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

Katie H. Costigan [a,*], Melinda D. Daniels [b], Joshuah S. Perkin [c], Keith B. Gido [c]

[a] *Kansas Cooperative Fish and Wildlife Research Unit, Division of Biology, Kansas State University, 116 Ackert Hall, Manhattan KS 66506, United States*
[b] *Stroud Water Research Center, 970 Spencer Road, Avondale, PA 19311, United States*
[c] *Division of Biology, Kansas State University, 116 Ackert Hall, Manhattan, KS 66506, United States*

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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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[*] Corresponding author.
E-mail address: costigan@k-state.edu (K.H. Costigan).

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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 join to form the Ninnescah River proper (Fig. 1). The river flows in an east–southeast direction along a gradually increasing precipitation gradient through the High Plains, Red Hills, and Wellington Lowland physiographies within the Central Plains. (Mandel, 2008). The High Plains physiography is characterized by loess deposits of 3–5 m thickness that overlie thick deposits of Pleistocene and/or Pliocene alluvium (Mandel, 2008). The Red Hills region is characterized by red Permian-aged shale, sandstone, and siltstone (Swineford, 1955) and the Wellington Lowlands is characterized by Permian-aged sandstone and siltstone as well as salt and gypsum deposits. The Ninnescah River is a tributary of the Arkansas River, and the lower reach of the Ninnescah River intersects a broad, flat, alluvial plain that is underlain by thick deposits of Pleistocene sands and gravel (Frye and Leonard, 1952). The Ninnescah drains primarily sandy areas and as a result channels are typically wide, shallow, and straight (Fig. 2). The upper reaches of the Ninnescah River (upstream of Reach 4; Fig. 1) are within a region of the High Plains Aquifer that has experienced no significant change (-10%) in groundwater levels in recorded history (Sophocleous, 2000). The annual hydrograph of the Ninnescah River is dominated by higher flows in the winter and low flows in the summer, although streamflow is partly regulated by Cheney Dam on the North Fork. Flows released from Cheney Dam are highly controlled, and the last high flow event was 18 months prior to the morphometric and sedimentary study undertaken here. There are three US Geological Survey (USGS) gages along the study segment, which measure increases in long-term (1980–2012) mean annual discharge from the headwaters to the mouth (0.48, 5.91, and 15.0 m^3 s^{-1}; Table 1; see Fig. 1 for location of USGS gages).

Morphometric parameters were measured within 11 study reaches located along 200 river kilometers of the Ninnescah River (Fig. 1). The South Fork is the dominant fork and there were seven study reaches on this fork (1–7) and four reaches on the Ninnescah River proper (8–11). Direct anthropogenic alterations to the Ninnescah River basin include: Cheney Reservoir is likely the largest sources of disturbance to the basin (constructed in 1964) and is located on the North Fork Ninnescah River; Reach 1 is impacted by a fishing lake and weir dam upstream, where water is diverted out of the river and into the lake and returned via an epilimnetic release; Reach 4 is impacted by small diversion dam and associated reservoir; and Reach 5 is impacted by a seasonal dam that is constructed annually (i.e., in place between April and October).

3. Methods

3.1. Data collection

Data collection was completed using field surveys supplemented with geographic information systems (GIS) based topographic and aerial image analysis of the study system. Channel characteristics measured in the field included local bed slope (S; m/m), bankfull width (B; m), and bankfull depth (Y; m). Bankfull depth and width were surveyed in the field at ten evenly spaced cross-sections within each study reach, and each reach was a length equal to ten channel widths (i.e., a scale over which reach stream morphology and processes are related) (Montgomery and Buffington, 1997). Sinuosity was extracted from aerial photographs taken during 2010, both within field sampling reaches and throughout the study system. The longitudinal profile of the study system of the Ninnescah River was determined from digital 1:24,000 topographic maps. Using topographic maps for longitudinal profiles introduce only minor error when applied in plains environments (Kemp, 2010). When possible, large meander bends were avoided and relatively undisturbed reaches (i.e., away from in-channel anthropogenic alterations) were selected for morphologic and sedimentary analyses.

To study longitudinal variations in sediment sizes, care must be taken to sample consistently. In gravel-bed rivers there is substantial local sorting (Bluck, 1982) and standard methods of grain sizes have been developed (Wolman, 1954) and thoroughly analyzed. Sand-bed channels have live beds (Henderson, 1963) that are continuously transporting sediment at most stages and have many scales of bedforms that may coexist, including ripples, bedload sheets, dunes, and lobes (Montgomery and Buffington, 1997). As with gravel-bed channels, there are local depositional variations in sand-beds that may confound the apparent longitudinal patterns of grain size. In an attempt to reduce any sampling error associated with the multiple bedforms present, five samples were taken to determine an integrated, cross-sectional, mean grain-size distribution. Examples of previous field sampling of sand-bed sediments include two grab samples of sand-bed material that

