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Characteristics of side channels in the River Ain, France

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ABSTRACT: Side channels are popular methods to reduce flood levels or to increase the ecological value of rivers. Here we asses four side channels in the River Ain (France). In combination with 1D model simulations, we identify the characteristics and processes regarding the erosion and sedimentation patterns. The relative slope of the channels, the bifurcation angle, bend flow and bank erosion turn out to be important parameters for the identification of the processes.

1 INTRODUCTION

Side channels are a common feature within natural rivers and they tend to disappeared in European and North-American rivers due to river training. Anthropogenic adjustments led to several changes in the river planform. For example, the narrowing of the main channel in the Donau to increase the flow depth at base flow (Schiemer et al. 1999), the construction of hydrodams in European and North American rivers (Surian 1999), and gravel extraction which leads to the incision of the main channel (Surian 1999, Rodrigues et al. 2006). In general, the abandonment of side channels caused an increase of flood levels and a decrease of the habitat diversity. Nowadays, river managers use side channels to reduce the flood levels and to increase the ecological value of the river. Recently constructed side channels show unexpected erosion and aggradation, and therefore regular maintenance is required. To reduce the maintenance costs, a better understanding of the processes influencing the morphological evolution of the system is essential.

A side channel system can be subdivided into the following elements: the bifurcation, the confluence, the side channel and the main channel. The characteristics of each of these elements have a large influence on the evolution and stability of the side channel system. At a bifurcation local flow patterns, as shown in Figure 1, can cause flow separation both in the side channel and the main channel, resulting in the formation of bars (presented as shallow areas in Fig. 1). Due to the reduced flow width, the flow velocities in the rest of the channel increases resulting in scour and bank erosion next to these shallow areas. These local flow patterns can influence the sediment division

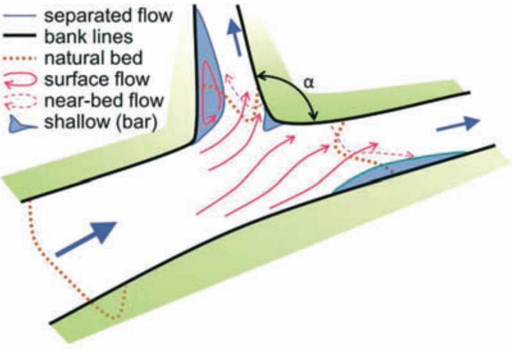

Figure 1. Flow patterns at a bifurcation (after Kleinhans et al. 2013).

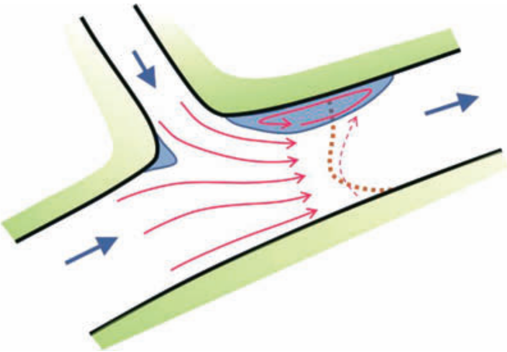

Figure 2. Flow patterns at a confluence (after Best 1987).

at the bifurcation. Other local characteristics which can influence the sediment division over the branches are the transverse bed slope effect and, if present, the effects of bend flow (Bolla Pittaluga et al. 2003, Kleinhans et al. 2008). At a confluence similar patterns occur (Fig. 2). Depending on the angle of the confluence, a flow circulation zone is formed in the downstream channel with the accompanying aggradation and, due to the reduction of the flow width, scour and bank erosion on the opposite side of the channel (Best 1987). The other two elements are the side channel and the main channel. In these channels the erosion and sedimentation processes depend on the discharge distribution which is related to the slope and the width of the channels and to the geometry of the bifurcation. If the side channel slope is larger than the main channel slope, this results in a relatively larger discharge in the side channel which may lead to erosion in the side channel. The morphological changes in these channels are governed by the backwater effect from the confluence and the discharge distribution at the bifurcation, but local variations in the geometry of the channels or vegetation can influence the evolution of the channels.

