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INFLUENCE OF RIPARIAN AND WATERSHED ALTERATIONS ON SANDBARS IN A GREAT PLAINS RIVER

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ABSTRACT

Anthropogenic alterations have caused sandbar habitats in rivers and the biota dependent on them to decline. Restoring large river sandbars may be needed as these habitats are important components of river ecosystems and provide essential habitat to terrestrial and aquatic organisms. We quantified factors within the riparian zone of the Kansas River, USA, and within its tributaries that influenced sandbar size and density using aerial photographs and land use/land cover (LULC) data. We developed, *a priori*, 16 linear regression models focused on LULC at the local, adjacent upstream river bend, and the segment (18–44 km upstream) scales and used an information theoretic approach to determine what alterations best predicted the size and density of sandbars. Variation in sandbar density was best explained by the LULC within contributing tributaries at the segment scale, which indicated reduced sandbar density with increased forest cover within tributary watersheds. Similarly, LULC within contributing tributary watersheds at the segment scale best explained variation in sandbar size. These models indicated that sandbar size increased with agriculture and forest and decreased with urban cover within tributary watersheds. Our findings suggest that sediment supply and delivery from upstream tributary watersheds may be influential on sandbars within the Kansas River and that preserving natural grassland and reducing woody encroachment within tributary watersheds in Great Plains rivers may help improve sediment delivery to help restore natural river function. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: Kansas River; sandbar; land use; Great Plains

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INTRODUCTION

Most large rivers in the Northern Hemisphere have been significantly altered by humans (Dynesius and Nilsson, 1994). Alterations to sediment transport, flow regime and sediment loads through river engineering, dams, and land use changes are among the leading stressors in these systems (Richter *et al*., 1997; Jacobson and Galat, 2006). These modifications may result in altered channel morphology, including a reduction of sandbars and associated shallow water habitat (Poff *et al*., 1997; Graf, 2006; Jacobson and Galat, 2006).

Conversion of natural land cover to agricultural or urban land cover in the riparian zone and watersheds of contributing tributaries can increase run-off rates and alter hillslope sediment delivery to channels, resulting in aggradation or degradation of the river channel (Knighton, 1998; Gerla, 2007), which may influence the number and size of sandbars. Additionally, urban areas are often associated with river engineering structures (e.g. wing dikes and bank stabilization), which have local influence on sediment deposition and the availability of sandbars. Large dams reduce flood magnitudes and frequencies and the amount of sediment available for deposition on sandbars (Graf, 2006), which limits sandbar creation and reduces disturbance to encroaching vegetation. Additionally, the degree of a tributary's influence in a system is modulated by relative contributing area (Benda *et al*., 2004), and anthropogenic alterations within large tributaries may have a high impact on sediment delivery and sandbar development in the receiving portion of the mainstem river channel.

Declines in the size and abundance of sandbars have been detrimental to aquatic and terrestrial organisms. Reduction of sandbar habitat in the Missouri River drainage has reduced nesting success of the federally threatened piping plover (*Charadrius melodus*) and the federally endangered least tern (*Sterna albifons*) (Kirsch, 1996; Stucker *et al*., 2012; Buenau *et al*., 2013). Sandbars are associated with increased heterogeneity in depths and water velocities, which may provide a nursery habitat for young fishes and increase biodiversity (Jacobson and Galat, 2006; Wyzga *et al*., 2009; Tracy-Smith *et al*., 2012). The federally endangered pallid sturgeon (*Scaphirhynchus albus*) and other native riverine fishes may select for river reaches with more sandbars, potentially because of enhanced feeding opportunities in

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complex channels (Bramblett and White, 2001; Eitzmann and Paukert, 2010a). The abundance of slow water and recirculation zones associated with sandbars may increase retention of drifting eggs and larvae, reducing the likelihood that they are flushed into unsuitable impoundment habitats (Widmer *et al*., 2012), which may help fishes with drifting life stages such as pallid sturgeon and plains minnow (*Hybognathus placitus*; Perkin and Gido, 2011; Braaten *et al*., 2012). Therefore, restoring or maintaining sandbars and shallow water habitats may be critical for the aquatic biota in these rivers, contingent upon benefits to native species outweighing benefits to non-native species with similar life histories, such as Asian carps (Deters *et al*., 2013).

