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Longitudinal variability in hydraulic geometry and substrate characteristics of a Great Plains sand-bed river

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ABSTRACT

Downstream trends in hydraulic geometry and substrate characteristics were investigated along a 200 km reach of the Ninnescah River in south central Kansas, USA. The Ninnescah River is a large sand-bed, perennial, braided river located in the Central Plains physiographic province and is a tributary of the Arkansas River. Hydraulic geometry characteristics were measured at eleven reaches and included slope, sinuosity, bankfull channel width, and bankfull channel depth. Results indicated that the Ninnescah River followed a predicted trend of decreasing slope and increasing depth and width downstream. There were localized divergences in the central tendency, most notability downstream of a substantial tributary that is impounded and at the end of the surveying reach where the Ninnescah River approaches the Arkansas River. Surface grain-size samples were taken from the top 10 cm of the bed at five points across the wetted cross-section within each of the 11 reaches. Sediment analyses demonstrated a significant trend in downstream fining of surface grain-sizes (D_{90} and D_{50}) but unlike previous studies of sand-bedded rivers we observed coarsening of substrates downstream of the major tributary confluence. We propose that the overall low discharge from the tributary was the primary reason for coarsening of the bed downstream of the tributary. Results of this study provide valuable baseline information that can provide insight in to how Great Plains sand-bed systems may be conserved, managed, and restored in the future.

1. Introduction

The hydrology and geomorphology of alluvial river channels are dependent upon the climatic and sedimentological regimes of contributing basins. Longitudinal profiles of rivers are representative of watershed evolution, geologic structure, and sedimentary dynamics of the basin (Sinha and Parker, 1996). Leopold and Maddock (1953) were the first to use the term 'hydraulic geometry', which is based on the assumption that the geometric and hydraulic properties of a river adjust in response to increasing discharge. As was originally proposed with the theory of hydraulic geometry, with increasing discharge there is expected to be a regular downstream trend that develops in channel characteristics, including width, depth, velocity, and friction of river channels formed in alluvium and readily adjustable to changes in discharge. At a single cross-section, changes in hydraulic geometry are a result of many processes that occur at different time scales and different flows (Schumm and Lichty, 1963; Wolman and Gerson, 1978; Moody et al., 1999). The geomorphic parameters driving the longitudinal patterns of hydraulic geometry include alternating degrees of channel confinement, tributary inputs, colluvial inputs (e.g. landslides), differential substrate erodibility, strong local controls on sediment supply, and spatial gradients and discontinuities imposed by Quaternary tectonics and landscape evolution (Marston et al., 1997; Brardinoni and Hassan, 2007). Longitudinal changes in hydrologic regime can also drive discontinuity as, for example, a river may flow from a mesic to an arid climate zone and become an influent river. Empirically, it has been demonstrated that hydraulic geometry partially depends on bank strength, which is influenced by the cohesiveness of sediment and vegetation (Leopold and Maddock, 1953; Parker, 1979; Hey and Thorne, 1986; Soar and Thorne, 2001; Xu, 2002; Church, 2006; Eaton and Church, 2007; Parker et al., 2007).

The longitudinal geomorphic regimes of humid rivers (e.g. Lee and Ferguson, 2002; Brummer and Montgomery, 2003; Tabata and Hickin, 2003; Comiti et al., 2007; David et al., 2010; Green et al., 2013), semi-arid (Kemp, 2010), and arid (e.g. Tooth, 2000a; Merritt and Wohl, 2003; Ralph and Hesse, 2010; Pietsch and Nanson, 2011) rivers have been well documented. In semi-arid systems that are anabranching there is a trend of diminishing channel dimensions that is attributed to storage of water in lakes, floodplains, lagoons, and through transmission losses during overbank flow events (Kemp, 2010). Desert systems, where channels breakdown in to smaller distributaries, show a decrease in channel dimensions especially channel width and area (Ralph and Hesse, 2010). Bankfull channel widths increase as contributing areas increase for humid, mountain systems (Brummer and Montgomery, 2003; Green et al., 2013). The varying trends in downstream hydraulic

