Dynamic control of the discharge distributions of the Rhine River in the Netherlands.

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ABSTRACT

The Rhine River in the Netherlands is characterized by two bifurcation points which lead to three branches. The discharge distribution over the bifurcation points is crucial, because the height of the dikes in the downstream parts is designed with respect to a specific design flood discharge. Deviations in this flood discharge at design conditions present potential risks. Uncertainties in the geographical conditions as well as in the modeling can cause unexpected changes up to 550 m^3/s. Two spillways (which height can be adapted once a year) near the bifurcation point are capable of coping with uncertainties up to 170 m^3/s. This indicates the need for extra discharge capacity and a dynamic steering of the discharge distribution. We propose a system of side channels that create extra connections between the branches, and show that Model Predictive Control is a potential candidate to account for the real-time steering of the spillways. The system can adapt floods, but also has advantages in periods of (extreme) low discharges.

1 INTRODUCTION

1.1 *Historic remarks*

Out of the 16 million people that live in the Netherlands, about 10 million live within direct protection of dikes and dunes. Some 25 % of the Netherlands lies below sea level and would be inundated without the protection of the dunes bordering the North Sea. In times of river floods, around 2/3 of the area of the Netherlands will be inundated if there were no dikes. Already in the early centuries (500-800 a.c.), the construction of a sophisticated flood protection system of dunes and dikes started. Over the centuries, and especially since the second half of the 20-th century, a lot of improvements and dike reinforcements have been executed. This has resulted in perhaps the highest level of safety against flooding found in Europe, and may be even world wide.

When we take a closer look at the river Rhine River in the Netherlands, it is interesting to note that three major branches can be distinguished, originating from the single Upper Rhine River that enters the Netherlands in the east (see figure 1).

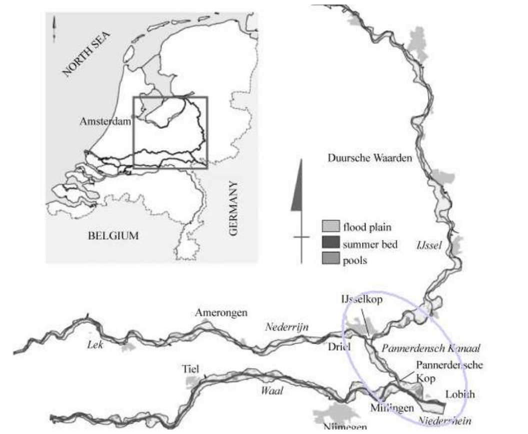

Figure 1: Situation sketch of the three Rhine branches.

Shortly after the Rhine River enters the Netherlands, the river bifurcates into two branches. The branch that goes up north, (Pannerdensch Kanaal or Pannerden Canal) bifurcates again into two branches, the Nederrijn or Lower Rhine River(going west, and ending in the North Sea) and the IJssel River (going North, and ending in Lake IJsel, the largest fresh-water lake in the Netherlands). From a historical point of view, this situation has not always been like that. In earlier times, the river IJssel River did indeed bifurcate from the Upper Rhine, but this bifurcation point was not stable. Sedimentation caused many problems, and often reduced the discharge to the IJssel River to an extent that hardly any shipping was possible. Around 300 years ago, an artificial connection between the Upper Rhine and the river IJssel River has been constructed which is now known as the Pannerden Canal. This man-made channel replaced the former natural connection.

The design of this new connection was far from obvious. In the beginning military/strategic reasons determined the location of the Pannerden Canal and its new mouth. For the stability of the bifurcation (shoaling) and the branch itself, it soon became clear that the lay-out of the bifurcation itself was of utmost importance. An incorrect design of the bifurcation point would lead to sedimentation at the bifurcating branch, which is known as the Bulle-effect. The stability appeared to be ensured when a long dam was used to separate the two branches. In this way, secundary flow effects where minimised (see figure 2).

In a more recent history, scale models have been used to optimise the design to ensure a fixed discharge distribution ratio over the two downstream branches of the Upper Rhine River: the Waal River and the Pannerden Canal (see Delft Hydraulics 1969)). More details about the history of the Dutch rivers can be found in Ten Brinke (2007) and Ven (2004).

Nowadays, the geometrical situation around the bifurcation points is fixed and maintained by the location of the main dike system. In fact, all the stretches of the three branches are confined between dikes. The geometry of both bifurcation points is such, that under design conditions (hence, extreme floods), about 2/3 of the main discharge is diverted towards the river Waal, 1/9 towards the Lower Rhine River, and 2/9 towards the IJssel River. The exact distribution depends of course on the total discharge. Table 1 summarises some discharge distributions.