In this paper, we asses four side channel systems of the River Ain (France). These channels have been naturally formed due to the meandering of the river and the formation of bars. The main research question is: What are the driving processes and parameters in the side channel systems and how do these influence the long term evolution of the system? We study the parameters and processes that drive the evolution of the channels and try to reproduce their effects using a simple 1D numerical model.

2 CASE STUDY: RIVER AIN

The river Ain is a tributary of the Rhône in the southeast part of France. The river is about 185 km long and has an average annual discharge of 120 m^3/s (Dieras et al. 2013). Peak flow discharges are relatively high and the 2-year and 10-year flood are respectively 760 m^3/s and 1200 m^3/s. The sediment grain size varies between 15 and 46 mm (Rollet 2007) and the average annual sediment load is 60,000 m^3/yr (Olivier et al. 2009). The bed slope is estimated between $1.2{\cdot}10^{-3}$–$1.8{\cdot}10^{-3}$ (Piégay et al. 2002). In the past hundred years the river has changed from a braided pattern into a meandering river. The meandering resulted in a large shift of the main channel and the incision of new channels. Over the years this has led to multiple cutoffs in the river (Piégay et al. 2002). In the sections below we describe four side channel systems at three locations in the river. In each of the cases avulsion occurs which is the process by which the river relocates from its present main course to a secondary course.

2.1 *Reconnection of an old river branch (Case A)*

Figure 3 presents the evolution of a side channel system near the village of Mollon. In the aerial view of 2000 a river branch is visible on the west side of the main channel. This branch was closed due to the formation of bars and vegetation in the channel. From 1991 and onwards the bend in the east channel, as seen in the aerial views, migrated and lengthened the east channel and thereby decreased the channel slope. This created a difference in the slope between the west channel and the east channel which was the driving force for the switch of the main channel (Van Dijk et al. 2014) occurring after a flood in 2003 (Dieras et al. 2013). The west channel increased rapidly in size, which

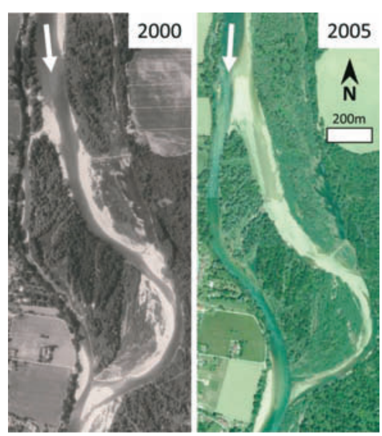

Figure 3. The evolution of a two channel system near Mollon (Case A) where the main channel switches due to a difference in channel slope. (IGN-France and Google earth).

was possible because the river banks were unstable (Piégay et al. 2002). After the switch of the main channel, the east channel aggraded gradually, which is likely caused by the difference in the slope between the channels and the bifurcation angle which is approximately 25°. The relatively small difference in slope corresponds to a gradual deceleration of the flow resulting in gradual aggradation of the channel. Due to the small bifurcation angle, flow separation (Fig. 1) did not occur and therefore a bar at the entrance of the east channel did not develop. After 2005 the aggradation of the east channel continued, which was enhanced by the smaller flow depth and the growth of vegetation.

2.2 *Side channel downstream of a river bend (Case B)*

Figure 4 shows the evolution of a river system where in 1968 a former branch of the river (see photo of 1954) is reconnected. A side channel system forms and avulsion occurs. In 1968 the channels have small difference in length and therefore the slope advantage is most likely small. However, the entrance of the side channel is located in an outer bend which means that due to the spiral flow in the river bend less sediment may have been transported into the side channel and relatively more sediment was diverted into the main channel. This is visible in the photo of 1970 where a bar migrates into the entrance of the main channel. In 1970 the side channel widens because of bank erosion. The main channel eventually closes due to large aggradation in the channel entrance.