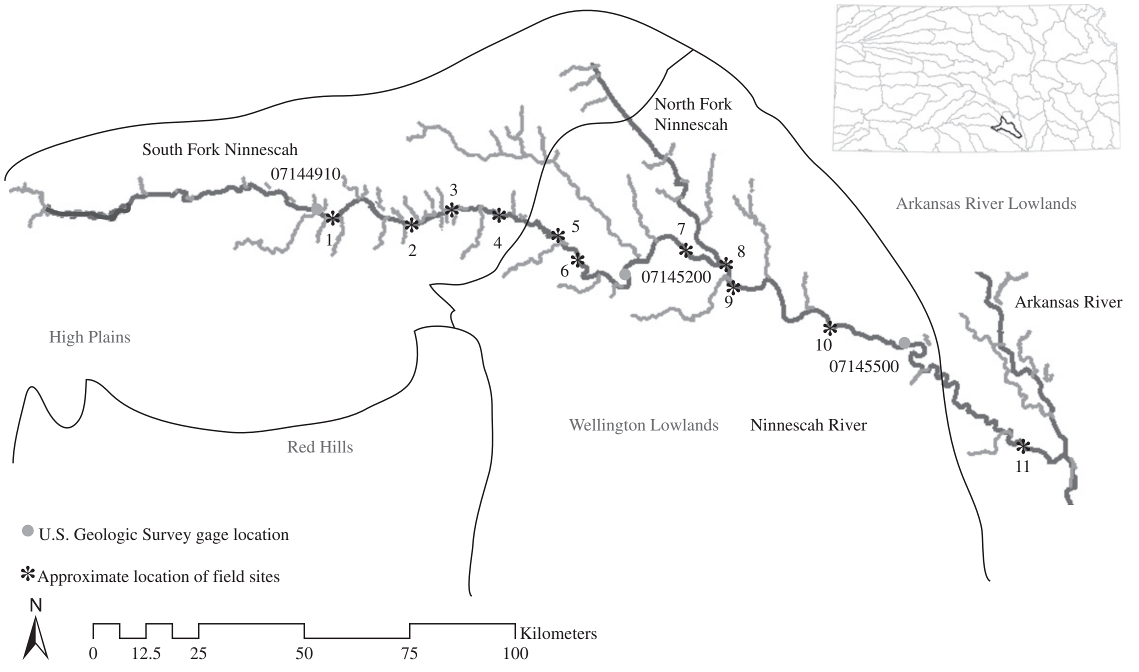

Fig. 1. The Ninnescah River basin and its location in Kansas showing field reaches and U.S. Geologic Survey gages. Text in gray denotes the boundaries of the major physiographic regions within the Ninnescah River basin.

Fig. 2. Photographs of field reaches in downstream order. 1–6 are the South Fork Ninnescah River and 7–11 are the Ninnescah River proper.

were from near the channel margins (Kemp, 2010) and three grab samples where two were taken from the channel margins and one from the thalweg (Lou et al., 2012). Edwards and Glysson (1988) note that sand-bed streams should be sampled until the streambed has been representatively sampled. Our sample points included the two channel margins, thalweg, and two additional samples at the midpoint between the channel margins and thalweg, which we believe is representative of the streambed. The materials from the top 10 cm of the bed were collected at each sample point.

Particle-size analyses were performed using standard dry-sieve analysis methods because the majority of the samples had greater than 84% of their weight in the sand fraction. Prior to sieving, each sample was oven dried for 24 h, cooled, and gently disaggregated. Large organic items were manually removed from the sample and discarded. Particles less than 2 mm were passed through a series of sieves at 0.5-φ intervals while particles larger than 2 mm were passed through sieves at 2-φ intervals. Mean grain size, sorting, skewness, and kurtosis were calculated using the Folk and Ward (1957) formulae following Blott and Pye (2001). Grain-size distributions were also documented for the impounded North Fork Ninnescah River to provide context for how this tributary may alter grain-size distributions on the main stem Ninnescah River.

3.2. Data analysis

Analyses focus on general relations between longitudinal position and morphological and sedimentary characteristics. Correlations between response variables (sinuosity, width, depth, width to depth ratio, sediment sizes) to location downstream from Reach 1 were determined with regression analyses. For regression analyses, response variable data were $\log_{10}$-transformed to address skewed distributions and assumptions regarding homogeneous variances (Brummer and Montgomery, 2003; Kemp, 2010). To address potential correlation among multiple response variables, we conducted a Principal Component Analysis (PCA) and plotted the primary Principle Component (PC 1) against longitudinal length to assess correlations between longitudinal location and stream attributes.

4. Results

4.1. Channel morphology

4.1.1. Channel structural parameters

The longitudinal profile of the Ninnescah River was concave (Fig. 3a). Concavity of the longitudinal profile was maintained by decreasing bed slope through the system (Fig. 3b). Bed slope and channel

Table 1
Hydrologic characteristics of the Ninnescah River along study reach (standard error of mean).

