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On the use of flexible spillways to control the discharge ratio of the Rhine in the Netherlands: hydraulic and morphological observations

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Abstract

Shortly after the river Rhine enters the Netherlands, it bifurcates into three branches. A predefined, fixed discharge distribution over the bifurcation points is vital, since the dikes are designed with a predefined distribution in mind. Recent observations show that the discharge distribution that is anticipated at design discharge conditions differs from the predefined one. One of the goals of the national program Room for the River is therefore to restore the discharge distribution. To control the hydraulic processes during flood events, the construction of two adaptable spillways in the direct neighbourhood of the bifurcation points is proposed as a possible solution. The spillways are capable of maintaining the proper discharge distribution. They can also act as regulators during the construction phase of the flood managements plans of the project Room for the River. Hence, the discharge ratio and thus the water levels are such that the safety-standards are not violated. The morphological consequences are most probably very small, provided that strong erosion during flood events can be prevented and the autonomous bed degradation stays within reasonable limits.

Introduction

The Rhine-branches in the Netherlands are typically lowland-rivers. They are relatively wide (the cross section of the main channel varies from 200 to 600 metres, while the section between the main dikes can be as wide as a few kilometres), slowly flowing rivers (velocities under average conditions vary between 0.5 m/s and 1 m/s, depending on the branch) with large floodplains that inundate roughly speaking every year. The riverbed is sandy, and often dune-covered. The hinterland is almost everywhere protected from flooding by dikes, apart from some specific locations where an end moraine from the last ice age is present and forms a natural protection. The Rhine enters the Netherlands from Germany at the village of Lobith. The first kilometres in the Netherlands the river is called Bovenrijn ('Upper Rhine'; throughout this article, the Dutch names for the rivers are used). The Bovenrijn bifurcates into two branches: the river Waal and the Pannerdens Kanaal (Pannerden Canal). In Fig. 1, a geographical reference map is shown.

The length of the Pannerdens Kanaal is actually not more than a few kilometres. It was dug downstream from the former bifurcation point of the Bovenrijn in 1707, as a shortcut between the Bovenrijn and the so-called Nederrijn (called 'Lower Rhine' in the Netherlands). It ends in the Nederrijn well before the next bifurcation point where the River IJssel branches off.

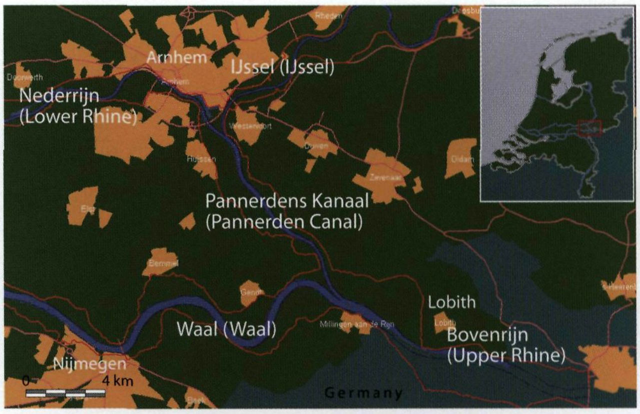

Fig. 1. Reference map. The Dutch and English names of the river branches are indicated. The red line indicates the location of the main dikes. The town of Lobith (bottom-right) is generally denoted as the place where the Rhine enters the Netherlands.

The former bifurcation point at the Bovenrijn no longer exists. The first kilometre of the river IJssel is also a man-made river stretch. In the 18th century the bifurcation of the IJssel from the Nederrijn was located in the inner bend of the Nederrijn. Natural processes caused sedimentation and hindered the access for shipping. Therefore, in 1777 a new bifurcation was constructed approximately 1 kilometre upstream in an outer bend. During the design special attention was paid to the currents around this point. Currents not only influence shipping but also the distribution of sediment (see Delft Hydraulics, 1969), which is an important item to control. The original bifurcation disappeared due to sedimentation over the years. In Fig. 2 the locations of the old and new bifurcation are given.

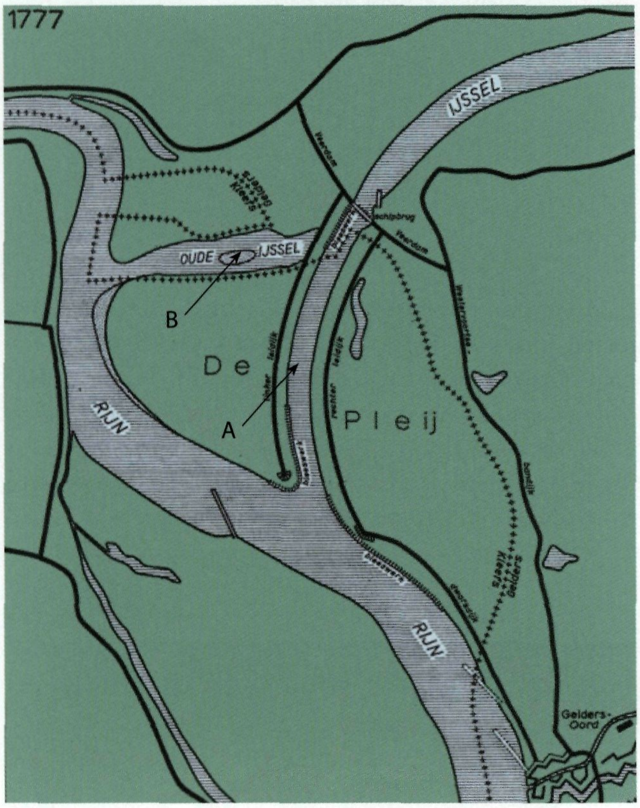

Fig. 2. The new and old bifurcation (denoted with 'A' and 'B') of the Nederrijn ('Rijn') and the IJssel. Reproduced from Van de Ven (1976). The Rijn enters from Germany in the south and flows towards the north (IJssel) and west (Rijn).