2.3 *Bend cutoff (Case C)*

The evolution of Case C is shown in Figure 5. These photos are taken at the same location as the photos of Case B, but many years later. The aerial images show two cutoffs which occurred in the end of 2002 and the first half of 2005 (Dieras et al. 2013). The photo of 2005 was taken at the end of the year. The aerial view of 2000 shows that the river bend increases the length of this reach significantly. It is therefore expected that during floods a chute cutoff is formed and avulsion occurs. In the photo of 2000 shows a gully (hidden by vegetation) at a location where in 2002 a second channel (Channel 2) forms. During another flood in 2005 the bend is again cutoff and Channel 3 is created. We mainly focus on this second cutoff (Channel 2 and Channel 3). Channel 2 connects with Channel 3 with a bifurcation angle around 60° (Dieras et al. 2013). The angle is relatively large and therefore flow separation may have occurred. Moreover, Channel 2 is twice as long as Channel 3 and the slope is therefore smaller resulting in a small conveyance and a large deceleration of the flow at the entrance of the channel. Instead of the gradual aggradation, as presented in Case A, a bar is created at the entrance of the channel due to the large difference in slope in combination with the large bifurcation angle. This bar prevents further sedimentation of the secondary channels resulting in the formation of oxbow lakes (Channels 1 and 2). Channel 3 remains open and becomes the new main channel.

2.4 *Mid-channel bar (Case D)*

Further downstream a mid-channel bar forms around 1990 (Fig. 6). Over the years this bar grows and as shown in the photo of 2005, this bar creates a secondary channel. This secondary channel evolves into the main channel as shown in the photo of 2010. Based on Landsat 7 images from the Earth Explorer of USGS we expect the switch of the main channel to have occurred in 2008.

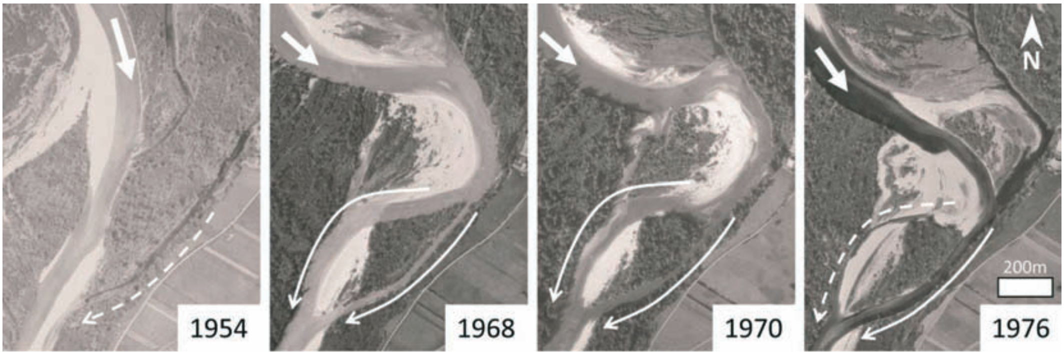

Figure 4. Side channel near Martinaz which is formed by an avulsion (Case B) is eroded because the bend upstream of the bifurcation diverts relatively less sediment into the channel. (IGN-France).

The secondary channel is shorter than the main channel and therefore it has a larger slope. However, the outflow of the secondary channel is located in the inner bend of the main channel and at this location the point bar of the river bend partially blocks the outflow as seen in the photos of 2002 and 2005. This reduces the discharge conveyance of the channel and therefore reduces the amount of erosion in the channel and of the bank. Over time the length of the main channel increases so the slope decreases, which causes an increase of the discharge in the secondary channel. In 2008 the secondary channel becomes the main channel. This switch is driven by the gradient advantage in the secondary channel and counteracted by the point bar. The images suggest that the evolution of the secondary channel could be hindered by limited bank erosion. However, this is unlikely since Piégay et al. (2002) described the banks as unstable and non-cohesive.