Station number	Station	Mean annual discharge ($m^3\ s^{-1}$)	Contributing area (km^2)
07144910	SF Ninnescah in Pratt, KS	0.5 (0.04)	303
07145200	SF Ninnescah in Murdock, KS	5.9 (0.3)	1684
07145500	Ninnescah in Peck, KS	15.0 (0.9)	5514

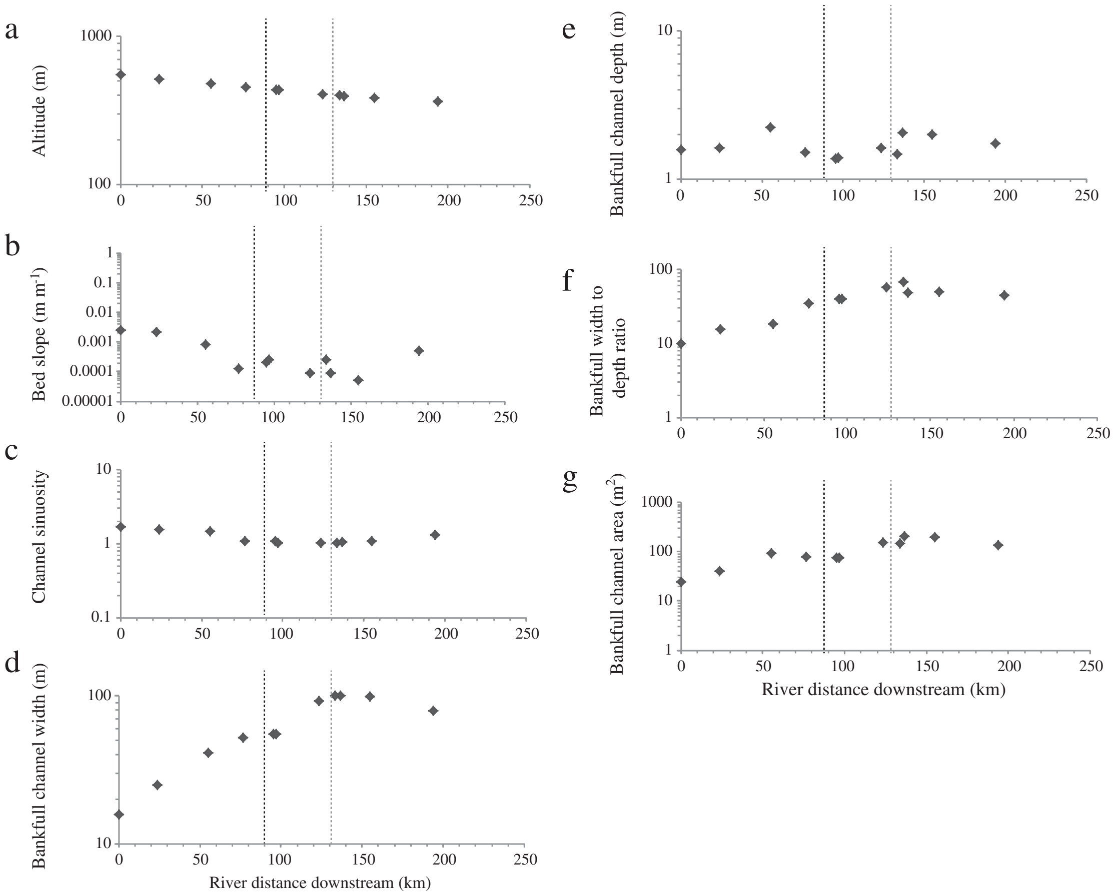

Fig. 3. Downstream trends in a) the longitudinal profile, b) bed slope, c) channel sinuosity, d) bankfull channel width, e) bankfull channel depth, f) bankfull channel width to depth ratios, and g) bankfull channel area. The black dashed line denotes the location of the seasonal dam and the gray dashed line denotes the location where the North Fork meets the South Fork Ninnescah, forming the Ninnescah River proper.

sinuosity (Fig. 3c) of the upper three reaches (1–3) were much higher than the lower reaches. Overall, the sinuosity of the Ninnescah River system was 1.15. Reaches 1–3 had a predominately meandering planform configuration (sinuosity > 1.35) and the rest of the system, with the exception of Reach 11, was much less steep and less sinuous, resulting in a predominately straight braided planform configuration. Regression analysis of channel sinuosity was marginally significant ($F_{2,9} = 4.9$, $p = 0.054$, $r^2 = 0.35$) with sinuosity decreasing downstream (Table 2).

4.1.2. Bankfull channel parameters

The Ninnescah River conformed to the expected longitudinal morphologic progression, where bankfull channel width and depth increased, but increases in depth were not statistically significant. Bankfull channel width of the Ninnescah basin increased five-fold from 15.7 m at the upper-most reaches (1) to 78 m at the lowermost reach (11) (Fig. 3d), yet the widest bankfull widths in the system are the intermediate reaches (reaches 7–10), where bankfull width is ~100 m. Reach 1 had a mean bankfull depth of 1.57 m and Reach 11 had a mean bankfull depth of 1.74 (Fig. 3e). Reach 3 had many exposed, incised banks and there was a disproportionally large increase in bankfull depth at this reach (Fig. 4). Reaches 9 and 10 had the highest bankfull depth of approximately 2 m. The slope of the overall regression equation for bankfull depth was insignificant ($F_{2,9} = 0.26$, $p = 0.62$, $r^2 = 0.03$; Table 2). Regression analyses demonstrated a significant ($F_{2,9} = 108.9$, $p < 0.001$, $r^2 = 0.92$) downstream trend in increasing channel width.