For a thorough historical analysis of the situation around the bifurcation points, we refer to Van de Ven (2004). From the attention that the bifurcation points got in the past, and still get nowadays, it may be clear that the distribution of the discharge has always been an important matter. In the past, it was vital for the important trade-cities along the river IJssel and it ensured that the western part of the Netherlands could be reached at high and low discharge conditions. Nowadays, the distribution of the discharge is much more related to safety and drinking water issues. In Fig. 3, an aerial view of both bifurcation points is shown.

There is not much international literature available about the bifurcation points of the river Rhine in the Netherlands. Apart from Frings (2005) and Sloff et al. (2003) very few references are available. In fact, there is not that much literature available about water and sediment distribution over bifurcation points in a natural situation in general. From a theoretical point of view, however, it is a very interesting topic and some papers have tried to tackle the problem from the model point of view (see Wang et al., 1995 and the references cited there, Bolla Pittaluga et al., 2001). For a more general overview on the subject of bifurcations we refer to Jagers (2003). Experimental studies and field measurements are reported in Bertoldi et al. (2001). Technically, they deal with channels around a braid bar, but their observations might be of use to get more insight in bifurcations of channels in general. In Wang et al. (1995), it is shown that, depending on the discharge-ratio of both branches, one of the branches closes due to sedimentation. This immediately indicates the relevance for practical situations where it is in general no option that branches of major rivers silt up. The lack of papers may be explained from the fact that bifurcation points are a typical delta-issue. In the total catchment area of the river Rhine except for the Netherlands, there are just no bifurcation points present and only confluents play a role. From a maintenance point of view however, bifurcations are harder to handle than confluents. Confluences do not require the maintenance of downstream distributions of water and sediment transport. The discharge and sediment load downstream are simply equal to the sums of the discharges and sediment loads in the two braches that come together.

Current discharge conditions

The dikes along the Dutch rivers are designed with respect to a design-discharge. In 1996, the Flood Protection Act (in Dutch: Wet op de Waterkering) has been accepted by the Dutch Parliament. In that act, the design discharge as well as the discharge ratio over the branches (at design conditions) is set and from that time on is supposed to be fixed. In 1996, the design discharge was calculated for the first time, as demanded by the Flood Protection Act. Based on a historical analysis of the peak discharges in the period 1901 to 1992, the design discharge was calculated to be 15,000 m^3/s at Lobith. The Flood Protection Act demands an evaluation of the design discharge every 5 years. Due to two periods of extreme discharges in 1993 and 1995 (11,000 and 12,000 m^3/s at Lobith), the design discharge increased in 2001 (at the first evaluation) with 1000 m^3/s to 16,000 m^3/s. Based on the design discharge, the design water levels are calculated. They serve as input for the design of the dikes. As a result of this approach, it is only natural that the discharge distribution over the bifurcation points must be regulated (at least at extreme conditions). In Table 1 and Fig. 4, this discharge distribution

Fig. 3. The bifurcation points of the Bovenrijn in the Netherlands. In the upper figure, the river IJssel branches off the Nederrijn (flow is from top to bottom), in the lower figure, the Bovenrijn bifurcates into the Pannerdens Kanaal and the river Waal (flow is from bottom to top). Photo's by B. Broekhoven.

(for the design discharge of 16,000 m^3/s at Lobith near the Dutch-German border) is indicated, as set in the Flood Protection Act. About 64% of the discharge at Lobith flows into the river Waal, and 36% is diverted to the Pannerdens Kanaal. The Nederrijn gets 42% of the discharge of the Pannerdens Kanaal and the remaining 58% is diverted towards the river IJssel.

To guarantee a large enough water supply at low discharge conditions (needed for e.g. shipping, drinking water and agriculture), three weirs have been constructed in the Nederrijn. If the discharge at Lobith decreases below 2300 m^3/s, they control the flow. As a consequence, the distribution at the Nederrijn-IJssel bifurcation point at low discharge differs from the distribution at high discharge. In Table 2, the distribution during two high-water events (1993, 1995), one recent low-water event (2003) and one near-average discharge (2500 m^3/s) is shown. The 1993 and 1995 events had a return period of about 60 years. The discharge distribution of those events coincides with the predefined by the Flood Protection Act (see Table 1). One should keep in mind however, that the peak-discharge (about 12,000 m^3/s) is still far below the present design discharge (with a return period of 1,250 years) of 16,000 m^3/s. In the fifth column of Table 2, the ratio at a discharge of 1000 m^3/s is shown. Up to a discharge of 2300 m^3/s at Lobith, the weirs in the Nederrijn control the

Table 1. Discharge distribution at design conditions (16,000 m^3/s at Lobith) in absolute values and (between brackets) in percentages. The combined discharge for the IJssel and the Nederrijn adds up to 5841 m^3/s, which is 6 m^3/s more than the discharge of the Pannerdens Kanaal. This is because alongside the channel, there is a pumping installation that is allowed to pump 6 m^3/s from the hinterland onto the canal during high discharge conditions.