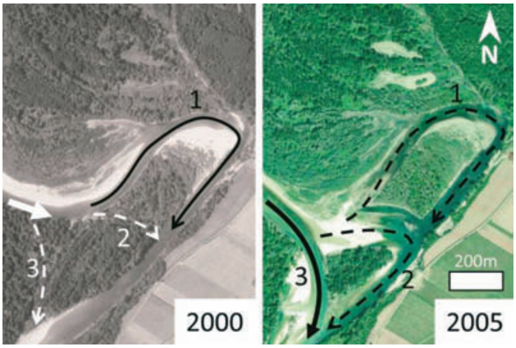

Figure 5. A river bend which was cutoff twice (Case C). The former river channels are blocked by large sedimentation at the entrance of the channel. (IGN-France and Google Earth).

2.5 *Synthesis*

The above description of the evolution of the side channels allow us to define the important parameters which influence the evolution of a side channel system.

1. The ratio of the slope of the side channel to the one of the main channel. The relative slope influences the discharge division at the bifurcation. If the slope is larger in the side channel than in the main channel, this can lead to a switch of the channels as seen in the presented cases (Van Dijk et al. 2014). The aggradation pattern in the closing channels is related to the relative slope. In Case A, and D, the difference in slope between the main channel and the side channel is small which results in gradual aggradation. However, in Case C the slope in the main channel is two times larger than in Channel 2 which causes a sudden deceleration in the channel and therefore local aggradation. In Case B, the difference of slope between the two channels is relatively small, but in this system the river bend likely influences the aggradation pattern.
2. The bifurcation angle. From previous research we know that if the bifurcation angle increases, the width of the flow separation zone increases (Constantine et al. 2010). The bifurcation angle of Case A is small (20°). This means that the flow separation zone is not present which prevents the formation of a plug bar and allows the channel to aggrade gradually. On the other hand, the bifurcation angle in Case C is much larger (60°) which most likely creates a flow separation zone at the entrance and in combination with the relatively small slope this results in a plug bar.
3. The effect of bend flow. Both Case B and D are affected by the presence of a river bend.

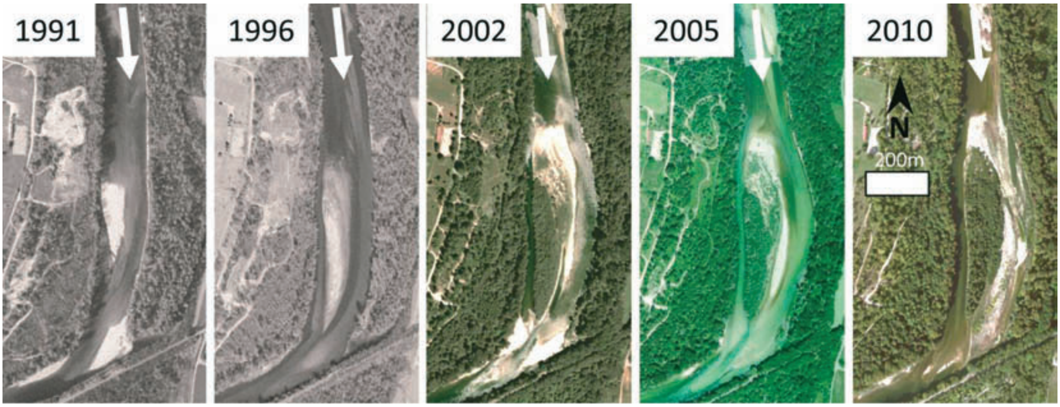

Figure 6. Formation of a bar in the main channel upstream of Pont de Chazey (Case D) which divides the flow in two channels. (IGN-France, Google Earth and Esri).

