2.	higher roughness of river bed (second part Waal)	-31	-69
3.	wind (11 days before DWL)	+22	-76
4.	wind (1 day before DWL)	-2	+1
5.	morphological processes	-92	-100

Table 4. Effectiveness of a control barrier at the bifurcation points of the Rhine using the control criterion: the disturbance at the *first* MSW-survey station of the branches is minimized.

case studies		**control objectives**	
		dividing the "pain" equally over the Rhine branches (%)	**concentrating the "pain" on a Rhine branch (%)**
1.	higher roughness of river bed (first part Waal)	+6	-60
2.	higher roughness of river bed (second part Waal)	-22	-9
3.	wind (11 days before DWL)	+7	-87
4.	wind (1 day before DWL)	-5	-21
5.	morphological processes	-92	-100

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 *Conclusions*

We can conclude from the results of the feasibility study:

- The uncertainty in a discharge measurement is relatively large: the uncertainty in the discharge distribution (1-2% of the discharge) is smaller than the uncertainty in a discharge measurement (5% of the measured discharge). The uncertainty in a water level measurement is, however, much smaller (0.1% of the measured water level). Therefore, it is concluded that the water levels are more suitable to control the barrier than discharges.
- Several control criteria can be used to control a real time barrier. Therefore, different control criteria are formulated in this study. The calculations with a one-dimensional hydraulic model with a real time control barrier show that the best results are produced when the real time control barrier is regulated on the control criterion: minimization of the maximum disturbance along one of the branches.
- It is shown that for some of the disturbances of the discharge distribution a control barrier might be helpful, but it is also shown that in some cases a control barrier does result in an increase of water levels.
- A control barrier results in an increase of water levels upstream of the control barrier at the bifurcation points in the Rhine. This results in an increase of the probability of flooding upstream of the bifurcation points.
- From the results it can be shown that a reduction of water levels downstream the bifurcation point of 10 centimetres takes relatively a long time: 3 or 4 days. Hence, short term disturbances which take place a couple of hours before the discharge peak can not be controlled.

8.2 *Recommendations*

In five case studies the impact of a real time control barrier at the bifurcation points is investigated. In each case study the water levels and the discharge distribution in the Rhine is disturbed in a different way. However more disturbances are possible (in reality). It is not known whether the case studies give a to positive or to negative impression of a real time control barrier. On basis of the case studies it is not yet possible to judge whether the overall probability of flooding can be reduced with a real time control barrier. More research is needed to conclude whether a real time control barrier is cost effective.

- Determination of the uncertainty in the water level in a probabilistic computation (with a real time control barrier); taking into account a large number of disturbances.

In this study the uncertainty in different measurement methods is investigated. However, by introducing a control barrier more uncertainties are introduced. These are uncertainties which are related to regulating and functioning of a control-structure. For further research it is recommended to determine the impact of these uncertainties on the probability of flooding.

- Assessment of the uncertainties which are related to regulating and functioning of a control-structure.

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