Discharge	m^3/s	(%)
Bovenrijn (Lobith)	16,000	(100)
Waal	10,165	(64)
Pannerdens Kanaal	5835	(36)
Nederrijn	3380	(21)
IJssel	2461	(15)

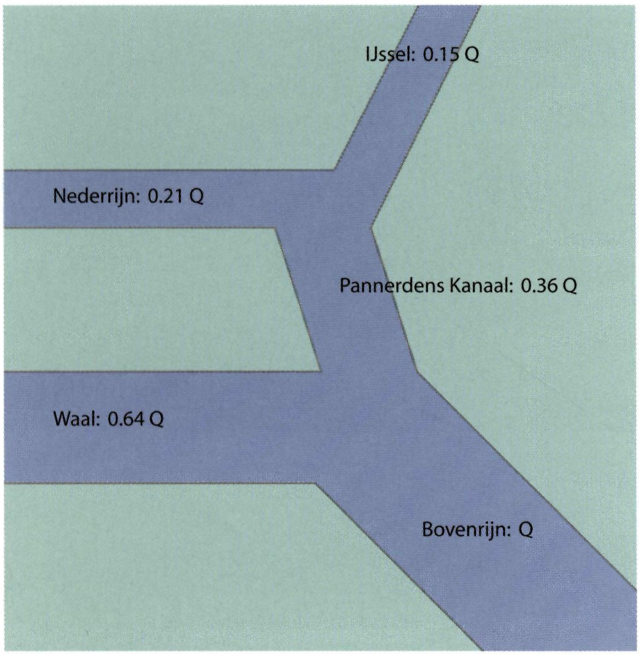

Fig. 4. Discharge distribution at design conditions (16,000 m^3/s at Lobith). The numbers refer to the ratio of the discharge at Lobith that the branches are accounted for.

distribution of water over the bifurcation points. If the discharge exceeds 2300 m^3/s, the weirs are completely opened and the Nederrijn is a free flowing river. In the last column, the present discharge distribution under design conditions is given. This is based on a calculation with the geometrical situation of 2001. Note that this deviates from the values given in table 1. Hence, the current discharge ratio is not as it should be according to the act.

There are three main reasons for the deviation of the discharge ratio. The first is the already mentioned increase of the design discharge. The increase of 1000 m^3/s leads to too much discharge for the IJssel, compared to the predefined discharge under design conditions. The second reason is that in the period between 1996 and 2001, several projects around the bifurcation points have been carried out. They influence the discharge ratio. The third reason is the autonomous bed degradation that occurs in the eastern part of the Netherlands (see also 'Morphological results').

Current control structures

The current discharge distribution that at present is anticipated for design discharge (at extreme conditions) is determined by some measures that are taken around the bifurcation points. The most important one is the spillway at the upstream entrance of the Pannerdens Kanaal (see figure 5). As soon as the discharge of the Bovenrijn exceeds 7500 m^3/s, the water overtops the spillway, and a secondary channel becomes active. After a few kilometres, the secondary channel flows back into the Nederrijn. The main dikes (i.e. the dikes that are constructed to stem the design water levels) are the most right ones in Fig. 5 (indicated with 'A'). Under low discharge conditions, a summer dike along the Pannerdens Kanaal (indicated with 'B') prevents water from flowing into the secondary channel.

At the Nederrijn-IJssel bifurcation point, the situation is somewhat different. The spatial planning of the bifurcation is such that under high water conditions, the predefined discharge ratio is met (provided that the ratio at the Waal-Pannerdens Kanaal bifurcation is correct). The main elements that take care of this are the geometric shaping of the bifurcation point itself and the special design of the groynes at the bifurcation point. This has been the subject of extensive

Table 2. Discharge distribution in various conditions in absolute values and percentages. Note that the discharge during the events of 1993 and 1995 is in agreement with the predefined discharge distribution as mentioned in the Flood Protection Act. In the last column of the table, the discharge distribution at design conditions is indicated. A comparison with Table 1 shows that the current discharge distribution at design conditions (based on a calculation with the geometrical situation of 2001) is not in line with the desired distribution from policy point of view. It is one of the tasks of the national program Room for the River to correct this.

	1993	**1995**	**2003**	**Free flowing regime (2500 m^3/s)**	**Conditioned (1000 m^3/s)**	**Calculation for the design discharge regime (16,000)**
Bovenrijn (Lobith)	11,129 (100)	11,916 (100)[1]	823 (100)	2500 (100)	1000 (100)	16,000 (100)
Waal	7133 (64)	7591 (64)	673 (82)	1700 (68)	800 (80)	9994 (62)
Pannerdens Kanaal	3996 (36)	4317 (36)	150 (18)	800 (32)	200 (20)	6006 (38)
Nederrijn	2351 (21)	2502 (21)	30 (4)[2]	450 (18)	30 (3)	3423 (21)
IJssel	1645 (15)	1817 (15)	120 (14)	350 (14)	170 (17)	2589 (17)

[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.

Fig. 5. The spillway at the Bovenrijn-Waal bifurcation point. The Pannerdens Kanaal flows to the left of the spillway, from bottom to top. The main dike is indicated with 'A', the summer dike with 'B'. Photo courtesy by B. Boekhoven.

studies in scale models. Over the years however, the situation that was originally carefully designed changed. Several projects in the floodplains near the bifurcation point were carried out and this changed the flow conditions. Also, in the floodplains near the city of Arnhem (downstream the bifurcation) there are some constructions which also influence the discharge distribution at medium to high discharge. This, and the (autonomous) bed-degradation (see section 'Morphological result') result in a discharge ratio that no longer agrees with the predefined ratio.

