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Mediative adjustment of river dynamics: The role of chute channels in tropical sand-bed meandering rivers

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ABSTRACT

This paper examines processes of chute channel formation in four tropical sand-bed meandering rivers; the Strickland and Ok Tedi in Papua New Guinea, the Beni in Bolivia, and the lower Paraguay on the Paraguay/Argentina border. Empirical planform analyses highlight an association between meander bend widening and chute initiation that is consistent with recent physics-based modelling work. GIS analyses indicate that bend widening may be driven by a variety of mechanisms, including scour and cutbank bench formation at sharply-curving bends, point bar erosion due to cutbank impingement against cohesive terrace material, rapid cutbank erosion at rapidly extending bends, and spontaneous mid-channel bar formation. Chute channel initiation is observed to be predominantly associated with two of these widening mechanisms; i) an imbalance between cutbank erosion and point bar deposition associated with rapid bend extension, and ii) bank erosion forced by spontaneous mid-channel bar development. The work extends previous empirical analyses, which highlighted the role of bend extension (elongation) in driving chute initiation, with the observation that the frequency of chute initiation increases once bend extension rates and/or widening ratios exceed a reach-scale threshold. A temporal pattern of increased chute initiation frequency on the Ok Tedi, in response to channel steepening and mid-channel bar development following the addition of mine tailings, mirrors the inter- and intra-reach spatial patterns of chute initiation frequency on the Paraguay, Strickland and Beni Rivers, where increased stream power and sediment load are associated with increased bend extension and chute initiation rates. The process of chute formation is shown to be rate-dependent, and the threshold values of bend extension and widening ratio for chute initiation are shown to scale with measures of river energy, reminiscent of slope–ratio thresholds in river avulsion. Furthermore, Delft3D simulations suggest that chute formation can exert negative feedback on shear stress and bank erosion in the adjacent mainstem bifurcate, such that the process of chute formation may also be rate-limiting. Chute formation is activated iteratively in space and time in response to changes in river energy (and sediment load), predominantly affecting sites of rapid channel elongation, and thereby mediating the river response.

1. Introduction

Meandering rivers are characterised by an interplay between processes that operate to increase channel length (the development and elongation of meander bends), and processes of bend cutoff (Stølum, 1996; Camporeale et al., 2005, 2008; Constantine and Dunne, 2008; Frascati and Lanzoni, 2009). These processes are driven in part by the hydraulics of river energy transfer, and in part by the mass–energy interactions that characterise bar development (Dunne et al., 2010; Zolezzi et al., 2012). Such interactions are complex; they may arise autogenically or be driven by external forcing (Nanson and Huang, 2008; Phillips, 2010), and disentangling the various drivers remains a key challenge in understanding how rivers 'come to be different', and how they are influenced by environmental change (Lewin and Brewer, 2001, 2003; Kleinhans, 2010; Ashworth and Lewin, 2012).

Most studies of long-term meandering dynamics have considered only the role of neck cutoff, which is to: i) reduce planform geometrical complexity driven by fluid dynamic processes; and ii) generate an intermittent noise that may influence the spatiotemporal dynamics of long river reaches (Camporeale et al., 2008; Frascati and Lanzoni, 2009). A consequence of (i) is that meandering river sinuosity tends to stabilise within relatively narrow limits of an average value reflecting the nature of interplay between reach elongation and bend cutoff (Stølum, 1996; Camporeale et al., 2005; Constantine and Dunne, 2008). The role of chute initiation and chute cutoff in meandering dynamics is less clear (see Hooke, 2007). Chute cutoff is considered to limit channel sinuosity (Howard, 1996), but since chute cutoff less efficiently reduces channel length than does neck

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cutoff, rivers dominated by chute cutoff must be subject to a high cutoff rate for the average value of sinuosity to be maintained (Constantine and Dunne, 2008).

Common to many analyses of the role of bend cutoff in meandering rivers is the use of sinuosity as a single metric describing the dynamical state of the system. Sinuosity is certainly a useful metric, as it relates directly to channel slope and stream power. However, the focus on sinuosity is severely restrictive in that it ignores other mechanisms by which energy may be mediated in alluvial channel environments, such as bar formation and dissection (Huang and Nanson, 2007; Phillips, 2010), or changes in channel width (Harmar and Clifford, 2006; Luchi et al., 2010). Coupled with neglect of the process of chute cutoff (except in the case of Constantine and Dunne, 2008), a focus on sinuosity essentially restricts the relevance of these analyses to a single class of planform pattern (this is acknowledged by Stølum, 1998); low energy meandering rivers that migrate slowly and are dominated by neck cutoff (see Kleinhans and van den Berg, 2011).

The rivers considered in this study display a planform pattern that is transitional between single-thread meandering and braided, driven primarily by chute channel dynamics (e.g. Grenfell et al., 2012; Fig. 1; see also Ferguson, 1987; Kleinhans and van den Berg, 2011, for a discussion of related transitional patterning processes). They are part of a class of 'large' rivers that has been little researched (sand-bed meandering), the largest example of which in terms of discharge would be the Mississippi River in the USA (Latrubesse, 2008). In addition, the rivers considered in this study are all located in tropical environments, which remain enigmatic in comparison with their temperate counterparts (Latrubesse et al., 2005).