In Case B, the side channel is connected to the outer bend of the river. This means that although initially the main channel was wider, deeper and conveyed more discharge, the side channel receives relatively less sediment due to the spiral flow in the river bend (Kleinhans et al. 2008). This gives the side channel an advantage which results in a switch of the main channel. In Case D the outflow of the side channel is located in an inner bend and is therefore partially blocked by a point bar. This blockage probably slowed down the evolution of the system.

4. Bank erosion. In each of the cases bank erosion is an important process because it allows a secondary channel to widen and to become the main channel. In this river, bank erosion does not form a limitation in the evolution of the system.

3 MODEL DESCRIPTION

The case study presents four parameters which have a large influence on the evolution of the side channel system. A 1D morphodynamic model developed by Kleinhans et al. (2011) is used to reproduce the hypothesized influence of the characteristics on the morphological evolution of a side channel system. However, the included processes in the 1D numerical model are limited. The bend flow effect and the bank erosion are parametrized and the bifurcation angle is not taken into account. The effect of overbank flow and the formation of chute cutoffs are not included.

3.1 *Model approach*

The 1D morphodynamic model by Kleinhans et al. (2011) predicts the evolution of the bifurcation in the side channel system. In that model, the side channel system is schematized as one upstream reach, two parallel branches and one downstream reach. The model calculates the hydrodynamics as described by Parker (2004) and for the sediment transport, Engelund & Hansen (1967) is used. The length of the branches is constant, but the slope of the channel can change if, for example, the sediment supply in one of the channels increases. For the confluence and the bifurcation, an additional equation is required. For the confluence, a mass balance of the sediment transport upstream and downstream is sufficient, but for the bifurcation, a nodal point relation is required.

Wang (1995) proposes a relation in which the division of the sediment transport is related to the discharge and the width of the downstream branches. Bolla Pittaluga et al. (2003) included the effect of a transverse bed slope. Due to a difference in conveyance between the downstream branches, the bed level at the upstream location of the two branches is different and at the bifurcation this creates a transverse bed slope. This transverse bed slope creates a transverse sediment flux which affects the sediment division over the downstream branches. Kleinhans et al. (2008) extend the relation even further and add the effect of an upstream bend. The spiral flow in the bend adds a transverse sediment flux and the size of this flux is related to the bend radius divided by the channel width.

Bank erosion effects are parameterized by including an additional term in the Exner sediment conservation equation (Kleinhans et al. 2011). Each time step the model estimates the new equilibrium channel width as a function of the discharge using the following equation:

$$W = \gamma Q^{\beta} \tag{1}$$

where W is the equilibrium width of the channel, γ is a parameter related to the discharge and the width of the upstream branch, and β is a constant parameter which varies between 0.4 and 0.55 (Gupta et al. 2014). The calculated equilibrium width using Equation (1) is compared to the width of the previous step. A fraction of the difference between these widths is assumed to occur as bank erosion or deposition and this fraction depends on the stability of the banks. This fraction does not affect the equilibrium width of the channels, but the timescale of bank erosion. To conserve mass, the width changes are included in the Exner equation.

3.2 *Input parameters*

The 1D model needs the downstream water level and the upstream discharge as boundary conditions. We use the sediment transport relation of Engelund & Hansen (1967) which is calibrated on the yearly transport of 60,000 m^3/yr (Olivier et al. 2009) based on measured discharges and flow depths. In the model, the upstream boundary condition is defined by the bankfull discharge of the river, which is constant. A constant bankfull discharge gives an underestimation of the morphological timescale of the system. Therefore, an intermittency value is introduced (Parker 2004) which is calculated based on the yearly sediment transport of the river, in such a way that the morphological timescale in the model is comparable with the one in reality.

The downstream boundary condition is given by the equilibrium depth, and the roughness is calculated from discharge and flow depth measurements. The initial condition assumes an initial discharge division of 10% in the side channel and 90% in the main channel.