Large-scale restoration efforts have been used to enhance sandbar habitats for native species in sand-bed rivers. In the Platte River, Nebraska, vegetation is removed annually to increase the sandbar area available for roosting sandhill cranes (*Grus canadensis*) and federally endangered whooping cranes (*Grus americana*) (Kinzel *et al*., 2009; Smith, 2010). Similarly, on the Missouri River, sandbars are mechanically built to restore nesting habitat for piping plovers and interior least terns (Stucker *et al*., 2012; Buenau *et al*., 2013). However, restoration projects often do not consider the processes causing the degradation (e.g. vegetation encroachment or sandbar erosion; Hobbs and Norton, 1996) and thus may be unsuccessful without continued maintenance (Palmer *et al*., 2007; Beechie *et al*., 2010; Christian-Smith and Merenlender, 2010).

Identifying the factors that have the greatest influence on sandbar availability will help direct restoration and management efforts to conserve and increase the availability of sandbar habitat and improve the sustainability of these efforts. The objective of this study was to determine which factors influence sandbar availability in the Kansas River, USA, and at which scale (i.e. local, directly upstream, or tens of kilometres upstream) they are most influential. We hypothesized that conversion of natural land cover to agricultural and urban cover in tributaries supplying the river with sediment tens of kilometres upstream would have the greatest influence on the availability of sandbars.

METHODS

Study area

The Kansas River is a 274-km seventh-order sand-bed river that begins at the Smokey Hill and Republican Rivers confluence and flows into the Missouri River at Kansas City, Kansas. The river is shallow and wide, with a mean depth of 1.5 m at mean discharge (214 $m^3 s^{-1}$; Makinster, 2006) and a mean bankfull width of 164 m (Eitzmann and Paukert, 2010b). Sandbars are common throughout the river, although channel complexity has been reduced, and historical accounts indicate that sandbars were more prevalent prior to settlement within the Kansas River basin (Metcalf, 1966; O'Neill and Thorp, 2011). No large dams occur on the mainstem Kansas River, but four large flood-control dams have been built on major tributaries to the Kansas River: Milford Reservoir (64-km^2 surface area) on the Republican River [confluence with the Kansas River at river kilometre (rkm) 274], Tuttle Creek Reservoir (50-km^2 surface area) on the Big Blue River (confluence with the Kansas River at rkm 230), Clinton Reservoir (28-km^2 surface area) on the Delaware River (confluence with the Kansas River at rkm 102), and Perry Reservoir (47-km^2 surface area) on the Wakarusa (confluence with the Kansas River at rkm 66). Additionally, three low-head obstructions, Tecumseh low-head dam (rkm 122), Bowersock Dam (rkm 85), and Johnson County weir (rkm 18), slow upstream water velocities for relatively short reaches ($<$5 km) and create short reaches with reservoir-like habitats (Eitzmann and Paukert, 2010b) that may influence downstream sediment transport at low flows. However, high flows capable of transporting sediment regularly top these structures. Tecumseh low-head dam and Johnson County weir contained side chutes during the study period, which presumably allowed bed-material transport (as evidenced by deposition of bed-material load immediately downstream), although bed-material load may be restricted by Bowersock Dam.

Agriculture (row crop) and grassland (rangeland and prairie) are the dominant land uses in the Kansas River watershed and comprise over 90% of the land use/land cover (LULC) within the basin (Homer *et al*., 2007). Urban cover composes 3% of the watershed (Homer *et al*., 2007), and five urban areas occur along the Kansas River. Kansas City is the largest city with a population of 147 700 and is located from rkm 0 to 16. Topeka (from rkm 130 to 145) is the next largest city with a population size of 122 000, followed by Lawrence (from rkm 82 to 85) with 82 000 residents, Manhattan (from rkm 237 to 241) with 44 700 residents, and Junction City (from rkm 272 to 274) with 18 000 residents (based on a 2003 census).