Table 2

Parameter estimates for regression relationship between ln transformed values for channel sinuosity (Si), width (B), depth (Y), width to depth (B:Y), grain size (D_{10}, D_{50}, and D_{90}), and distance.[a]

	a	*b*	*SE*$_b$	r^2	*F*	*p*
ln Si	1.42	−0.0022	0.0015	0.35	4.9	0.054
ln B	15.13	0.4932	0.0442	0.92	108.9	<0.0001
ln Y	1.59	0.0008	0.0015	0.03	0.26	0.620
ln B:Y	9.56	0.2892	0.0335	0.88	64.3	<0.0001
ln D_{10}	0.40	−0.0005	0.0003	0.23	2.6	0.14
ln D_{50}	0.99	−0.0032	0.0013	0.44	7.0	0.027
ln D_{90}	4.04	−0.0209	0.0020	0.57	11.7	0.008

[a] Here *a* and *b* are parameters in the relation $\ln y = \ln a + bx$ where *x* is measured in km downstream from site 1. SE_b is the standard error of the coefficient *b*; r^2 is the coefficient of determination; *F* is the value of the F distribution; *p* is the significance probability.

Bankfull width to depth ratios and area (Fig. 3f, g) followed a similar pattern of bankfull depth and width of increasing longitudinally, with the intermediate reaches having highest values. As the drainage density of the river increased longitudinally, width to depth ratios increased significantly ($F_{2,9} = 64.3$, $p < 0.0001$, $r^2 = 0.88$). A marked increase in width to depth ratios was measured coincident with the change in planform configuration from meandering to braided.

4.2. Sediment characteristics

Grain-size distributions for 50 of the 55 samples were unimodal. The five bimodal samples were obtained from Reach 1 where the second mode is a minor secondary peak of small gravel particles in an otherwise predominately sand sample. Since only one reach had a small bimodal grain-size distribution, aggregate analysis of grain-size distribution employed standard parameters such as mean, median, sorting, skewness and kurtosis. Overall, the sediments were predominantly

Fig. 4. Photograph of a cut bank at Reach 3.

moderately sorted, coarsely skewed or symmetrical, and mesokurtic or leptokurtic in nature (Table 3; Fig. 5).

The sorting coefficients ranged from 1.6 to 3.6, indicating a narrow range of moderately well to poorly sorted (Fig. 5; Table 3). The upper two reaches of the study system were poorly sorted. Reach 1 had the highest sorting coefficient but also had the lowest skewness and kurtosis coefficients. Reach 5, located downstream of an ephemeral run-of-river dam, was also poorly sorted. Between reaches 5 and 6, a systematic decrease in mean grain size, median grain size, sorting, skewedness, and kurtosis occurred. Between reaches 7 and 8, where the North Fork joins the South Fork, a slight increase in the sorting coefficient, skewness (from symmetrical to coarsely skewed), and kurtosis occurred.

The texture of sediment samples was described using the size scale of Blott and Pye (2001) (Fig. 6). Reach 1 was the only reach with gravel as the dominate particle size fraction (Fig. 6a; b). Texture analysis demonstrated that the upper portions of the watershed had the highest proportions of sediment in the gravel size fractions and the further downstream the more sand sized fractions were present. Between reaches 7 and 8, the North Fork joins the South Fork and forms the Ninnescah River proper, contributing to an increase in larger particles at Reach 8. The longitudinal trend was a decrease in the gravel fraction and increase in sand fractions, and Reach 11 had a very small percentage of gravel within the samples. Cumulative grain-size frequencies also demonstrate that there are no distinct breaks in the slope of any of the site curves (Fig. 6b).

Trends in the percentiles of the substrate sediment indicated that the bed material of the Ninnescah River fined systematically downstream (Fig. 7). Regression analysis indicated the surface D_{90} and D_{50} were modeled well (Table 2), but the relationship for D_{10} was not strong ($F_{2,9} = 2.6$, $p = 0.14$, $r^2 = 0.23$). There were significant trends in downstream fining of D_{90} ($F_{2,3} = 11.7$, $p = 0.008$, $r^2 = 0.57$) and D_{50} ($F_{2,3} = 7.0$, $p = 0.027$, $r^2 = 0.44$). The slope of the regression for D_{90} was an order of magnitude steeper than D_{50} and D_{10}, with D_{50} slope steeper than D_{10}. Downstream fining of surface D_{50} was especially evident in the upper reaches of the system where D_{50} between reaches 1 and 3 decreased four-fold (2100 μm to 500 μm). Between reaches 3 and 10, there was a slight fining trend in D_{50}. As the Ninnescah River approached the Arkansas River (below Reach 11), D_{50} increased abruptly by 300 μm between reaches 10 and 11. Overall, measurements of surface D_{50} in the Ninnescah River ranged from 427 to 2133 μm. Grain-size distributions taken from the North Fork Ninnescah River document that the site was characterized as gravelly sand with a D_{50} of 713 μm.

4.3. Overall assessment

The first two axes of the PCA explained 85.6% of the variation in the response variables across the 11 reaches (PC 1 = 68.9%, PC 2 = 16.7%; Table 4). Longitudinal patterns along PC 1 are strong for reaches 1–7 and PC 2 for reaches 8–11 (Fig. 8). The first axis contrasts sites with larger grain size, channel sinuosity and altitude with wide sites with high width to depth ratio, in which upstream sites are loading negatively on this axis and downstream sites are loading positively. The second axis is characterized by highly positive (0.507) loading of D_{10} and highly negative loading of bankfull depth (−0.612). Principal component 3 explained 9.0% of the variation in the dataset and was characterized by highly negative loadings of bankfull depth (−0.716).