Figure 2: The Waal-Pannerden Canal bifurcation.

Also the sediment is divided over the bifurcation points, but in a different ratio: the Waal River gets almost 90% of the sediment load, the Lower Rhine River and IJssel River get the remaining 5% each. This has to do with the fact that both the Pannerden Canal as well as the IJssel River suffer from limited supply of sediment transport which is due to the geometrical situation around the bifurcation points. As a consequence the bed of the IJssel River is armoured (for more details, see Schielen et al. (2007)).

1.2 *Current situation*

Maintaining the discharge distribution ratio’s around the bifurcation points is vital.

This has to do with the current system of flood defence in the Netherlands. The Dutch dikes along the river are constructed such, that the so called design discharge can safely be transported towards the sea and Lake IJssel River. Due to the geographical conditions (and verified by model calculations), this design discharge (currently set on 16.000 m^3/s at Lobith) is expected to divide itself by the ratio as given in table 1 (5th column), where a tolerance of 50 m^3/s is allowed. According to that specific discharge, the design water levels have been calculated and the crest heights of the dikes were derived (using a freeboard of at least 50 cm, to take into account uncertainties, wind set up, settling properties). It is obvious that whenever the discharge ratio differs too much from the assumed value, a potential dangerous situation might happen. Two spillways (close to both bifurcation points) have to control the discharge ratio to some extent (see figure 3). One is already present, another one is under construction. As is proposed in Schielen et al. (2007), these spillways will be adapted regularly (e.g. once a year, before the flood season) whenever calculations show that the discharge ratio will not be within the agreed bounds.

	1993	1995	2003	Design conditions
Upper Rhine	11.129(100)[1]	11.916 (100)	823 (100)	16.000 (100)
Waal	7.133 (64)	7.591 (64)	673 (82)	10.165 (64)
Pannerden Canal	3.996 (36)	4.317 (36)	150 (18)	5.835 (36)
Lower Rhine	2.351 (21)	2.502 (21)	30 (4)[2]	3.380 (21)
IJssel	1.645 (15)	1.817 (15)	120 (14)	2461 (15)

Table 1 (reproduced from Schielen at al. (2007)): Discharge distribution in 1993, 1995, 2003 and under design conditions, in m^3/s and percentages

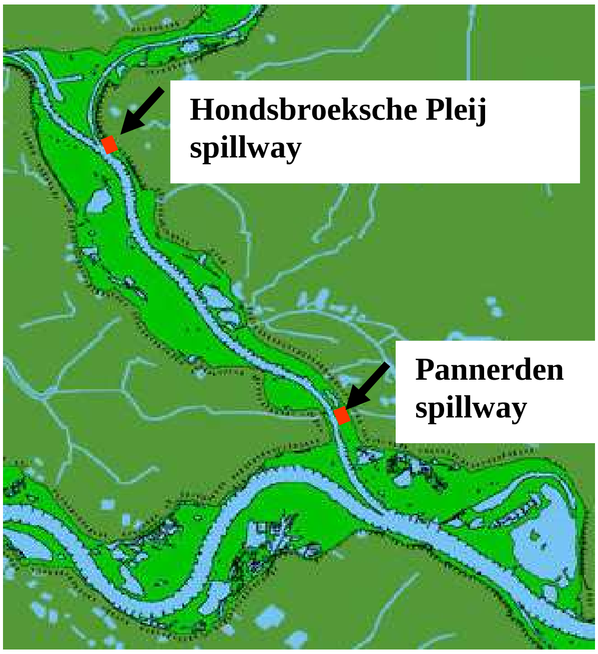

Figure 3: Location of the two spillways for discharge-control on a yearly time scale

However, deviations in the actual discharge ratio (with respect to the assumed/calculated value) are possible due to a number of different causes which come down to the fact that the actual situation might be different than is taken into account in the model-calculations. The most important uncertainties are

- Uncertain flood plain roughness (vegetation succession)
- Uncertain low water bed roughness (bedforms, shoals)
- Morphological changes around the bifurcation points
- Wind
- Model uncertainties as such

These uncertainties actually call for a *dynamic* (i.e. during a flood wave, real-time)

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[1] In fact, the discharge of the Bovenrijn was somewhat higher. During the event of 1993, some discharge was retained around the Pannerden bifurcation point.