Note that both bifurcations consist of a large branch and a smaller one, where the smaller one branches off in the outer bend of the original branch. In both cases, this is due to a well-chosen design. Due to the secondary flow effects (which are always present in curved channels, see Bulle, 1926; Van Bendegom, 1947; Rozovskii, 1957; De Vriend, 1981; De Heer & Mosselman, 2004), most sediment is transported towards the inner bend. As a result, only a very limited amount of sediment is transported towards the smaller branch (i.e the Pannerdens Kanaal or the IJssel).

Organization

The organization of this article is as follows. In the next section, we explore the problem related to the discharge-distribution at both bifurcation points. This issue is closely related to a large number of flood plain plans that will be carried out in the coming years as part of a national flood management program. In the section 'Proposed solution and objective', a possible solution to this issue is proposed and the objective of the article is given. After that the results are discussed and the article ends with a discussion and conclusions.

Problem statement

Accommodating the increase of the design discharge and restoration of the proper discharge distribution at both bifurcation points are the main aims of the national program Room for the River (see *www.ruimtevoorderivier.nl*). This program involves the restoration of the flood plain at about 30 locations and dike reinforcement at various locations. The latter should only be applied, however, when no spatial solutions (which lower the water levels at extreme conditions) are available. Dike reinforcement is not considered to be a robust solution. Besides, it increases the risk in the protected areas because of higher water levels. The program Room for the River should be finished in 2015. The fact that the current discharge ratio at present is not in line with the Flood Protection Act has direct consequences for the selected projects in Room for the River around the bifurcation points. Projects downstream of a bifurcation point do influence the discharge distribution by backwater effects. By choosing the measures carefully the discharge ratio can be steered. This indicates however, that also the planning procedure of the actual construction phase of the projects is a delicate one where the elements of the individual plans need to be tuned to each other.

The individual projects of Room for the River in the neighbourhood of the bifurcation points affect the discharge ratio. Furthermore, each plan is supposed to achieve a certain minimal decrease in water level at design discharge conditions. The set of plans is designed such that after the construction of all the plans, the anticipated discharge ratios at the bifurcation points agree with the predefined discharge ratios. However, also during the construction phase, the anticipated discharge distribution at the design discharge must coincide with the predefined ratio (preferably at all times). As the construction phase takes roughly 7 years or so, this twofold goal is hard to reach.

In planning measures around the bifurcation point of the Nederrijn and IJssel, another consideration plays a role. This has to do with an expected increase in design discharge as a result of climate change. The program Room for the River aims to be a robust program. It is expected that once the projects have been carried out, no further large measures need to be taken for the decades to come because it is not likely that the design discharge will increase again with a substantial number. On the other hand, on a longer time scale the program does anticipate on a further increase in design discharge, which is mainly based on climate change scenarios. For the Rhine branches, indications are that climate change eventually will lead to a design discharge of 18,000 m^3/s at Lobith (for background information on the climate change scenario's and the consequences for the Netherlands, we refer to the website of the Intergovernmental Panel on Climate Change (*www.ipcc.ch*) and the website of the Royal Dutch Meteorological Institute (*www.knmi.nl*)). Now, an important observation has to be made. The geographic conditions at the downstream part of the branch Nederrijn are such that the river cannot accommodate more discharge than the (approximate) 15% it gets from the 16,000 m^3/s. The floodplains of the Nederrijn in the western part of the Netherlands are too narrow, so lowering them hardly increases the discharge capacity. Besides, there is hardly any room for dike relocation. Hence, the only other solution is dike reinforcement, although that is no preferred option from policy point of view (and as indicated, it increases the risk). This has consequences for the discharge distribution at the bifurcation points. The agreements are set, that whenever the (design)discharge increases above 16,000 m^3/s, the Nederrijn is spared: the increase is distributed over the two other branches Waal and IJssel. The distribution then becomes as indicated in Table 3 (for comparison, the discharge ratios for 15,000 and 16,000 m^3/s are repeated). In short, the problem is thus to control the discharge ratio at the bifurcation points.

Table 3. Discharge distribution for the former and current design discharge (15,000 and 16,000 m^3/s at Lobith) and the design discharge that may be expected in the future due to climate change (18,000 m^3/s at Lobith).

Discharge	**Bovenrijn (Lobith)**	**Waal**	**IJssel**	**Nederrijn-Lek**
15,000 and 16,000	100	64	15	21
18,000	100	65	16	19

Proposed solution and objective

One possibility to tackle the problem related to the discharge-ratio at the bifurcation point of the Bovenrijn and Waal is to carefully plan the individual parts of the proposed projects around the bifurcation points: an excavation of a floodplain in one branch could be combined with lowering of summer dikes at another branch. Carried out together, the negative effects of both individual plans on the discharge distribution may cancel (approximately). Such a solution, however, demands very accurate communication and co-ordination.

Another solution to the problem is to select one specific location in the neighbourhood of the Waal-Pannerdens Kanaal bifurcation point that is used to compensate for negative effects on the discharge distribution due to measures elsewhere. As indicated, there is already a spillway located on the east-bank of the Pannerdens Kanaal, which seems to be a good candidate. If a project on for instance the river Waal is carried out, the spillway might be heightened to compensate for the effect of the measure on the discharge distribution. This heightening (or lowering) should be done in such a way that the measure is reversible. Also at the Nederrijn-IJssel bifurcation a flexible spillway is proposed. This spillway is combined with a dike relocation (see Fig. 6). The main task of this spillway is to spare the Nederrijn when the discharge exceeds 16,000 m^3/s and hence, to ensure that the long-term discharge distribution can be realised in the first place. At that discharge, the spillway overtops, and all extra discharge of the Pannerdens Kanaal is diverted into the IJssel. In this way, it is ensured that the Nederrijn gets no more discharge than it can accommodate downstream. The possible increase in discharge due to climate change is no problem for the

Fig. 6. An aerial view of the Hondsbroekse Pley. In orange is the original main dike indicated. In blue the projection of the new dike. The red lines indicate the centre line of the main channels. The proposed position of the future spillway is indicated.