5. Discussion

This study characterized the longitudinal patterns of channel hydraulic geometry and substrate of a large alluvial sand-bed river located

Table 3
Particle size (standard error) characteristics and sorting, skewness, and kurtosis classifications from Blott and Pye, 2001.

Site	Mean (μm)	Median (μm)	Sorting (σ_G)		Skewness (Sk_G)		Kurtosis (K_G)	
1	2064.3 (311.4)	2132.8 (383.2)	3.6 (0.2)	Poorly	−0.01 (0.06)	Symmetrical	0.72 (0.04)	Platykurtic
2	922.0 (95.9)	813.0 (80.4)	2.4 (0.1)	Poorly	0.3 (0.04)	Coarse skewed	1.02 (0.07)	Mesokurtic
3	535.9 (98.2)	494.6 (72.0)	1.9 (0.2)	Moderately	0.2 (0.02)	Coarse skewed	1.18 (0.12)	Leptokurtic
4	914.9 (82.7)	824.7 (57.2)	1.9 (0.1)	Moderately	0.3 (0.02)	Coarse skewed	1.06 (0.05)	Mesokurtic
5	757.7 (67.2)	678.0 (46.6)	2.1 (0.2)	Poorly	0.3 (0.02)	Coarse skewed	1.20 (0.06)	Leptokurtic
6	433.0 (14.0)	426.9 (15.5)	1.6 (0.02)	Moderately Well	0.09 (0.02)	Symmetrical	1.09 (0.03)	Mesokurtic
7	533.1 (12.9)	526.3 (16.3)	1.7 (0.02)	Moderately	0.09 (0.03)	Symmetrical	1.11 (0.03)	Mesokurtic
8	647.7 (44.0)	600.0 (39.3)	1.9 (0.2)	Moderately	0.2 (0.04)	Coarse skewed	1.12 (0.03)	Leptokurtic
9	724.0 (40.1)	655.9 (22.0)	1.7 (0.1)	Moderately	0.06 (0.03)	Symmetrical	1.10 (0.04)	Mesokurtic
10	468.9 (20.3)	455.0 (21.9)	1.6 (0.05)	Moderately Well	0.2 (0.03)	Coarse skewed	1.11 (0.03)	Mesokurtic
11	440.1 (13.1)	713.0 (45.7)	1.6 (0.03)	Moderately Well	0.07 (0.02)	Symmetrical	1.07 (0.03)	Mesokurtic

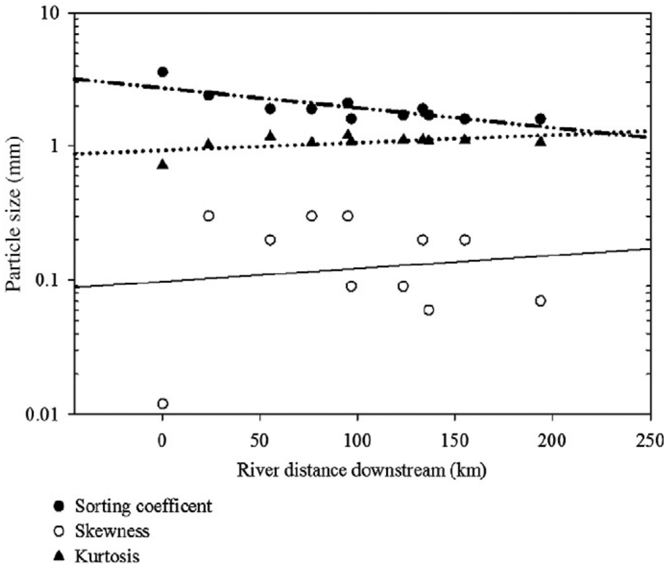

Fig. 5. Downstream trends in sorting coefficient, skewness and kurtosis.

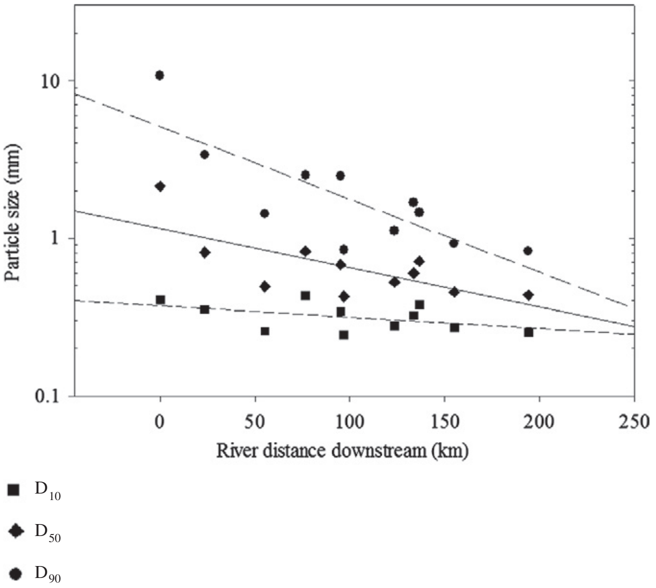

Fig. 7. Downstream trends in grain surface sizes D_{90}, D_{50}, and D_{10}.

