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Timescales, mechanisms, and controls of incisional avulsions in floodplain wetlands: Insights from the Tshwane River, semiarid South Africa

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ABSTRACT

Avulsion (relocation of a river course to a new position) typically is assumed to occur more frequently in rivers with faster sedimentation rates, yet supporting field data are limited and the influence of sedimentation rate on avulsion style remains unclear. Using analysis of historical aerial photographs, optically stimulated luminescence dating of fluvial sediments, and field observations, we document three avulsions that have occurred in the last 650 years along the lower reaches of the semiarid Tshwane River in northern South Africa. Study of the modern river and abandoned reaches reveals that a downstream decrease in discharge and stream power leads to reduced channel size and declining sediment transport capacity. Bank erosion drives an increase in channel sinuosity, leading to a decline in local channel slope, and to a further decrease in discharge and sediment transport. Local sedimentation rates >10 mm a^{-1} occur within and adjacent to the channel, so over time levees and an alluvial ridge develop. The resulting increase in cross-floodplain gradient primes a reach for avulsion by promoting erosion of a new channel on the floodplain, which enlarges and extends by knickpoint retreat during periods of overbank flow. Ultimately, the new channel diverts the discharge and bedload sediment from the older, topographically higher channel, which is then abandoned. Our findings support the assumption that avulsion frequency and sedimentation rate are positively correlated, and we demonstrate that incisional avulsions can occur in settings with relatively rapid net vertical aggradation. The late Holocene avulsions on the semiarid Tshwane River have been driven by intrinsic (autogenic) processes during meander belt development, but comparison with the avulsion chronology along a river in subhumid South Africa highlights the need for additional investigations into the influence of hydroclimatic setting on the propensity for avulsion.

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1. Introduction

Avulsion is the shift of a river course to a new position on a floodplain or delta and is a key process by which many rivers form new channels and adjust laterally (Smith et al., 1989; Slingerland and Smith, 2004; Stouthamer and Berendsen, 2007; Phillips, 2011). Following avulsion, the original channel may be abandoned or it may continue to operate alongside the new channel as a distributary or anabranch. Avulsions have significant implications for the lateral redistribution of water, sediment, and nutrients and thus are a key influence on floodplain and delta geomorphology, sedimentology, and ecology (Makaske et al., 2002, 2012; Slingerland and Smith, 2004; Tooth et al., 2007; Phillips, 2012; Ralph et al., 2016). Avulsions also affect human land use and settlement in these environments, as shown by various archaeological investigations in Holocene palaeoenvironments (e.g., Morozova, 2005; Macklin and Lewin, 2015).

Despite the importance of avulsion along many rivers, the controls on the frequency and style of avulsion remain unclear. Avulsion frequency and vertical sedimentation rate are commonly assumed to be positively correlated so that avulsions occur only infrequently on slowly aggrading rivers but more frequently on rapidly aggrading rivers (Bridge and Leeder, 1979; Bryant et al., 1995; Mackey and Bridge, 1995; Schumm et al., 1996; Slingerland and Smith, 1998; Jerolmack and Mohrig, 2007; Stouthamer and Berendsen, 2007; Hajek and Wolinsky, 2012; Hajek and Edmonds, 2014). This reflects the fact that

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most sedimentation occurs within or near the channel, forming levees and/or alluvial ridges. These topographic features increase cross-floodplain gradient, promoting overbank flow away from the channel and providing a slope advantage for new channels forming through floodplain scour (Brizga and Finlayson, 1990; Jones and Schumm, 1999). While an assumption of a positive correlation between avulsion frequency and vertical sedimentation rate is thus physically reasonable, well-constrained field data are lacking to quantify the relationship more precisely over Holocene and longer timescales (Tooth et al., 2007; Phillips, 2009, 2012; Donselaar et al., 2013).

The relationships between avulsion style and sedimentation rate are less clear. Nevertheless, at least two of the three main avulsion styles, defined by Slingerland and Smith (2004) as progradational, incisional, and reoccupational (also termed 'avulsion by annexation') are commonly associated with different sedimentation rates (Table 1).

Irrespective of the frequency and style of avulsion, previous studies have shown that for avulsion to occur the river must be near an avulsion threshold and that the final trigger is typically a large flood or closely spaced series of floods (Jones and Schumm, 1999). A variety of local physiographic and climatic factors can influence the timing and patterns of flooding, as well as the locations of newly avulsing channels. These include decreases in floodplain confinement (Tooth, 1999, 2005), ice jams (Smith and Pearce, 2002), vegetation encroachment or debris blockages such as log jams (Ralph and Hesse, 2010; Phillips, 2012), beaver dams (Polvi and Wohl, 2013), hippopotami trails (McCarthy et al., 1992; Ellery et al., 2003; Tooth et al., 2007), and substrate composition (Aslan et al., 2005).

