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Bifurcation instability and chute cutoff development in meandering gravel-bed rivers

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ABSTRACT

Chute cutoffs reduce sinuosity of meandering rivers and potentially cause a transition from a single to a multiple channel river. The channel bifurcation of the main channel and the mouth of the incipient chute channel controls sediment and flow partitioning and development of the chute. Recent channel bifurcation models suggest that upstream bend radius, gradient advantage, inlet step, and upstream sediment supply at the bifurcation are important factors in the evolution of bifurcations. Our objective is to unravel the relative importance of these factors for chute cutoff success and development. We compare results from a morphodynamic three-dimensional (3D) model and a one-dimensional (1D) model with nodal-point relation with field observations of chute cutoffs in a meandering gravel-bed river. The balance between increased gradient advantage and flow curvature upstream of the chute channel bifurcation was systematically investigated with the 1D model. The 3D model runs and the field observations show the development of two types of chute cutoffs: a scroll-slough cutoff and a bend cutoff. The morphodynamic 3D model demonstrates that chutes are initiated when flow depth exceeds the floodplain elevation. Overbank flow and a significant gradient advantage result in a bend cutoff. The outcome of the 1D model shows that channel curvature at the bifurcation determines the success or failure of the chute cutoff when the chute channel is located at the inner bend, as in the case of scroll-slough cutoffs. We conclude that chute initiation depends on floodplain characteristics, i.e., floodplain elevation, sediment composition, and the presence of vegetation. Chute cutoff success or failure is determined by the dynamics just upstream of the channel bifurcation and location of the chute channel in the bend, which determines channel curvature and gradient advantage. These findings have ramifications for the prediction of chute cutoff in a wide range of rivers under natural and managed conditions and for the understanding of stratigraphy and architecture of deposits.

1. Introduction

River bifurcations are found in rivers across a large range of scales, from flow around a bar to a splitting river at the delta apex. River bifurcations are crucial elements in many rivers (Kleinhans et al., 2013): multithread anastomosing rivers (Kleinhans et al., 2012), chute cutoffs in meandering rivers (Grenfell et al., 2012), and braid bars in braided rivers (Ashmore, 1991; Federici and Paola, 2003; Zolezzi et al., 2009). Empirical classifications of channel patterns (Kleinhans and van den Berg, 2011) suggest a close association of chute cutoffs with meandering river styles at the transition to braiding. A *chute cutoff* develops by a shortcut over a point bar and is presently more difficult to predict than *a neck cutoff*, which occurs when two migrating bends intersect (Howard, 1996). Understanding the controls on chute cutoffs and the stability of the bifurcate meander bends may yield insight into the transition between braided and meandering rivers (e.g., Marston et al., 1995; Grenfell et al., 2012). Furthermore, the understanding of chute cutoffs is essential for understanding stratigraphy (McGowen and Garner, 1970). The process of chute cutoffs reduces the discharge through the main channel and as a result decreases outer bank erosion (Hooke, 2003; Kleinhans et al., 2011; Grenfell et al., 2014). Furthermore, chute cutoffs locally increase the sediment load causing deposition elsewhere, which affects navigation through the river (Zinger et al., 2011). Recently, significant progress was made in understanding the dynamics of chute cutoffs in field studies (Constantine et al., 2010b; Micheli and Larsen, 2011; Grenfell et al., 2012), while morphodynamic models have remained underemployed for this purpose (Howard, 1996; Zolezzi et al., 2012). Here we study the controlling factors for initiation and development of chute cutoffs based on field observations, a morphodynamic three-dimensional (3D) model, and a one-dimensional (1D) model with a nodal-point relation for the partitioning of flow and sediment.

Field studies described the initiation of chute cutoffs either by: headward incision of a channel that captures an increasing volume of the overbank flow (Gay et al., 1998; Zinger et al., 2011), extension downstream from an erosional embayment (Constantine et al., 2010b), or a

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combination of both processes (Kleinhans and van den Berg, 2011). Conceptually, distinguishing two types of chute cutoffs is useful: (i) scroll-slough cutoffs through sloughs on point bars (Fisk, 1947; Grenfell et al., 2012), or (ii) a bend cutoff across the point bar by incision. Sloughs form where inner-bank attachment of scroll bars is interrupted. Floods usually trigger chute cutoff, which requires high water levels and high rates of bed load transport unlike neck cutoff (Lewis and Lewin, 1983; Howard, 1996; Ghinassi, 2011; Zinger et al., 2011). Following a successful chute cutoff, the reduced sediment transport capacity in the abandoned branch is smaller than the supply that leads to closure by a sandy plug bar (Constantine et al., 2010a; van Dijk et al., 2012). Later, the residual channel is slowly filled by overbank flow and deposition of fine material (Toonen et al., 2012; Dieras et al., 2013).

Bifurcation development is determined by the division of water and sediment to the downstream branches in relation to their conveyance and transport capacity (Wang et al., 1995; Bolla Pittaluga et al., 2003; Hardy et al., 2011). The division of water and sediment between both branches can change over time as a result of change of the downstream branches, for example channel widening (Miori et al., 2006) or lengthening. Also, conditions in the upstream channel affect the partitioning: particularly helical flow because of curvature, presence of bars (Kleinhans et al., 2011), and inlet steps (Bertoldi et al., 2009) that cause gravity-driven sediment deflection on the transversely sloping bed (Bolla Pittaluga et al., 2003; Kleinhans et al., 2008). When sediment input into the downstream branches, determined by the partitioning at the bifurcation, differs from sediment transport capacity in the downstream branches, determined by the downstream conditions, then one of the branches will close (Constantine et al., 2010a; Kleinhans et al., 2011). The division of discharge and sediment at the bifurcation is described in several nodal point relations (e.g., (Wang et al., 1995; Bolla Pittaluga et al., 2003; Kleinhans et al., 2008)). Bifurcation asymmetry is determined by the inlet steps, i.e., bed level difference between both branches at the upstream branch (Bertoldi et al., 2009) and gradient advantage of one downstream branch. The transverse bed slope and curvature-driven helical flow — related to bend radius — have a significant effect on the division of bedload sediment between both branches in meandering rivers (Kleinhans et al., 2008). This suggests that chute cutoff processes may also be affected by upstream channel curvature.