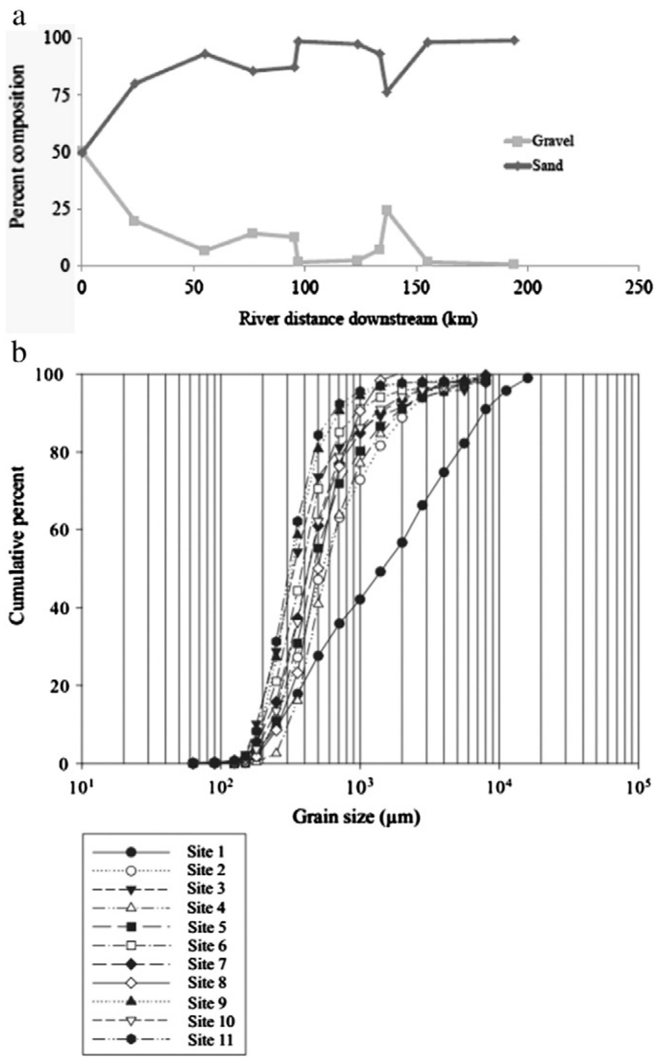

Fig. 6. Analysis of (a) sediment grain texture with gravel and sand size classifications from Blott and Pye (2001) and (b) cumulative grain-size frequency curves.

in South-central Kansas. Our results complement similar previous studies of hydraulic geometry from other channel types that demonstrated channel width (e.g. Montgomery and Gran, 2001; Brummer and Montgomery, 2003) and depth (e.g. Mueller and Pitlick, 2005; Splinter et al., 2010; Green et al., 2013) increasing longitudinally. There are many examples where channel widths and depths decrease downstream including channel break down (Ralph and Hesse, 2010) and rivers transitioning from humid to semi-arid environments (Kemp, 2010).

While results of this study demonstrate that bankfull channel width increases in the downstream direction, there were no significant changes in bankfull channel depth in the downstream direction. Wolman and Gerson (1978) note that in dry land rivers, channel width approached a fairly universal asymptotical value of 100–200 m once the catchment area exceeds 50 km^2, which we also observed in our study of the Ninnescah River. The finding that width increased significantly more than depth is consistent with previous studies that have attributed this to mean depth and mean velocity remaining constant throughout the system (Ashmore and Sauks, 2006; Bertoldi et al., 2008), where the increases in discharge are accommodated by an increase in channel width. Multi-thread channels are characterized by very shallow cross-sections, and width increases faster than depth by activation of new threads. In addition, much of the floodplain sediments of the Ninnescah River form non-cohesive, easily eroded banks and previous studies have demonstrated that fluctuations in channel width are large when

Table 4
Principal component loadings and explained variance for the first three components for channel sinuosity (Si), altitude (E), bankfull width (B), bankfull depth (Y), width to depth ratio (B:Y), slope (S), and grain size (D_{10}, D_{50}, and D_{90}).

	PC1	PC2	PC3
Si	−0.338	−0.392	0.027
E	−0.372	−0.015	0.144
B	0.386	0.076	−0.239
Y	0.048	−0.612	−0.716
B:Y	0.378	0.243	−0.044
S	−0.375	−0.165	0.125
D_{10}	−0.219	0.507	−0.566
D_{50}	−0.352	0.256	−0.237
D_{90}	−0.375	0.238	−0.120
Explained variance	2.489	1.226	0.898
Explained variance (%)	68.9	16.7	9.0
Cumulative % of variance	68.9	85.6	94.5