Most previous studies of avulsion have focused on humid rivers in tropical or temperate regions and, despite some notable exceptions (Smith et al., 1997; Judd et al., 2007; Tooth et al., 2007; Donselaar et al., 2013; Li et al., 2014; Li and Bristow, 2015; Ralph et al., 2016), fewer studies of avulsion have focused on dryland rivers. In particular, while some dryland rivers are associated with extensive floodplain wetlands that in part owe their formation to avulsive redistributions of water and sediment, well-constrained field data necessary to define the relationships between sedimentation rate, avulsion frequency, and avulsion style remain limited (Tooth et al., 2007). To clarify these relationships, this study develops a chronology of floodplain sedimentation and avulsion for the lower reaches of the Tshwane River, located in the upper Limpopo River catchment in semiarid, northern South Africa (Fig. 1A). The aims of this study are to: (i) combine analysis of aerial photography with optically stimulated luminescence (OSL) dating to determine the spatial pattern and chronology of avulsions; (ii) assess whether avulsion frequency and sedimentation rates are positively correlated; (iii) evaluate the influence of sedimentation rates on avulsion style; and (iv) discuss the relative importance of intrinsic (e.g., flow-sediment dynamics) and extrinsic (e.g., hydroclimatic) factors in controlling avulsion.

2. Regional setting

The geology of the upper Tshwane River catchment comprises mainly Pretoria Group shales and quartzites and Bushveld Complex granites. The middle and lower catchment comprises mainly sandstones, mudstones, and shales of the Karoo Supergroup (Ecca and Irrigasie formations) but outcrop is limited. The Tshwane headwaters arise in the Magaliesberg at ~1470 masl, and the river flows north toward the Pienaars River (Fig. 1B). Slope, discharge, and stream power decrease downstream; and the channel becomes less confined, smaller, and more sinuous as it traverses extensive (1–2 km wide) floodplain wetlands (Larkin et al., 2017; see Table A.1). In the lower reaches, the Tshwane River is characterised by a prominently leveed, single-thread, meandering channel of variable sinuosity and is flanked by numerous oxbows, palaeochannels 1–5 km long, and backswamps (Figs. 1C and 2A). Near the diffuse confluence with the Tshwane, the Pienaars River displays similar characteristics (Fig. 1C). The Tshwane-Pienaars floodplain wetlands remain in a near-natural condition, with human influences restricted to some subsistence grazing on the floodplain. Collectively, the floodplain wetlands cover ~55 km^2, and their geomorphology indicates that river avulsion has been a key process in their development. Other than the study by Larkin et al. (2017), the rivers and floodplain wetlands have not been subject to previous detailed investigations, with avulsion chronologies remaining unknown.

Rainfall in the study area is strongly seasonal with distinct wet (November through March) and dry (April through October) seasons. Mean annual precipitation in the Tshwane catchment is ~585 mm, falling mostly during convective thunderstorms, while mean annual potential evaporation is ~1750 mm (Working for Wetlands, 2008; Gauteng Department of Agricultural and Rural Development, 2011). Flow in the Tshwane River is perennial but strongly seasonal, with high wet season flows (>60 m^3 s^{-1}) and low dry season flows (<4 m^3 s^{-1}; Department of Water Affairs Hydrological Services, 2015). During the wet season, the Tshwane River floodplain is inundated regularly, but during the dry season, low flows are confined to the main channel, while oxbows, palaeochannels, and backswamps gradually desiccate. The lower Tshwane River transports a mixed load of slightly gravelly sand, silt, and clay, but there are no sediment transport measurements. The floodplain surface is comprised mainly of clay, with sandier sediment restricted to active channel beds and levees. Palaeochannels have been infilled to varying degrees by clastic and organic sediment but typically are preserved as <1.5-m-deep depressions with minor levees.

3. Methods

Historical aerial photograph analysis and OSL dating was used to determine the spatial pattern and chronology of avulsions. Aerial photographs at 1:32,000 and 1:36,000 scale from 1950, 1972, 2005, and

Table 1
Summary of the three main avulsion styles.
(after Slingerland and Smith, 2004)

Avulsion style	Process of new channel formation	Relationship with sedimentation rate	Examples	References
Progradational	Overbank flows form large crevasse splays, in which a channel network develops and extends downstream, eventually forming a new channel	Most commonly associated with relatively rapid vertical sedimentation rates (>1 mm^{-1})	Cumberland Marshes and upper Columbia River, Canada Rhine-Meuse Delta, Netherlands Baghmati River, India Pantanal, Brazil	Smith et al. (1989); Morozova and Smith (2000); Stouthamer and Berendsen (2000, 2001); Makaske et al. (2002, 2012); Jain and Sinha (2004); Assine (2005)
Incisional	Overbank flows returning to a channel erode a knickpoint that retreats upstream and forms a new channel once it reconnects with the original channel	Most commonly associated with relatively slow vertical sedimentation rates (<1 mm^{-1})	Cooper Creek, Australia Klip River, South Africa	Knighton and Nanson (1993); Gibling et al. (1998); Tooth et al. (2007)
Reoccupational	Reoccupation and reworking of an abandoned channel on the floodplain	Associated with slow and rapid vertical sedimentation rates	Lower Mississippi River, Nueces River, and Trinity River, USA	Aslan and Blum (1999); Aslan et al. (2005); Phillips (2009)

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