Waal-Pannerdens Kanaal bifurcation point. The spillway can easily be adapted such that the Waal gets more discharge. This solution can ensure that up to design conditions, the height of the water levels in the downstream parts of the branches will not exceed the critical levels because the predefined discharge ratio is maintained. Hence, it will be a sustainable solution.

The objective of this article is to discuss the hydraulic effectiveness and the hydraulic and morphological consequences of the proposed spillways at both bifurcation points.

Results

Hydraulic results

During the research-phase of Room for the River, numerous projects along the Rhine branches have been studied in order to determine a well-balanced set of measures that 'solve' the problem of Room for the River. This is to say that the water levels along the branches drop below the designated ones by enlarging the discharge capacity (apart from the stretches where dike-reinforcement cannot be avoided). Furthermore, the discharge ratio is to be restored. The reference situation roughly resembled the geometrical conditions of 2004. Under those conditions, the discharge distribution over the various branches has been calculated (see Table 4). All calculations have been carried out with a 2-dimensional hydraulic model, based on the shallow water equations. They are implemented using a staggered grid method. The cells are in average approximately 40 metres wide. This model is generally used within the Ministry of Transport, Public Works and Water Management for almost all its activities that deal with flood management and flood protection. Clearly, the discharge ratio deviates significantly from the predefined one (see the third column in Table 4).

Table 4. Calculated discharge ratio at current (geometrical situation of 2004) conditions and the deviations from the predefined ratio.

	Predefined discharge ratio in m^3/s	**Current discharge ratio in m^3/s**	**Difference between current and predefined ratio in m^3/s**
Q-Waal	10,165	9994	−171
Q-Pan. Kanaal	5835	6006	171
Q-Nederrijn	3380	3423	43
Q-IJssel	2461	2589	128
Q-Lobith	16,000	16,000	0

It is beyond the scope of this article to discuss the full process of how the set of measures for Room for the River is determined. Here, we only present some aspects of the final set. In Fig. 7, a calculated result of the discharge at design conditions near the bifurcation of the Waal and Pannerdens Kanaal is given, taking into account all the projects that are planned in Room for the River. Depicted is the discharge per grid cell, i.e. the product of the local velocity and the local depth. Hence, integration over a cross-section of a branch gives the total discharge of the branch. The spillway at the Waal-Pannerdens Kanaal bifurcation point is clearly visible and controls the discharge. The height of the spillway is fixed

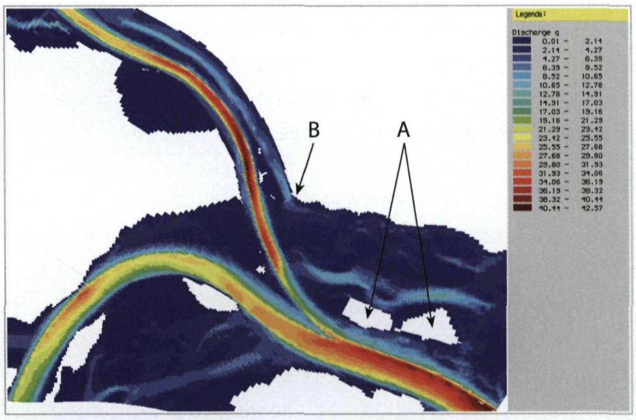

Fig. 7. The discharge at the bifurcation of the Bovenrijn into the Waal and the Pannerdens Kanaal. The colors denote the discharge per grid cell (i.e. the product of local velocity and local water depth). The white spots indicate emerged areas even under design conditions. Secondary channels in the floodplain can be identified with the light blue colors (see for instance the arrows at 'A'). The spillway is indicated with the arrow 'B'. The secondary channel behind the spillway is clearly visible.

at 13.48 m. above mean sea level. Note that projects downstream the bifurcation point determine the hydraulic conditions at the bifurcation point through the backwater effects. It indicates that adjustments at the spillway should be studied in combination with the detailed plans of the (downstream) neighbouring floodplains.

At the Nederrijn-IJssel bifurcation point, the spillway is supposed to be closed (at design conditions). This should be clear, since the assumption is that the spillway is supposed to function (i.e. increase the discharge towards the IJssel) whenever the discharge is higher than design conditions. Under those circumstances, the flow overtops the spillway and the exceeding discharge is directed towards the IJssel.

All the measures of Room for the River have been built into the reference-model and a calculation of this situation with a design discharge of 16,000 m^3/s has been made. The results for the anticipated design discharge ratio are summarized in Table 5. Deviations from the predefined one are given in the third column. These deviations are acceptable and cause no extra risk of flooding (a rule of thumb indicates that an extra discharge of 100 m^3/s for the river Waal leads to an increase of the water level of 4 cm only). It can therefore be concluded that the two spillways may lead to a discharge ratio that is in line with the predefined one as stated in the Flood Protection Act.

Table 5. Calculated discharge ratio after the projects of Room for the River have been carried out and the deviations from the predefined ratio.