4 RESULTS

For each case in Section 3 numerical simulations are carried out to see if we can reproduce the influence of the different processes on the morphological evolution of the systems. In each simulation the length of the channels varies. The base case represents the solution based on the relation by Bolla Pittaluga et al. (2003) which therefore excludes the effects of a river bend and the effects of bank erosion.

4.1 *Slope and bank erosion effects in Case A*

The side channel as shown in Figure 3 is simulated with the 1D numerical model and the results are presented in Figure 7. The base case (Fig. 7-I) shows the evolution of the channels when the east channel (continuous line) is 200 m longer than the west channel (dotted line). The graph shows that over time more discharge is diverted into the west channel which corresponds to large erosion in this channel. However, bank erosion is not included in the base case which limits the conveyance of the west channel to 60%. When bank erosion is included (Fig. 7-II), the aggradation of the east channel is much slower than compared to the base case. This is caused by the relatively lower flow velocities in a shallow and wide channel compared to a deep and narrow channel which results in a smaller transport capacity. In the base case the switch of the main channel occurs after 15 years and in the case with bank erosion the switch occurs after more than 30 years. However, photos show that the west channel was reconnected upstream to the river around 1996 (Dieras et al. 2013). It is therefore expected that the switch of the course of the main channel occurs after about 7 years. Piégay et al. (2002) describe the river banks as unstable and this characteristic is included by increasing the fraction of the channel width change as explained in Section 3.1. Figure 7-III presents the results of the computation with increased bank erosion and it shows a main channel switch after 5 years which shows that the amount of bank erosion has a large influence on the timescale over which the main channel changes its course. Moreover, the graph shows that the discharge ratio after 30 years is larger than in the base case. In reality this difference is even larger due to the growth of vegetation in the right channel which accelerates and increases the aggradation in the channel.

4.2 *The effect of bank erosion and bend flow in Case B*

In Case B the secondary flow caused by the river bend is expected to have a large effect on the evolution of the side channel. The difference in length between the channels is small, but the width differences are large. In the base case, where the bend effect and bank erosion is ignored, the initial channel width forms a limitation to the bed level changes and the timescale over which the main channel changes its course is large. This is a result of the small difference in slope (Fig. 8-I). When the bend effect is included (Kleinhans et al. 2008), this gives an additional driving force for the avulsion causing the branch in the inner bend to aggrade and the branch in the outer bend to erode (Fig. 8-II). The width of the channels still forms a limitation and when bank erosion is included (Fig. 8-III) this leads to an even larger discharge difference between the two branches and an almost closure of the former main channel. It is therefore clear that the river bend has a large effect on the timescale of the morphological evolution and that the erodibility of the banks has an influence on the inequality of the discharges in an equilibrium situation.

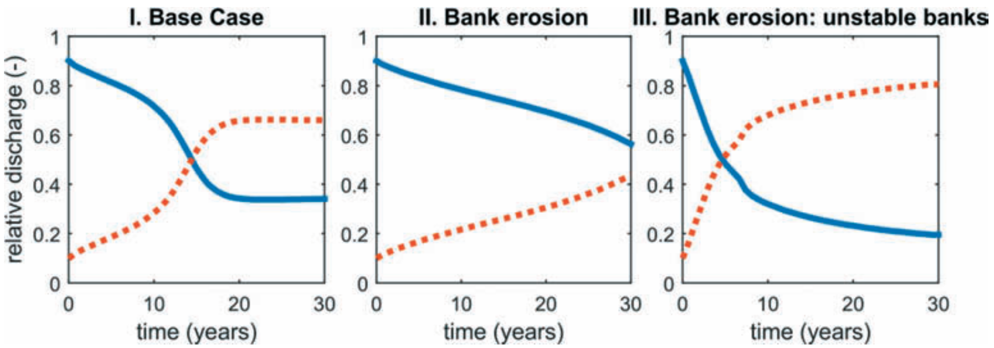

Figure 7. The variation of the discharge division in Case A where the dotted line is represented by the left channel and the continuous line by the right channel. The figures show that bank erosion has a large influence on the timescale of the morphological evolution and the size of the discharge inequality of the branches.