Data collection

We divided the Kansas River into bend series, with two consecutive river bends denoting a series; each bend series began and ended in a channel crossover (the area where the channel transitions from one bank to the other; Figure 1; Figure 2), and the mean length of the bend series was 6.12 km (SE = 4.15 km). Bend series were identified using aerial photographs of the Kansas River from the US Army Corps of Engineers taken on 29 February and 1 March

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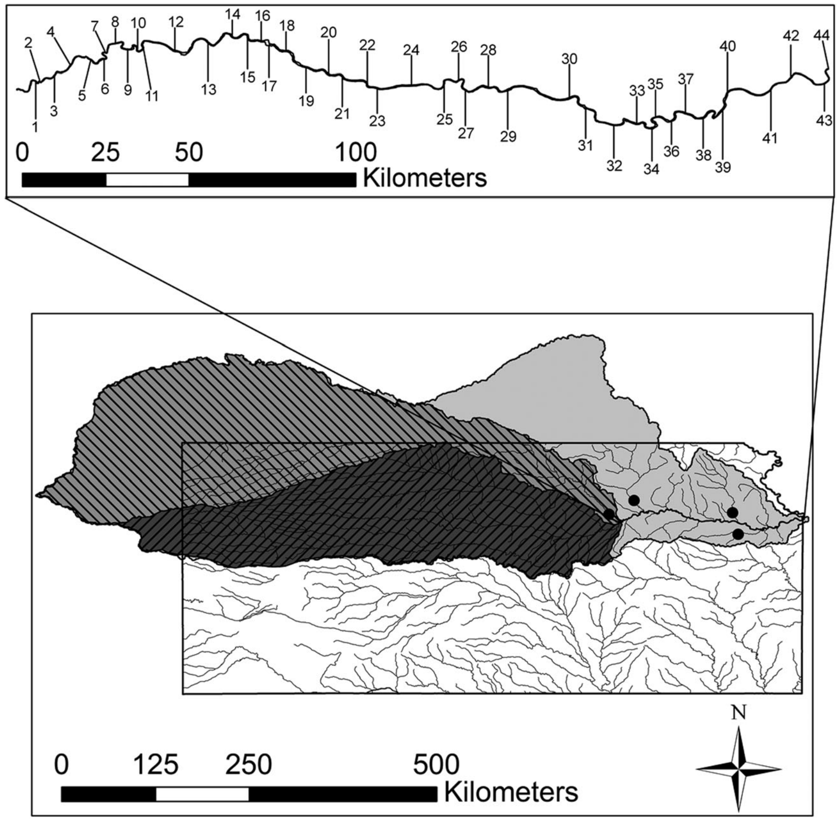

Figure 1. The Kansas River (black line) and bend series used in this study; in the upper panel, each number marks the end of a bend series and the start of the next. The Kansas River basin is highlighted by the light gray shading, and the Smoky Hill and Republican River basins, which converge to form the Kansas River, are highlighted with cross-hatched dark gray and light gray shading respectively. Additionally, black dots denote the locations of major impoundments within the Kansas River basin