	Predefined discharge ratio in m^3/s	**Current discharge ratio in m^3/s**	**Difference between current and predefined ratio in m^3/s**
Q-Waal	10,165	10,199	34
Q-Pankanaal	5835	5801	−34
Q-Nederrijn	3380	3344	−34
Q-Yssel	2461	2461	0
Q-Lobith	16,000	16,000	0

As said before, during the construction phase of Room for the River, the discharge distribution (under design conditions) must be maintained as defined in the Flood Protection Act. Therefore, it is worthwhile to study the range of discharges that can be handled with the spillway at the Waal-Pannerdens Kanaal bifurcation point. In Fig. 8, we present the difference in discharge between two calculations, one with and one without a spillway. The geometrical situation for both calculations is the same. The difference in discharge towards the river Waal for both situations turned out to be roughly 50 m^3/s. This indicates that a maximum of about 50 m^3/s can be guided towards the Pannerdens Kanaal by adaptation of the spillway. Hence, effects in the discharge ratio that measures around the bifurcation points may have, and which lead to an increase in discharge less than 50 m^3/s for the Waal can be compensated by adaptation of the spillway at the Pannerdens Kanaal. Note however, that as a result of the adaptation also the flow field within the Pannerdens Kanaal changes. The discharge over the spillway increases with 200 m^3/s and the discharge in the main channel decreases with 150 m^3/s (see also Fig. 8). This means that also the water levels in the secondary channel increase with respect to the reference situation. This may have implications for the height of the dikes.

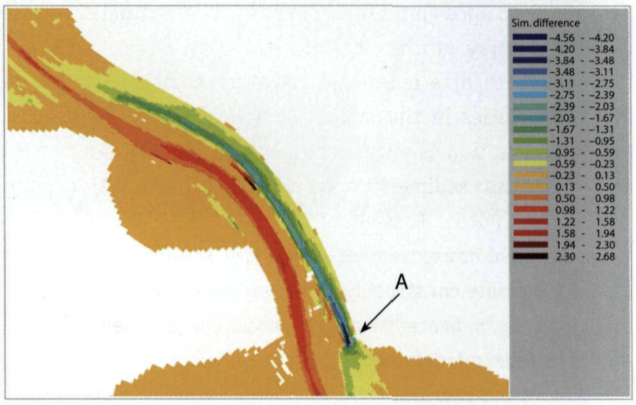

Fig. 8. The difference in discharge per grid cell between the situation with and without a spillway at the bifurcation point of the Waal and the Pannerdens Kanaal. The red color in the Pannerdens kanaal indicates that there is a decrease of about 150 m^3/s through the main channel. The blue color (starting at the spillway, see 'A') indicates that there is an increase of nearly 200 m^3/s discharge over the spillway (as can be found through appropriate integration over a cross section of the Pannerdens Kanaal.

These results indicate that the two spillways at the bifurcation points can act as main 'taps' for maintaining the design discharge distribution over the Dutch Rhine branches. During the construction works of 'Room for the River', once every year or so an inventory of ongoing activities should be made, and a hydraulic calculation of the actual situation should indicate whether an adaptation of the spillways is needed. Whenever necessary, the height of the spillways can be adapted. It is emphasized that such an adaptation should only be made once a year, before high discharges are to be expected. In the preceding months, the state of the river system can be monitored and calculations showing the needed adaptation of the spillways can be made. Hence, the system is then ready for the high discharge period. It is not the intention to adapt the spillways during a high discharge event. The uncertainty that goes together with the prediction of the exact form of the flood wave is considered to be too large to allow for adaptations on such a short notice.

Morphological results

In general, the construction of flexible spillways around bifurcation points will probably have very little influence on the morphological processes. The spillway at the Waal-Pannerdens Kanaal bifurcation point overflows a few times a decade only. The proposed spillway at the Nederrijn-IJssel bifurcation point would overflow far less frequently, only when the Bovenrijn discharge exceeds 16,000 m^3/s. Even though the main effects on the morphology take place at the highest discharges, the frequency of these events is so low that in practice the effects are far less than the morphological processes during more average discharges (Ten Brinke, 1998). The construction of the flexible spillway at the Nederrijn-IJssel bifurcation point is combined with dike relocation and this could result in lower stream velocities in the main channel. The overall effect on the sedimentation is very small. (see Mosselman & Suryady, 2005). Besides, sediment loads around the bifurcation point are supply limited. Possible extra sedimentation will rapidly be transported downstream. Therefore, it is not to be expected that the flexible constructions cause morphological problems.

As already indicated, one of the reasons for deviations in the discharge ratio is the bed degradation. Apart from the degradation due to erosion dredging also causes bed degradation. This, as well as a respons to the normalization interventions in the 19th and 20th century, resulted in a lowering of the riverbed of all branches (see Fig. 9 and Ten Brinke, 2005). The bed level at the Nederrijn-IJssel bifurcation point, however, seems quite stable. Since some 15 years, sediment extraction is only allowed in the most downstream parts of the Rhine branches in order to stop the lowering of the bed. Observations show, however, that the degradation of all branches continues, at least up to 1999 (see Fig. 9), although the data of the last decade (1990 - 1999) suggests that the rate of degradation decreases significantly.