Rivers larger than the Lower Mississippi ('mega-rivers', mean annual discharge > 17 000 $m^3 s^{-1}$) tend to develop anabranching patterns, and do not fit within empirical channel pattern continua based on stream power (Latrubesse, 2008; Kleinhans and van den Berg, 2011; Nicholas, 2013). In contrast, the rivers considered in this study display a morphology and behaviour that is at least partly decipherable from the perspective of stream power-based classifications (Kleinhans and van den Berg, 2011; Grenfell et al., 2012); i) they migrate actively across alluvial floodplains, and have prominently-scrolled floodplain surfaces (see Fig. 1 and supporting KML files), and ii) they display a variable tendency toward chute initiation, and a variable tendency to form stable islands at meander bends (Grenfell et al., 2012). This paper revisits and extends the analysis of Grenfell et al. (2012) to consider controls on the spatial and temporal variation in chute formation in greater detail, with a view to understanding drivers of morphological change in tropical meandering rivers, and the nature of feedback processes that mediate the effects of change.

2. Chute channel dynamics and channel planform transitions

2.1. Spatial analysis of chute channel dynamics

Using automated and reproducible ArcInfo GIS utilities, planform attributes were quantified for 213 meander bends on sand-bed reaches of three tropical meandering rivers; the Strickland in Papua New Guinea, the lower Paraguay on the Paraguay/Argentina border, and the Beni in Bolivia (Grenfell et al., 2012). The history of chute initiation and infilling was tracked at each bend over an ~40 year image record, and binary logistic regression analysis was used to determine whether chute channel initiation was statistically more probable at bends with particular planform characteristics (e.g. curvature or sinuosity) or dynamics (e.g. rate of migration in the direction of the valley axis trend, defined as translation, versus rate of migration perpendicular to the valley axis trend, defined as extension, Fig. 2). The only statistically significant predictor of chute initiation at a bend was the average rate of bend extension, accounting for 30–60% of the variation in the data for each river ($p < .01$). An increase in the rate of bend extension significantly increased the probability of chute initiation at a bend.

Grenfell et al. (2012) considered several reasons why the rate of bend extension was important to chute initiation. First, rapid extension is associated with bend apex widening, where cutbank erosion outpaces point bar deposition (Brice, 1975). This leads to wide scroll bar spacing (Hickin and Nanson, 1975), and alignment of intervening sloughs that favours flow across a developing point bar. Second, the formation of widely-spaced sloughs breaks the continuity of vegetation encroachment on point bars, which easily keeps pace with and even promotes point bar deposition where migration is slow. In addition, the island that forms between chute and mainstem bifurcates is rapidly colonised and stabilised by robust grasses (e.g. *Phragmites karka* in Papua New Guinea), and this focuses scour in the adjacent chute. Third, through ongoing extension following chute formation, the chute adopts an axial location within the bend (mid-bend, cf. Lewis and Lewin, 1983) such that the alignment of upstream flow favours the mainstem bifurcate. In addition, ongoing extension increases the chute-mainstem bifurcation angle and chute gradient advantage, such that chutes at extending bends are kept open through 'quasi-balance' by factors that interact to limit bedload influx and increase chute competence (Kleinhans et al., 2008).

Allmendinger et al. (2005) showed that temperate channels with forested banks tend to be wider than those with grassed banks, and framed their interpretation of these width differences in terms of the effect of vegetation on the balance between cutbank erosion and point bar deposition. They observed differences in both bank erosion

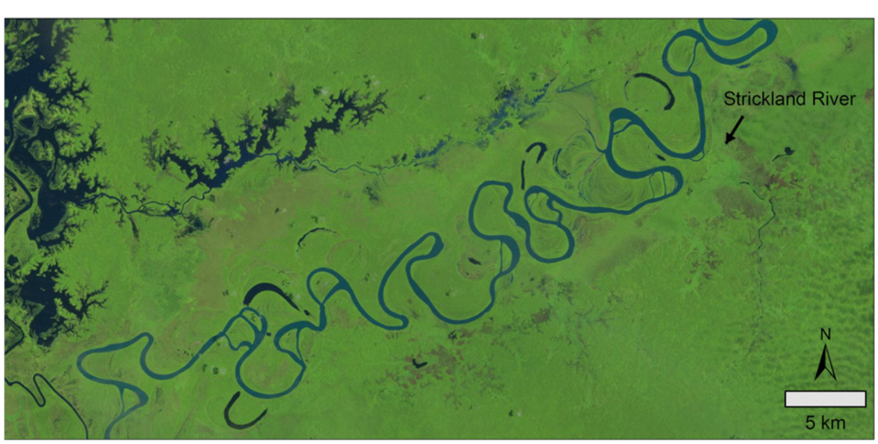

Fig. 1. A sand-bed reach of the Strickland River in Papua New Guinea. Rapid bend extension here leads to wide scroll-slough spacing and associated initiation of chute channels, resulting in a planform dynamic and pattern that is transitional between single-thread meandering and braided (see Grenfell et al., 2012).