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geometry of different river types are a result of differences in exterior and interior controls on drainage, differing rates of transmission loss, the presence or absence of riparian vegetation, and the differences in precipitation regimes (Tooth, 2000b). Hydraulic geometry has been explored extensively but remains a core technique in understanding river systems (Knighton, 1998) and is often employed as an environmental and engineering design tool (e.g. environmental flows analysis) (Reid et al., 2010).

Planform patterns are known to change, or metamorphose (Schumm, 1985), longitudinally and these transitions are important features within the riverscape related to hydraulic geometry. Changes in flow strength and sediment feed rate are the two classical, yet still debated, explanations for planform metamorphosis (Kleinhans, 2010). Sand-bed rivers transition from meandering to braided planforms longitudinally as a function of stream power, which gradually increases in the downstream direction (Kleinhans, 2010). No known 'hard' thresholds exist for the transition of meandering to braided planforms and it is widely accepted that this transition is gradual. Sand-bed channels are perhaps the least understood of the channel types, and there are many scales of bedforms that may coexist including ripples, bedload sheets, dunes, and lobes (Montgomery and Buffington, 1997). Sand-bed rivers have live beds (Henderson, 1963) that are continuously transporting sediment at most stages, and as such they are effectively transport limited. Much of the floodplain sediments of sand-bed rivers are formed from non-cohesive easily eroded materials, and fluctuations in channel width are large when compared to fluctuations in bed elevation (Schumm and Lichty, 1963; Friedman et al., 1996). In sand-bed channels, the large volumes of sand transport promote the formation of wider channels (Osterkamp, 1980).

Rivers are widely acknowledged to demonstrate downstream fining of bedload. Numerous studies have examined the downstream fining of sediments, but most were based on data from small, gravel-bed streams over a length less than 200 km (Church and Kellerhals, 1978; Ferguson et al., 1996; Rice, 1998; Constantine et al., 2003; Frings, 2008). Graphic mean grain-sizes in anabranching streams show significant trends of decreasing particle sizes longitudinally (Kemp, 2010). Mountain, gravel-bed streams show an initial coarsening of mean grain size until a threshold of drainage area is reached, followed by fining of sediment (e.g. Brummer and Montgomery, 2003; Green et al., 2013). Sand-bed rivers often experience significant fining of sediment longitudinally, where tributaries are not of a sufficient size to introduce sedimentary inputs to significantly punctuate this fining trend (Benda et al., 2004; Frings, 2008). Lateral sediment sources, if sufficiently large or dissimilar enough, introduce material that has characteristics established independently of processes operating longitudinally in the main channel (Rice, 1998). Understanding these dynamics is critical because sand-bed rivers transition from very coarse sand to a fine sand–silt mixture, changing the dominant mode of sediment transport, bedform dimensions, and the size of over-bank deposits (Frings, 2008).

Due to extreme climatic variability, the rivers of the Great Plains are some of the most dynamic in the world (Matthews et al., 2005; Dort, 2009). Rivers of the Great Plains are of three basic types; large rivers that originate in the Rocky Mountains, streams that originate on the prairie, and intermittent and ephemeral channels that originate on the prairie (Wohl et al., 2009), all of which may be straight or sinuous (Schumm, 1963). During the historical period (before 1968; Perkin and Gido, 2011), large rivers of the Great Plains were characterized by very wide, shallow channels that were largely devoid of woody vegetation (Williams, 1978). Historical studies in the region have demonstrated changes in channel geometry attributed to variable flow conditions, with sometimes drastic changes associated with large floods (Smith, 1940; Schumm and Lichty, 1963; Friedman et al., 1996). While the 1930s were characterized by a prolonged drought in the Great Plains and an overall decrease in mean annual discharge, the decade was also punctuated by several extreme flood events (Schumm, 2005). As a result, changing precipitation regimes coupled with irrigation have affected rivers of the Great Plains. This process is exemplified by the Platte River, where there has been substantial channel narrowing and a reversal in hydraulic geometry in which channel width has decreased in the downstream direction (Schumm, 2005). Channel sinuosity and migration patterns have also been altered by anthropogenic alterations within Great Plains watersheds (Friedman et al., 1998).