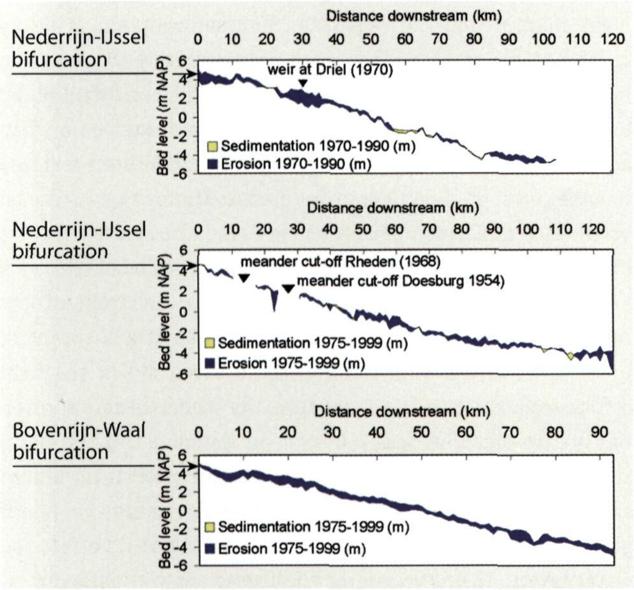

Fig. 9. Bed level changes in the period 1970/1975 - 1990/1999 for the Nederrijn (top), IJssel (middle) and Waal (bottom). Reproduced from Ten Brinke (2005).

For the Pannerdens Kanaal the bed degradation is an important process, because the branch tends to increase its discharge as a result, with possible negative consequences for the discharge distribution. Hence, stabilisation of the riverbed of all branches is an important measure for the (near) future. In the upstream river parts (around the bifurcation points) it is already no longer allowed to extract sand from the riverbed. Shallow parts of the shipping channel are continuously deepened by dredging but the material has to be dumped afterwards in deeper parts upstream of the same river branch. In this way, no material is extracted from the river. This is an ongoing process that is expensive. An ongoing bed degradation, however, has even larger financial consequences: constructions need to be stabilised and measures to counteract the lowering of groundwater levels have to be carried out. There are some initial ideas, which involve armoring the complete bed around the bifurcation points, but this is quite a drastic measure. As already indicated, as a result of climate change higher discharges in the river may be expected. In this case the river IJssel will transport a relatively higher discharge than the river Nederrijn. This will not automatically result in a higher sediment transport to the river IJssel (due to bend effects and the current state of the top layer). This lack of sediment could result in an increasing erosion further downstream, in de middle part of the IJssel.

From the preceding, it can be concluded that bed degradation has a large effect on the discharge distribution. In order to understand the morphological consequences of bed degradation, and to gain understanding of the morphological behaviour of bifurcation points, we summarise some facts related to the characteristics of the subsoil around the bifurcation points as well as the upstream sediment supply.

The subsoil of the two bifurcation points (Waal-Pannerdens Kanaal and Nederrijn-IJssel) is quite similar. In both cases the top layer consists of fine to very fine gravel with a grain size varying from 2 to 7 mm (Fig. 10). The underlying material consists of a much smaller grain size of approximately 1 mm.

A possible consequence of local pavements of the riverbed is erosion further downstream where the top layer of the riverbed is finer-graded. The sediment input into the IJssel is low with respect to flow conditions ('supply limited transport'). The result is a paved riverbed at the bifurcation point. As a consequence of the strong erosive current, fine sediment in the middle IJssel is eroded from the main channel. There is a risk that during high discharges, (roughly speaking larger than 10,000 m^3/s) this pavement could break up, resulting in erosion of the finer material underneath and destabilization of the bifurcation point (see Bolwidt et al., 2006). Altogether, it is clear that due to the above-mentioned processes, the sediment distribution differs from the discharge distribution.

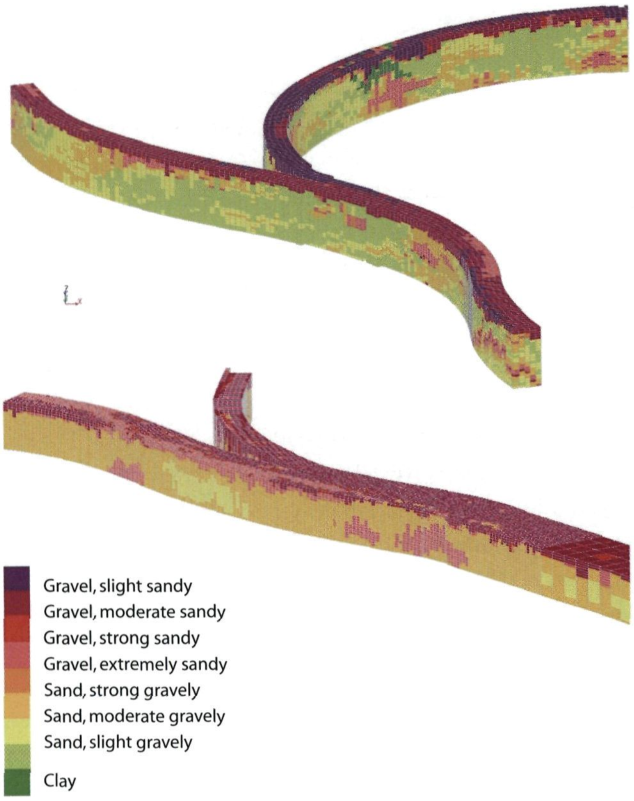

Fig. 10. Subsoil of the Nederrijn-IJssel bifurcation (top) and Waal-Pannerdens Kanaal bifurcation (below). The vertical depth is 5 metres, the horizontal reach is approximately 5 kilometres. Reproduced from Ten Brinke (2005).

The river Waal transports most of the sediment load. During high discharges 90% of the sediment load from the Bovenrijn is transported through the Waal branch (while this branch carries only about 67% of the Rhine discharge; Ten Brinke, 2005). From the remaining 10% about 60% is transported through the Nederrijn. The information is summarized in Fig. 11.