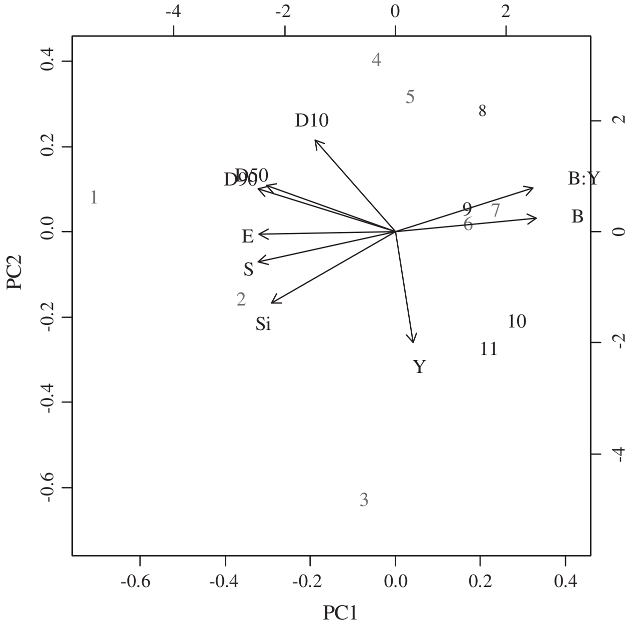

Fig. 8. Principal component analysis for the first two principal components for channel sinuosity (Si), altitude (E), bankfull width (B), bankfull depth (Y), width to depth ratio (B:Y), slope (S), and grain size (D_{10}, D_{50}, and D_{90}).

compared to fluctuations in bed elevation for channels with noncohesive banks (Schumm and Lichty, 1963; Friedman et al., 1996). The low width to depth ratios in the upper portions of the watershed are an artifact of low discharge in this region, resulting in narrow, shallow channels (Splinter et al., 2010).

Where the North Fork joins the South Fork, we documented a slight change in bankfull channel width and a large increase in channel depth as the stream adjusted to the new sediment and water loads from the tributary. The North Fork Ninnescah River is impounded, which is likely the cause of the changes in channel width and depth documented at Reach 8. Hackney and Carling (2011) found a net narrowing of the channel downstream of confluences by 1%; however, there were reaches with large amounts of narrowing and widening influenced by large variations in the geology of their study area. Channels downstream of confluences have been shown to narrow 15% following impoundment within the tributary network (Curtis et al., 2010). On the Ninnescah River, we only saw a slight change in channel width, thus the additional discharge from the North Fork was likely accommodated by a local increase in channel depth rather than by widening, which has been observed elsewhere (e.g. Lane, 1955). The results of this study demonstrate that on the Ninnescah River, increased channel width plays a more significant role in maintaining channel conveyance than channel depth when there are lateral inputs of water from tributaries. This pattern constitutes a hydraulic geometry adjustment that has been documented in other river types (e.g. Knighton, 1987; Best, 1988; Hackney and Carling, 2011).

Due to the systematic decrease in downstream channel slope, we expected to observe finer-grained sediment in the lower reaches of the study. The results of sediment sampling reveal a grain-size fining that is especially prevalent in the upper portions of the study system, between reaches 1 and 3. One of the most expressive forms of downstream fining was the gravel–sand transition (e.g., Sambrook and Ferguson, 1995), which occurred between reaches 1 and 2 on the South Fork Ninnescah River. Punctuated trends in downstream fining, as seen on the Ninnescah, are often associated with discontinuities in slope (Ferguson et al., 2006). At the gravel–sand transition, rivers reduce their slope resulting in decreases in bed shear stresses, which contribute to the abruptness of the gravel–sand transitions (Frings, 2011), although the gravel–sand transition is not always associated with a change in slope (Shaw and Kellerhals, 1982). Between reaches 1 and 3, a dramatic downstream decrease in slope developed that resulted in a decrease in shear stresses, which can result in coarser grains not becoming entrained and a decreased transport capacity of the system (Frings, 2008). Abrupt changes in longitudinal trends of slope represent critical transition points where there are departures from the central tendencies of a river (Reinfelds et al., 2004). The slope discontinuity in the Ninnescah River is concurrent with the observed gravel–sand transition and not coincident with any external control, such as variable geology or external sediment inputs, which can cause changes in slope (e.g. Ferguson, 2003). In addition to the gravel–sand transition observed in the upper portion of the watershed, there were significant trends in downstream fining of sediment throughout the Ninnescah River system. The results of cumulative grain-size frequencies demonstrate that there were no breaks in slopes of these graphs (i.e. Middleton, 1976), which suggests that the Ninnescah River does have a live bed and that there are no clear traction and saltation components in the bed sediments throughout the study reach. The two mechanisms for downstream fining are abrasion and selective transport of sediment. Abrasion of sediment leads to stable fining patterns and selective transport preferentially entrains finer grains earlier than coarser grains. In rivers with a concave longitudinal profile, selective transport results in stable downstream fining, which causes difficulty when attempting to differentiate the relative importance of abrasion and selective transport (Frings, 2008). The Ninnescah River basin drains loess, alluvium, and sandstone and as such it is not a supply limited systems. There is no evidence to suggest that the sand–gravel transition is a result of a change from transport to supply limitation. Intermittency of small headwater prairie streams is a common feature. In the Great Plains headwater streams are characterized as harshly intermittent with distinct periods of flood and drying (Dodds et al., 2004) with high flood frequency and low predictability (Samson and Knopf, 1994). It is likely that during flow events in the headwaters, they are contributing replacement sediment that would prohibit coarsening of the main channel.