Anthropogenic disturbances within Great Plains catchments are especially disruptive because Great Plains rivers are extremely responsive to altered discharge and sediment supply (Montgomery and Buffington, 1997). Many rivers of the Great Plains have been transformed from sparsely wooded with wide channels to more modern configurations with extensive riparian woodlands and much narrower channels (Frith, 1974; Williams, 1978; Currier, 1982; Currier et al., 1985; Martin and Johnson, 1987; Sidle et al., 1989; VanLooy and Martin, 2005). While many rivers of the Great Plains have been substantially hydrologically and geomorphically altered by the expansion of woodlands, there have also been concurrent changing land use patterns including pumping of groundwater, irrigated agriculture, intense grazing, extirpation of bison, and intensive road development (Currier, 1982; Eschner et al., 1983; Fausch and Bestgen, 1997; Falke and Gido, 2006; Falke et al., 2011). Great Plains rivers have also experienced widespread and dramatic changes to their hydrologic regimes resulting from construction of reservoirs that fragment riverscapes, retain sediments, and disconnect longitudinal hydrologic connectivity (Pringle, 2003; Costigan and Daniels, 2012). With a change in the hydrology of a system there is likely to be widespread changes to the longitudinal channel and sediment characteristics, as has been demonstrated on the Platte River (Schumm, 2005). An analysis of the naturally occurring longitudinal geomorphic channel characteristics will provide valuable baseline information that can provide insight into how Great Plains sand-bed systems may be conserved in the future.

Previous studies have documented channel changes to Great Plains rivers through time, and more specifically with respect to channel response of riparian woodland expansion (e.g. Frith, 1974; Williams, 1978; Currier, 1982; Currier et al., 1985; Martin and Johnson, 1987; Sidle et al., 1989; VanLooy and Martin, 2005) and changing precipitation regimes (Smith, 1940; Schumm and Lichty, 1963; Schumm, 2005). Bankfull channel width and depth of mountain and lowland river systems are known to increase longitudinally associated with increases in contributing watershed area as well as additions of tributaries (Leopold et al., 1964). While the downstream trends in hydraulic geometry of rivers are generally well understood, relatively few studies have investigated the downstream patterns in hydraulic geometry of large sand-bed rivers.

This study examines the modern-day longitudinal changes in hydraulic geometry and sedimentary characteristics along a 200 km reach of the Ninnescah River, a large, perennial, sand-bed river located in south central Kansas. We present field measurements supplemented with geospatial data from 11 study reaches to document the longitudinal changes in hydraulic geometry and substrate characteristics. The objectives of this research are to: (a) assess patterns in downstream grain-size fining, (b) determine occurrence of abrupt longitudinal changes in grain size (e.g. a gravel-sand transition), and (c) document deviances in expected trends in hydraulic geometry (e.g. downstream of geomorphically significant confluences). We hypothesized that the geomorphology of the Ninnescah River would follow the typical longitudinal progression in which bankfull width and depth, bankfull width to depth ratio, and bankfull area increase in the downstream direction. In addition, we expected mean grain sizes would systematically decrease in the downstream direction, with reaches located close to significant sources of lateral sediment and water (e.g. geomorphologically significant tributaries) punctuated by sediment coarsening and channel widening and deepening.

2. Study system

The Ninnescah River originates in the semi-arid, mixed-grass prairie ecoregion in south-central Kansas, where the North and South Forks