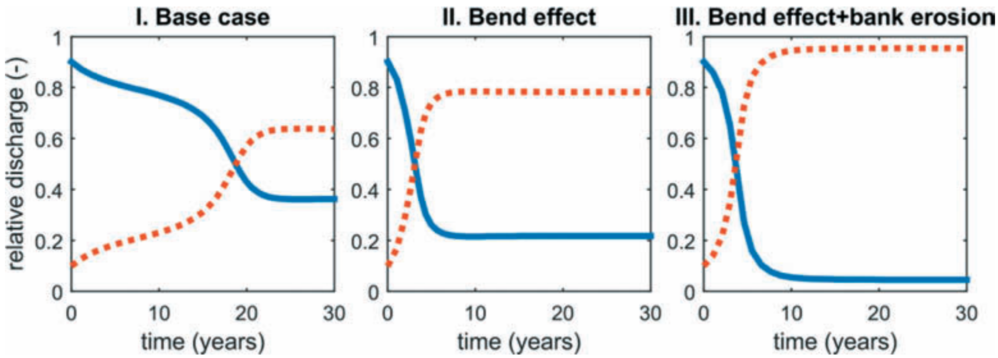

Figure 8. The variation of the discharge division in Case B with the dotted line as the new main channel and the continuous line as the former main channel. The figures show the large effect of a river bend and the influence of bank erosion.

4.3 *Large channel slope differences Case C*

Figure 9 shows the results were Channel 2 is the main channel and Channel 3 is just created (Fig. 5). The model does not take the cutoff processes into account and the simulation starts when Channel 2 and 3 are already created. Moreover, the model starts with an equilibrium bed profile and therefore does not take into account bed level variations which may have been created during a cutoff process. In Section 3 it was suggested that the bifurcation angle is likely to have an effect on the morphological evolution of the system, but this is not included in the 1D model. Channel 2 is twice as long as Channel 3 and therefore the slope of Channel 2 is much smaller leading to the closure of this channel. Figure 9 shows that the switch of the main channel occurs almost immediately, which is due to the large difference in slope. The relatively large slope in Channel 3 attracts a large amount of discharge leading to a narrow and deep channel for the base case, but the channel is still limited by the non-erodible banks. The differences between the branches become larger when bank erosion is included (Fig. 9-II). However, including bank erosion does not significantly change the results because of the large difference in slope between the two channels.

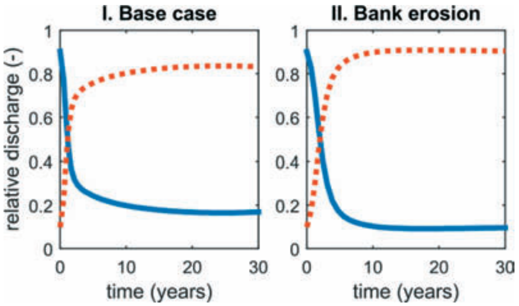

Figure 9. The variation of the discharge division in Case C. Due to the large differences in bed slope, the switch of the main channel occurs almost immediately.

4.4 *The evolution of the channels around a mid-channel bar Case D*

In Figure 6 it was shown that a mid-channel bar formed in the river. This bar divides the channel in a secondary and a main channel. The secondary channel is shorter and therefore steeper. It is expected that, due to the relatively larger slope, the discharge in this channel is larger and therefore causes a switch of the main channel. The model predicts this switch after 5 years, as shown in Figure 10-I. However, this does not correspond to the reality as presented in Figure 6. It is unlikely that bank erosion delays the switch with so many years since the banks are unstable, and therefore another effect is present. As mentioned in Section 2, the point bar at the confluence of the two channels likely decreases the conveyance of the secondary