During periods of low discharges the weirs in the Nederrijn are closed, and hardly any sediment is transported through the Nederrijn. About 90% of the sediment load of the Pannerdens Kanaal is transported into the IJssel. In absolute loads, however, the sediment load is much smaller than during high discharges (Frings and Kleinhans, submitted).

The Pannerdens Kanaal suffers from similar problems as the IJssel does: there is also a supply limited transport. As a result, the sediment transport is less than might be expected from the discharge. The data visualized in Fig. 10 indicates that the sediment transport is supply-limited in the entire Pannerdens Kanaal. There is no fine sediment available in the downstream part of the Pannerdens Kanaal that can be transported. The conclusion is that almost the entire reach is more or less paved.

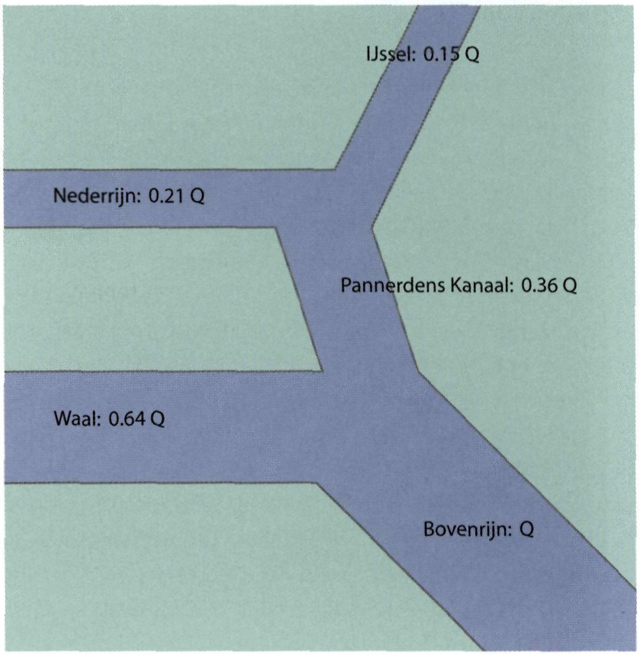

Fig. 11. Sediment distribution during high discharges. The numbers behind the branches refer to the ratio the different branches get of the sediment load that enters the Netherlands at Lobith. A very limited amount of sediment is retained in the Pannerdens Kanaal. After Ten Brinke et al. (2001).

Discussion

A word of caution in interpreting the hydraulic and morphological results around the bifurcation points is in place. It should be noted that the uncertainties in the calculated discharge distribution are substantial. The main components in the deviations from the intended distributions are the wind-direction, the conditions of the roughness of the main channel and the vegetation in the floodplain. A heavy north-eastern storm (wind speed approximately 25 m/s) can lead to an extra discharge of 200 m^3/s for the river Waal under extreme conditions, which is about 2 percent more than accounted for (Schropp, 2002). This may lead to an increase in water level of about 8 cm. The probability for this combined occurrence of events however, is very low. Also, the conditions of the main channel (more roughness after a period of relatively high discharge) can lead to a significant deviation of the intended distribution (Van Vuren, 2005). Finally, a source of uncertainty is the fact that the actual situation in the field differs from the one in the models. The model-situation often has a time-lag of at least three years compared to the field-situation. Apart from that, there will always be unaccounted situations (unexpected, temporarily elements in the flood-plains) which are not present in the models but do effect the water levels. The freeboard of the levees (with a minimum of 50 cm) is expected to take all the combined uncertainties into account.

Conclusion

Maintaining a fixed discharge ratio over the bifurcation points of the Dutch Rhine is very important. The height of the dikes of the branches is such that they should withstand the design discharge at Lobith (16,000 m^3/s), under the assumption that the discharge divides over the bifurcation points in a predefined ratio (see Table 1). Deviations of this ratio should stay within small limits because otherwise the risk of overtopping the dikes along one of the branches is present.

In the next decade, about 30 projects in and out of the floodplain will be carried out as part of the national program Room for the River. The projects in the neighborhood of the bifurcation point inevitably affect the discharge distribution. One way to maintain the discharge distribution during the construction phase (which starts roughly in 2008) is to carefully plan and organize the projects in time to compensate for negative effects. In practice, this seems hard to handle. In this paper, it is proposed that the discharge ratio can be controlled by constructing 'taps' in the vicinity of the two major bifurcation points in the form of flexible spillways. They should be constructed such, that they can be easily adapted to compensate for negative consequences of projects in or out of the floodplain. Calculations show that with the proper height of the spillways, the deviation of the discharge ratio with respect to the predefined ratio is within acceptable bounds. Adaptation of the construction is relatively easy to carry out and can thus be used to maintain the discharge ratio during the construction phase of the projects of Room for the River. The morphological consequences of the spillways are most probably small. On the other hand, a high discharge may destabilize the bifurcation points due to the fact that the pavement of the upper layer breaks up and fine material of the lower layer is released. A possible solution for this problem is difficult, although there are some ideas to armor the complete bed around the bifurcation points.

Autonomous bed degradation has a substantial effect on the discharge distribution. Hence, this should be stopped or minimized. One measure to achieve this is the present dredging policy where dredged shallows are dumped in the same river nearby. Flexible spillways might be able to correct a part of the alteration of the discharge distribution due to bed degradation by erosion. In this way the proper discharge distribution is maintained without too many extra measures while the morphological consequences are limited.

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