[2] During low discharges, the weirs are completely closed. The Nederrijn only get’s a very small discharge for flushing, in order to prevent ecological problems with stagnant water.

control of the discharge ratio. To achieve this, we propose a system of side channels around the bifurcation point with *flexible* spillways, in combination with (near) real time hydraulic calculations to steer the height of the spillways. This system has the extra advantage that also during low discharges, steering possibilities are possible, for instance to facilitate agriculture during droughts, or to prevent salt intrusion in the western part of the Netherlands by diverting extra discharge towards the Lower Rhine River.

2 Hydraulics of bifurcations

2.1 *General*

In general the actual discharge distribution at bifurcations is entirely dependent upon the downstream geometrical and roughness conditions in both branches. These conditions are subject to time-dependent changes: the geometry may change by human intervention (e.g. dike set back, flood plain excavation) and natural changes in the bedlevel (e.g. aggradation or degradation of one branch). Vegetation succession and the temporal development of bedforms are important for the actual hydraulic roughness values. It is therefore important to implement predictions of vegetation and bedform developments in the models used to establish the discharge distribution ratio's. Monitored data of vegetation development can be translated into flood plain roughness changes in the model.

2.2 *Bed forms*

It is expected that bed forms influence the discharge ratio to quite some extent. Bed forms like dunes and ripples increase the roughness of the bed, and hence water levels. These aspects have yet not been taking into account properly in the various hydraulic models. Models that are used for flood level predictions have been calibrated on measured water levels (and subsequently verified on another event). The summer bed roughness is used as calibration coefficient. In this way the individual components (e.g. grain size, dune dimensions) that contribute to the bed roughness are not distinguished. This also means that the *evolution* of bed forms during a flood wave is not yet incorporated into the models. This, however, might be an important factor. In Paarlberg et al. (2008) an attempt has been made to couple a dynamic dune development model with a simple 1D hydraulic model. In this way, a feedback between dune development (and hence increasing roughness) and water level prediction turns out to be possible, which leads to improved predictions.

Wang (1995) studied bifurcations using nodal point relations. He assumes a uniform sedimentation or erosion in the bifurcating branches and is then able to predict whether both branches are stable, or whether one of the bifurcating branches is closed due to sedimentation. The criterion is a relation between k (a site-specific factor, dependent on the local geometry) and m (the sediment transport is proportional to the velocity to the power m). Later, Bolla Pittaluga et al. (2001) have studied the same problem using a model with more physics included.

Until now, *dynamic* bifurcation analysis's, in the sense that free morphological development of two bifurcating branches is described with the aid of a (simple) 2D morphologic model, give poor results. Improvements are expected when the physics of cross-sectional slopes, armouring and graded sediments are better described in the models (Havinga et al. 2005). Kleinhans (2002) made an interesting observation concerning interactions up- and downstream of the Waal-Pannerden Canal bifurcation. He observed in the downstream branches extreme and opposite hysteresis of sediment transport and dune parameters as a function of discharge. This can be explained from the fact that the Pannerden Canal splits from the Upper Rhine in an outer bend. Consequently the coarser sediment flows into the

Pannerden Canal and the relative finer parts enter the Waal River. Discharges and velocities are higher in the latter river, so the mobility of the sediment will be higher and it may be expected that dunes will form more quickly in the Waal River than in the Pannerden Canal. The different bedform behaviour result in different roughnesses in the branches and hence different water levels at the bifurcation points which modify the discharge distribution ratio.

3. Related functions

3.1 Flood management

At this moment, a large project is carried out in the Netherlands, called Room for the River (see www.ruimtevoorderivier.nl). Due to an increase of the design discharge in 2001 (from 15.000 m^3/s to 16.000 m3/s at Lobith), some 40 projects at various location along the three branches have been developed to increase the transport capacity. As a result, the water level at design conditions decreases and hence, no dike reinforcements will be necessary (dike reinforcement it technically possible, but is no longer seen as a robust solution). The two main goals of Room for the River are an increased level of flood protection and improving of what is known as the 'spatial quality' of the river landscape (a combination of amongst others landscape value, recreational aspects and ecology).. The program also aims at restoring the discharge ratio, as it is gradually deviating from the assumed ratio and is out of balance right now. It is clear that the order of execution of the different projects is especially important around the bifurcation points. A dike relocation downstream a bifurcation point for instance, can have a lowering effect on flood levels near the bifurcation point, inducing an increase in discharge in that particular branch.