Tributary junctions are locations in the network where channel and valley morphology change and where there is deviation from the central tendency expected sensu the Network Dynamics Hypothesis (Benda et al., 2004). The North Fork Ninnescah River is the dominant tributary within the study reach and is impounded, which is likely the cause of the increase in mean grain size immediately downstream of this junction (Kondolf, 1997). The downstream impact of dams on sediment grain size is often very significant (e.g., Heath and Plater, 2010). Geomorphically significant tributaries (Benda et al., 2004) are the most common source of grain-size discontinuities in gravel bedded rivers, typically resulting in an increase in the mean grain size (Frings, 2008). Following Horton's Laws regarding stream network architecture and the theory of geomorphically significant confluences, it is expected that geomorphically significant confluences are those higher up in the network (Horton, 1945; Benda et al., 2004). Following the logic of these theories, tributary confluences are likely to be less significant in downstream portions of the network because streams tend to be large. Our findings of grain-size coarsening below a major tributary confluence contradict the theory that sand-bedded rivers observe no coarsening of substrates below confluences (Frings, 2008). Instead, our findings are in agreement with the distinct tributary coarsening effects observed in gravel bedded rivers, higher up in the network (i.e. smaller streams). Three theoretical explanations have been proposed to explain the lack of tributary coarsening in sand-bedded rivers: 1) in sand-bedded rivers with large floodplains, tributary channels have the same gradient as the main channels, resulting in the lack of grain-size coarsening at confluences (Frings, 2008); 2) tributary inputs do not affect mean grain-size distributions on sand-bed rivers because of network geometry, where the upper reaches have more tributary inputs than lower reaches (Benda et al., 2004; Frings, 2008); and 3) the ephemeral, intermittent, or low flow nature of many of the tributaries of the Ninnescah River and as such are more effective in transporting coarse sediment than perennial rivers are (Laronne and Reid, 1993; Singh et al., 2007).

Two unique attributes of the Ninnescah study system correspond with these theories and provide possible explanations for our results. First, although the Ninnescah River does have a wide floodplain, there are regional geologic controls that alter the channel slope downstream of the major confluence. At the furthest downstream reach on the Ninnescah, approaching the confluence with the Arkansas River, there is a marked increase between reaches 10 and 11 in mean channel slope of 24%, increase in channel sinuosity by an order of magnitude, and decreases in channel width and depth by 20% and 14%, respectively. Playfair (1802) noted that tributary streams join the principal stream at the level of the principal valley and that the tributary and main stream must be lowering at the same average rate in the vicinity of their junction. Following Playfair's law, the Ninnescah River must adjust itself to meet the Arkansas River. The coupling of the Arkansas River and Ninnescah River is a control on the geomorphic function of the Ninnescah River, especially in the lower portions of the watershed. The Arkansas River is believed to have once followed the current course of the Ninnescah River (Schoewe, 1949). Deflection northward of the Arkansas River was caused by gradual uplift of a large structure whose axis extended in a north–south direction, and as uplift progressed the Arkansas River was forced to migrate northward around the anticlinal structure forming the Great Bend of the Arkansas River. Between reaches 10 and 11, the Ninnescah River approaches the Arkansas River, entering the Arkansas River Lowlands in a region that is coincident with the termination of the anticlinal structure that forced the Arkansas River northward. A second probable driver of the observed coarsening is the impoundment on the North Fork Ninnescah. Impoundments are well known to cause downstream coarsening (Graf, 1980; Curtis et al., 2010), and the coarsening effect of Cheney Dam on the North Fork Ninnescah may be propagating downstream to the confluence with the Ninnescah River proper.

Our understanding of Great Plains and semi-arid rivers lacks in comparison to that of arid and humid region rivers. We are at a critical tipping point within the Great Plains. Dryland and irrigated corn and cattle production are projected to increase through the next 40 years (Steward et al., 2013), where groundwater levels have already been lowered by these practices. Global circulation models predict more frequent, intense precipitation events with long intervening dry periods, and an additional loss of streamflow by 30% within the next 40 years (Milly et al., 2005). Large Great Plains rivers have undergone widespread and dramatic alteration with their discharge regimes as a result of impoundment structures (Costigan and Daniels, 2012). The Ninnescah River represents a unique system within the Great Plains that is not within the high intensive corn and cattle production zone or where there are large impoundments. The results of this study provide important baseline data for a minimally disturbed river that are helpful to guide restoration and management of rivers in semi-arid regions.

6. Conclusions

This study presents results from field, lab, and geospatial analyses of longitudinal linkages between reach-scale morphology and sedimentary characteristics of a large sand-bed river. The results demonstrated that channel structural components followed the typical expected hydraulic patterns longitudinally, with significant trends in increases in bankfull channel width and width to depth ratio, and a significant trend for decreasing channel sinuosity. Bankfull channel depth did not have a significant longitudinal trend. The Ninnescah River had a significant trend in downstream fining of surface sediment (D_{50}, D_{90}) that is probably reflective of a combination of hydraulic sorting and sediment supply from the catchment. The North Fork Ninnescah River confluence had a disproportionally large influence on channel and sedimentary characteristics relative to what is typically believed. As the Ninnescah River approached the Arkansas River floodplain, there were deviations in the central tendency as the Ninnescah River adjusted itself to meet the Arkansas River. Given changes in land use/land cover in the Great Plains and expected climate change, the results of this study provide valuable baseline data for the geomorphic and sedimentary patterns of large, semi-arid, sand-bed rivers.

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