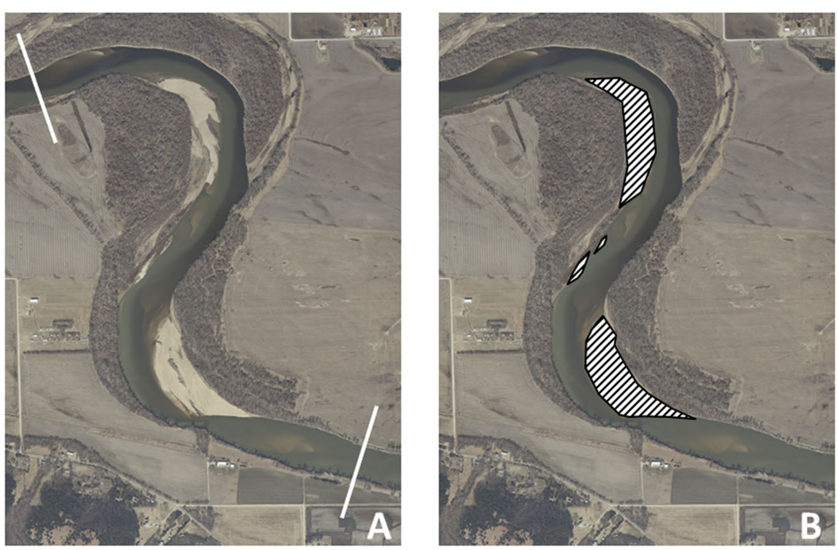

Figure 2. Delineation of a bend series and sandbars. Two consecutive river bends denoted a bend series; white lines (A) denote the channel crossover that designated the beginning and end of a bend series. Sandbars, highlighted with cross-hatching (B), were classified through manual interpretation and considered to be areas of visible sediment surrounded by water or between the water surface and most pronounced vegetated bank. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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2008, with a resolution of 0.3 m per pixel, at a discharge of approximately 25–40% daily exceedance (Figure 3). Meander bends in large alluvial rivers are similar to pool-riffle sequences often used to segregate small streams into functional units (Knighton, 1998) and provided a geomorphic unit appropriate for inference. The influence of LULC on sandbars within a bend series was addressed at three scales to account for upstream influences. The local-scale incorporated factors within a bend series of interest, the adjacent-scale incorporated factors from the adjacent upstream bend series and the segment-scale incorporated factors from one to five bend series upstream, except in the five upstream bend series that had fewer than five bend series upstream (these bend series incorporated LULC from the adjacent upstream bend series to the most upstream bend series). Five bend series were chosen to define the segment scale to provide a larger cumulative scale for inference. The upstream most bend series was excluded from adjacent and segment-scale analyses because there were no bend series upstream of this one.

Riparian LULC (i.e. land cover along the mainstem Kansas River) was obtained from the Kansas Land Cover Patterns Mapping Initiative (Peterson *et al*., 2010; Table I), using 200 m beyond bankfull height on each side of the river to delineate the riparian zone, which encompassed the floodplain within a series of levees (Eitzmann and Paukert, 2010b). The riparian LULC was standardized as a proportion of the total riparian area within a bend series, to account for differences in the areas of bend series. The cumulative contributing area and LULC of tributaries flowing into a bend series were obtained from the Kansas GAP analysis

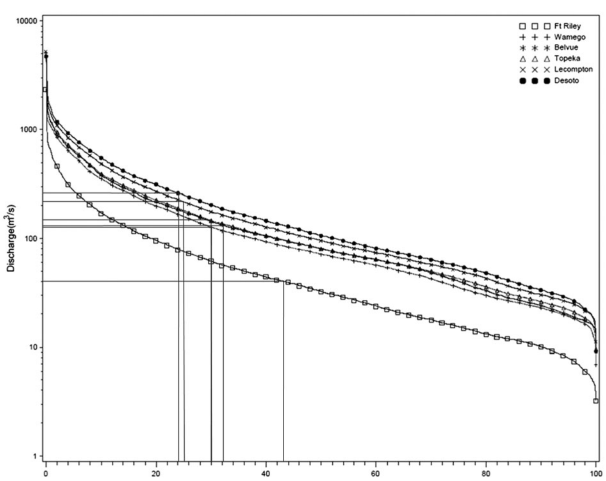

Figure 3. Discharge at US Geological Survey gauges within the Kansas River, in relation to percent flow exceedance from January 1964 to January 2012. Lines indicate the discharge at each gauging station during the acquisition of the aerial photographs, which were 39, 129, 122, 142, 215, and 255 $m^3 s^{-1}$ at Fort Riley, Wamego, Belvue, Topeka, Lecompton, and Desoto respectively