A boundary condition of Room for the River however, is that also *during* the construction phase, the anticipated discharge distribution at design conditions must coincide with the predefined ratio (preferably at all times). As the construction phase takes roughly 7 years or so, this will be hard to accomplish. This problem can be tackled in carefully planning the different construction phases of the projects around the bifurcation points: e.g. an excavation of a floodplain in one branch could be combined with lowering of summer dikes in another branch. Carried out together, the negative effects of both individual plans on the discharge distribution may cancel (approximately). However, this demands very accurate communication and co-ordination, which is hard to accomplish.

3.2 Navigation

Inland Water Transport (IWT) is a very important mode of transport for the Netherlands and Germany. More than 50 % of goods arriving from overseas in the Port of Rotterdam seaport are transported to Germany by ship over the Rhine River. The main Rhine branch, the Waal River, is Europe's busiest river in that respect. The river lay-out thus has also been designed to maintain certain minimal dimensions of the navigation channel. For the WaalRiver, a channel width of 150 m is adopted with a minimum water depth of 2.8 m during Agreed Low Water (ALW) conditions which occurs 5% of the time. The other branches maintain a channel of 2.5 m deep at ALW and varying widths (depending on the local situation).

3.3 Fresh water supply

Until 1970 the discharge to the IJssel River during low discharges happened to be rather low. Navigation was hampered by small water depths and the Lake IJssel River did not receive enough fresh water to fight salt intrusion of the northern part of the Netherlands. Also the irrigation demands along the IJssel River increased in the second half of the last century. To guarantee a large enough water supply to the IJssel River at *low* discharge conditions three weirs have been constructed in the Lower Rhine. If the Rhine River discharge at Lobith drops below 2300 m^3/s, they control the flow. By means of movable weirs (visor-gates*)*, the discharge through the Lower Rhine is gradually decreased until the minimum flow of 30 m3/s is reached. In this way more water is conveyed through the IJssel River, enabling larger sailing depths and a larger supply of fresh water to the Lake IJssel.

4 Uncertainties

4.1 General

The design flood levels (which are an important element in the testing of existing dike heights and are input for the design of new dikes) are calculated using sophisticated 2D-hydraulic models. However, , a number of uncertainties exist that cause deviations between measured water levels from the calculated water levels.. It is important to have insight in these uncertainties and their impact on the discharge-distribution.

In Velzen (2003), a distinction is made between the natural variability of the system, and uncertainties due to the modeling. The natural variability of the system is caused by natural processes as e.g. wind and morphological processes. Uncertainties due to modeling are caused by e.g. extrapolation, lack of knowledge of physical processes and calibration. It has been shown that the combined uncertainties can add up to a standard deviation of about 13 cm in the design water level for the different branches. Translated into discharges, it indicates a standard deviation of about 150 m^3/s for Lower Rhine River and IJssel River, and 300 m^3/s for the Waal.

A more detailed study towards the specific uncertainties and their impact upon the discharge distribution (Schropp (2003)) showed that calculations were very sensitive to hydraulic roughness and to morphological developments. Other elements (e.g. wind, model parameters,) appeared to be less important. Altogether, the standard deviation due to a combination of uncertainties was shown to be as much as 260 m^3/s for the Waal, and about 200 m^3/s of Lower Rhine River and IJssel River, provided that all the effect are correlated.

In a more recent study, Ogink (2006) estimates the total effect (σ) to be 130-180 m^3/s for the Waal, and 85-100 resp. 85-90 for the Lower Rhine River and the IJssel River. Note that the 90% confidence interval can be approached by 3.3 σ. So the 90% confidence interval in the deviations in the discharge distribution ratios can be as large as 550 m^3/s.

4.2 Dynamic river management

In the Netherlands floodplain rehabilitation or –restoration to increase bio-diversity is an important issue (and is actually also part of Room for the River). In rehabilitated floodplains farmland is replaced by natural vegetation that has to be managed in order to maintain agreed flood levels. Extra flow profile in excavated floodplains and side channels must balance the extra hydraulic roughness from the vegetation. It is inevitable however, that the roughness of rehabilitated floodplains will remain uncertain to some extent. Especially in the backwater region of bifurcations, dynamic changes in hydraulic roughness should be maintained as it directly influences discharge distributions.