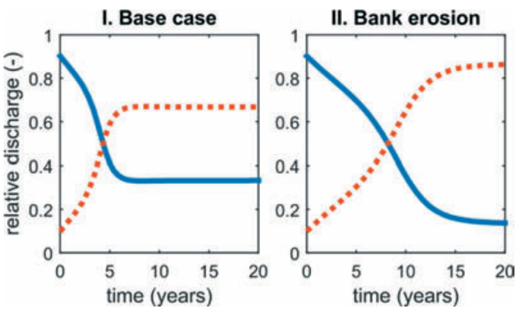

Figure 10. The discharge variation in the bifurcates of Case D. The steeper channel becomes the main channel and bank erosion delays the switch of the channels.

channel, but this effect is not included in the 1D numerical model.

5 DISCUSSION

In this paper we assess the main processes and characteristics of the side channels in the river Ain. The side channel systems in Case A and C were clearly created after a flood event. Due to overbank flow gullies were formed which later became chute cutoffs. In our analysis we assume that after the creation of the new channel, the bed is in equilibrium. Local variations of the bed are therefore not included and this could lead to differences in the morphological timescales of the system. During the cutoff process, erosion occurs in the downstream part of the new channel which migrates upstream. This upstream migrating erosion can cause a larger conveyance in the channel and therefore may reduce the duration of the avulsion.

In the channels where the slope is relatively small aggradation occurs which results in the closing of the branch. In Case A this aggradation is gradual and distributed over the whole channel. The photo of 2005 (Fig. 3) shows that the channel does not convey any discharge during base flow which allows vegetation to grow. During higher flow condition this vegetation increases the roughness of the channel, which increases the flow depth and decreases the flow velocities, and captures sediment enhancing the aggradation of the channel (Rodrigues et al. 2006). In Case C the growth of vegetation is expected to play a smaller role because the channel is blocked by the upstream plugbar and remains inundated.

The grain sizes in this area of the River Ain vary between 15 and 46 mm. Measurements of the sediment mobility in the river were done (Rollet 2007) and show that during bankfull discharge only smaller grainsizes (20 mm) are transported. During flood peaks of 650 m^3/s, which approaches a 2-year flood (760 m^3/s), all particles are mobile. This shows that during bankfull conditions armoring of the bed occurs and the sediment transport capacity might not be reached. The influence of the partial transport is not directly visible in the images, but likely has an effect on the morphological timescale of the system depending on the flow conditions. The 1D numerical model with the sediment transport relation of Engelund & Hansen (1967) does not take the immobility of the larger particles during lower discharges into account. To correct for this error we calibrated the transport relation on the average annual sediment load. However, it does mean that the model does not correctly reproduce the sediment transport during bankfull discharge. The effect of mixed sediment on the evolution of the side channel system and the incorporation of mixed sediment in an numerical model require therefore more attention.

The aerial and satellite images give useful insight into the morphological evolution of the side channel systems. The main limitation is the frequency of images. Due to the low frequency of the images, certain processes which occur just before or after an avulsion are not visible and are therefore excluded in this analysis.

6 CONCLUSIONS

From the analysis of the photographs it follows that the main parameter is the difference in the slope between the main channel and the side channel. This difference is the main driving force for an avulsion. If a river bend is present just upstream of the bifurcation, the secondary circulation can enhance or reduce the effect of the slope difference. The 1D numerical model is able to reproduce the effects of the slope difference and the river bend on the evolution of the side channel system. The model also shows that the amount of bank erosion can have a large effect on the morphological timescale of the system. From the photographs and from literature it follows that the bifurcation angle has a large influence on the closing mechanism of the secondary channel. A large bifurcation angle (Case C) can result in the formation of a plugbar which prevents the aggradation of the downstream part of the channel resulting in an oxbow lake. The influence of the bifurcation angle is not included in the numerical model.

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