The rate of channel closure depends on the bifurcation angle between the chute and main branch (Constantine et al., 2010a). A large bifurcation angle leads to rapid decrease of the channel width of the former main branch. However, van der Mark and Mosselman (2013) showed that the bifurcation angle seems not to affect the sediment division significantly. The problem is that a bifurcation angle may appear as sharp at the scale of maps or aerial photography. Indeed for very sharp corners a bifurcation angle may be indicative of highly 3D situations with flow separation (Constantine et al., 2010a; Blanckaert, 2011), but when flow is more gently curved the bifurcation is more appropriately described by curvature as a proxy for helical flow structure and its effects on sediment transport (Kleinhans et al., 2013; van der Mark and Mosselman, 2013).Here we show that the closure rate is predictable from relative bend radius and the normalized chute channel length.

The objective of this paper is to assess the effects of upstream channel curvature, gradient advantage, inlet steps, and sediment load division on bifurcation initiation and development of chute cutoffs. Here we used morphodynamic modelling (Delft3D) of a dynamic meandering gravel-bed river that exhibits chute cutoffs to quantify the necessary conditions for chute cutoffs. We also use the 1D model of Kleinhans et al. (2011) to systematically explore in a large number of runs the combined effects of upstream channel curvature and gradient advantage across the potential cutoff channel. We compare the 3D model results with field observations, experiments, and the 1D-nodal-point model (described in (Kleinhans et al., 2011)). The idealized model setup was inspired by the River Allier, which is a meandering gravel-bed river dominated by chute cutoffs, and by our scale experiments (van Dijk et al., 2012).

Table 1
Flood occurrence Allier at Chatel-de-Neuvre for 1986–2012.

Recurrence interval (y)	Discharge (m^3/s)
2	620
5	880
10	1100
20	1200

2. Recent history of channel planform dynamics

The River Allier upstream of the city of Moulins (France) is a dynamic meandering gravel-bed river with chute cutoffs on the transition from scroll bar and neck cutoff-dominated meandering rivers to weakly braided rivers (river nr. 112 in the data set in Kleinhans and van den Berg (2011), see their Fig. 13). Here the maximum reach-averaged sinuosity is 1.5 with bend migration rates up to 60 m/y. The River Allier flows in a valley with a gradient of 3.3 m/km and is a tributary of the River Loire in central France (46°29′53″N., 3°19′38″E.). It is a rain-fed river with a flashy hydrograph and a mean annual discharge of 140 m^3/s and mean annual flood discharge of 500 m^3/s. Table 1 indicates the flood frequency that is based on data collected between 1986 and 2012.

Bend migration and chute cutoffs perpetually changed the meander planform. The River Allier became temporarily weakly braided after a bridge was built and a high flood peak led to cutoffs of several channel bends in 1980 (Fig. 13 in (Kleinhans and van den Berg, 2011)). The event with multiple simultaneous chute cutoffs occurred once, whereas single-bend cutoffs occurred frequently. Gradient advantage for these cutoffs varied (Table 2, 1–4). For example, the current channel and remnants of former channels shown in Fig. 1 at Tilly were formed because of several flood events in 1994, 2003, and 2008, which all led to single-bend cutoffs. Here, the chute channel was more than twice as short as the main meander channel (Table 2, 5–7). After cutoffs, new meander bends developed and increased the sinuosity of the river.

Successive site visits between 2003 and 2011 showed the development of a chute cutoff on a nonvegetated point bar at a bend near Château de Lys (Fig. 2A). The chute cutoff was initiated in 2004 (Fig. 2B) and remained open for a few years (2009; Fig. 2C). Initially, the chute cutoff developed through a scroll-slough. Later, the chute channel disappeared (2011; Fig. 2D) and observations suggested that two different mechanisms could affect the development of the cutoff. First, migration of the channel upstream led to closure of the chute channel with a plug bar upstream as the inner-bend chute channel received more sediment. Second, high lateral migration rate of the chute channel led to a merge with the outer main channel. Aerial photographs showed that the same bend studied in this paper had multiple scroll-slough cutoffs between 1990 and 2002 as the upstream bend continuously migrated in downstream direction (Table 2, 8–10). Currently, a

Table 2
Chute cutoffs observed from aerial images between 1980 and 2008 in the River Allier: chute cutoffs related to a multiple bend cutoff event in 1980 (1–4), bend cutoffs (5–7), and scroll-slough cutoffs (8–10).

Number	Location	Year	Channel length		Advantage
			Chute (m)	Meander (m)	
1	Chemilly	1980	842	1177	1:1.4
2	Château de Lys	1980	924	1261	1:1.4
3	Le Vizier	1980	1101	1834	1:1.7
4	Bressolles	1980	1062	2082	1:2.0
5	Tilly	1994	551	1769	1:3.2
6	Tilly	2003	801	1847	1:2.3
7	Tilly	2008	890	1653	1:1.9
8	Château de Lys	1994	699	811	1:1.2
9	Château de Lys	2002	454	525	1:1.2
10	Château de Lys	2004	724	1014	1:1.4