5 Discharge control

Summarizing the elements mentioned in the previous sections, it becomes clear that the control of the discharge distribution ratio can be done in two ways: a once-a-year adaptation of the spillways near the bifurcation points or a system that allows for a dynamic steering of the discharge during the passing of the flood wave. If we want to account for the non parallel execution of the different Room for the River projects (near the bifurcation points) or take into account small uncertainties due to for instance wind, the first steering method seems to be sufficient. Calculations show that adaptation of the spillway near Pannerden can alter the discharge up to 50 m^3/s, while the spillway near the IJssel River-bifurcation point accounts for an adaptation of 170 m^3/s. However, this method is not sufficient to correct the inherent inaccuracies in the discharge distributions due to the uncertainties mentioned in section 4.1, (up to 550 m3/s).

To enable corrections of deviations in the discharge distributions resulting from uncertainties with flexible (i.e. adaptation within hours) spillways are required, which have to be operated using state-of-the-art prediction models. From pre-feasability studies carried out by students (Hermeling (2004) and Wit (2004)) it can be concluded that rather large by-passes are needed to correct deviation of several hundreds of cusecs .

Figure 4: an example of an inlet construction as found in the German part of the Rhine River.

Dimensions of these flood channels are in the order of 200 m wide, several meters deep and 5 to 10 km long. It will be hard to find the space for these channels in floodplains or on the other side of the dikes (for an impression see figure 4). The gates of the flood channels can be of a simple robust nature (see figure 4). The problem is the exact timing of operating flood channels. Feedback algorithms and model predictive control (MPC) are interesting candidates as steering tools.

5.1 *Model Predictive Control*

In a simple way, the real-time control of the channels by means of movable weirs, can be done by comparing measured water levels along the branches with expected water levels (at the specific discharge). This is simple feed-back control. Also feed forward control is possible, in which not the measured water levels are the trigger, but the estimated (if possible measured) uncertainty (e.g. wind, roughness) is the trigger. In both cases, a simple 1D-hydraulic model can then be used to evaluate the strategy. In Arnold (2004) this has been done by using a flexible weir in the low water bed downstream the bifurcation point. Obviously, this weir causes increased water levels upstream. Therefore, one of the recommendations was to use a side channel as control mechanism. Another (striking) conclusion was that the applied method sometimes leads to unwanted effects (oversteering).

Controlling the discharge distribution in this way does not take into account the feedback of the system due to the control-actions itself. Model Predictive Control however, uses (model) predictions to determine the control actions. The intended control-goals are then achieved more effectively. A general description of MPC and some applications can be found in Van Overloop (2006).

Lemans (2007) carried out a preliminary study on the potency of MPC to control the discharge distribution along the Rhine branches. Important starting point in that study was that the most upstream *existing* weir in the Lower Rhine branch was used to adapt the discharge distribution. A more or less obvious conclusion was then that during design flood conditions, the weir has little potential. Reason is that the majority of the discharge under flood conditions is transported through the floodplains, and hence outside the impact of the weir. During average floods (return period of once a year to once every 5 years) the control possibilities were much more promising.

In periods of extreme low discharges, control strategies, applied to the open-and-close regime of the weir, can help to reduce the salt intrusion in the Western part of the Netherlands, by increasing the transport capacity of the Lower Rhine River to the expense of the IJssel River and the Waal River. In order to guarantee the fresh water storage in Lake IJssel, however, it is necessary to *increase* the discharge of the IJssel River (which flows into Lake IJssel) *before* the drought-period starts.

Lemans showed that MPC, applied to retention areas, can be rather successful. For side channels the exact time of adjusting the control structure is very important, comparable to inlet structures. In the case of retention areas, an optimal retention strategy is to ‘shave’ the peak of the upstream discharge, in accordance with the storage capacity in the retention area (see figure 5).

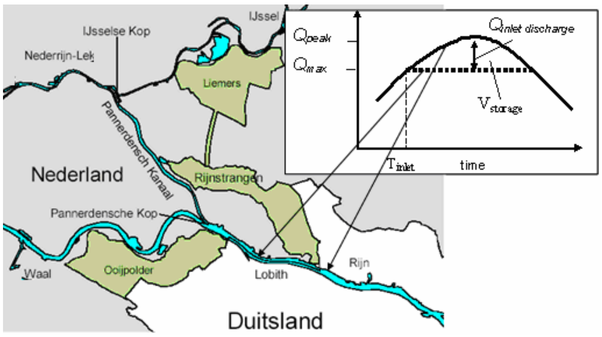

Figure 5: Impact of Rijnstrangen retention area on flood wave

In that way, the downstream discharge is decreased as much as possible. The area between the Upper Rhine River and the Pannerden Canal, the Rijnstrangen area was modeled in a simple way, with an inlet structure at the Upper Rhine near Lobith and an outlet at the Pannerden Canal. MPC was used to adjust these structures, thus controlling the discharges.

This means of control depends on the (predicted) discharges in the two branches and the water level in the retention area. Due to the receding prediction horizon in where MPC optimizes the different states of the modeled system, MPC could deal with uncertainties in predicted discharges. Finally an optimal control strategy could be realized.

6 Proposal

From the previous section, it can be concluded that MPC has interesting properties with respect to the adjustment of the discharge ratio during low, medium and even high discharges, especially in cases when i) the right time of control is of utmost importance, ii) the water system has different control locations and iii) predictions of triggers are uncertain.

However, using existing structures restricts the control possibilities and can cause increasing flood levels upstream. Therefore, we propose to apply the principles of MPC to a new system of long side channels, to control and (if necessary) adjust the discharge distribution ratio of the bifurcation points.

The system we propose is schematically visualized in figure 6. We consider four by-passes along the branches near the bifurcation points. The Upper Rhine River is connected with the Pannerden Canal and the Waal, and the Pannerden Canal is connected with the IJssel River and the Lower Rhine River. All flood channels are provided with flexible spillways, that can be operated real-time, to control the discharge in the channels. Their combined capacity should meet the demand for the maximum adaptation of the discharge distribution ratio over the bifurcation points in the order of 300-500 m^3/s. A closer analysis may reveal that one of the connections is obsolete. The control possibilities of this system will increase further if extra storage capacity is introduced, using e.g. the Rijnstrangen area. This proposal is now being studied. The feasibility will be demonstrated with model studies. The proposed by-passes do not have to be completely new. Until the beginning of the 20th century the Rijnstrangen area was a natural water connection to the north during floods and can be used again as a flood channel. Also the by-pass between the Pannerden Canal and the IJssel River at the Hondsbroeksche Pley (under construction) fits in this scheme, The connection between the Upper Rhine River and the Waal River will be the hardest to realize, considering the restricted available space and also because of the length of this flood channel (estimated 10-20 km).

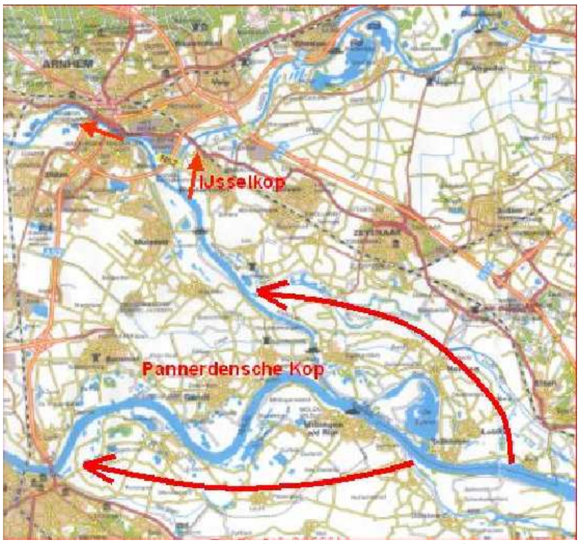

Figure 6: proposed by-passes for a dynamic control of the discharge distribution

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It is expected that the proposed system of side channels can be used as a discharge control instrument to enforce deviations from the natural discharge distribution ratios over the entire discharge regime. In this way the system can also be used as an instrument to support policy-decisions during low-discharges, as well as extreme high (above the design discharge) conditions. In the latter case, it can be regarded as a means suitable for crises-management.

7. Conclusions

The actual discharge distribution at bifurcations is dependent upon the downstream geometrical and roughness conditions in both branches. As these conditions are time-dependent it is important to implement predictions of vegetation and bed form developments in the models used to establish the discharge distribution ratio’s.

Proper steering of discharge distributions can be accomplished by increasing the flow profile and/or decreasing the hydraulic roughness in one branch.

For minor corrections of the discharge distribution ratios over the Dutch upper Rhine branches, it is sufficient to make the height of existing summer dikes and spillways flexible, in the sense that they can be adapted once a year (in average).

To cope with the inaccuracy in the discharge distributions real-time corrections are demanded. A system of flood channels, equipped with movable weirs, connecting the upstream river with the downstream branches, can steer the discharge distributions during a flood wave.

The reliability of such a channel system can be increased when MPC is applied. The robustness increases even further when retention areas are introduced in the channel system.

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