program database (Homer *et al*., 2007; Figure 4). The total area of tributary LULC was used to account for the disproportionally large influence of larger tributaries on riverine habitat (Benda *et al*., 2004). If a major impoundment was present on a tributary, only the LULC below that impoundment was included in the analyses because flow and sediment contributions upstream of a dam were likely attenuated by the reservoir, although the degree is dependent on hydrologic events and reservoir operations (Williams and Wolman, 1984; Johnson, 1994; Kondolf, 1997). Because major impoundments can influence the flow and sediment regime of rivers (Kondolf, 1997; Poff *et al*., 1997), the proportion of mean discharge from the four major impoundments in the Kansas River basin (Milford, Tuttle Creek, Clinton, and Perry reservoirs) was calculated for each bend series. Records from US Geological Survey gauging stations immediately downstream of each of the dams (gauges 06857100, 06887000, 06890900 and 06891500) were used to calculate mean discharge from each impoundment from 1964 to 2012, and the cumulative mean discharge from each dam above a bend series was divided by the mean discharge, from 1964 to 2012, at the nearest upstream US Geological Survey gauging station of the Kansas River (gauges 06879100, 06887500, 06888350, 06889000, 06891000 and 06892350). Additionally, because no gauging records were available for discharge immediately upstream of the Big Blue River (impounded by Tuttle Creek Reservoir) confluence and its large contribution of flow to the Kansas River, the mean discharge in bends between the Big Blue River and the nearest downstream gauge (06887500) was assumed to be similar.

Bankfull stream power, an index of sediment transport and bank erosion (Knighton, 1998), was calculated for each bend series.

$$\text{Bankfull stream power} = \frac{\rho g Q S}{w} \qquad (1)$$

where ρ is the density of water at 20°C (0.99 $kg\,m^{-3}$), g is the acceleration as a result of gravity (9.81 $m\,s^{-2}$), Q is the bankfull discharge ($m^3 s^{-1}$), S is the channel slope of the Kansas River, and w is the mean bankfull width (m) within a bend series. Bankfull discharge was considered to be the flow pulse that recurred, on average, every 1.5 years (Simon *et al*., 2004) and was calculated for each of the six US Geological Survey gauging stations on the Kansas River, using the Indicators of Hydrologic Alteration software (Richter *et al*., 1996). The time period 1964–2012 was used to calculate bankfull discharge because this period represented a modern regulated flow regime after large tributary dams were created in the early 1960s. The bankfull discharge from the nearest upstream gauging station was used in calculations of bankfull stream power for each bend series. The

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Table I. Mean values, ranges, and data sources of variables for all bend series and models used to evaluate the response of sandbars to land use–land cover (LULC) within the watersheds encompassing the Kansas River

Attribute	Mean	Range	Models included in	Data source
Dependent variables				
Sandbar density (number km^{-2})	10.04	1.03–29.51	All	Aerial photos, Army Corps of Engineers
Sandbar area (m^2)	175656.40	88.00–634 041.00	All	Aerial photos, Army Corps of Engineers
Independent variables				
Bankfull power (W m^{-2})	0.02	0.01–0.04	Bankfull stream power[a]	This study
Proportion of discharge from major impoundments	0.51	0.32–0.59	Major impoundments	This study
Proportion of riparian cropland	0.33	0.00–0.67	Riparian cropland[a,b], riparian altered land use[a,b], riparian land use[a,b]	Peterson *et al*., 2010
Proportion of riparian urban cover	0.10	0.00–0.94	Riparian urban cover[a], riparian altered land use[a], riparian land use[a]	Peterson *et al*., 2010
Proportion of riparian grassland	0.18	0.00–0.61	Riparian grassland[a], riparian land use[a]	Peterson *et al*., 2010
Proportion of riparian forest cover	0.37	0.00–0.57	Riparian forest cover[a], riparian land use[a]	Peterson *et al*., 2010
Tributary contributing area (km^2)	3505.65	0.00–111 053.00		Homer *et al*., 2007
Area of tributary cropland (km^2)	446.00	0.00–17 082.00	Tributary watershed cropland[a], tributary watershed altered land use[a], tributary watershed land use[a]	Homer *et al*., 2007
Area of tributary urban cover (km^2)	13.50	0.00–218.00	Tributary watershed urban cover[a], tributary watershed altered land use[a], tributary watershed land use[a]	Homer *et al*., 2007
Area of tributary grassland (km^2)	773.31	0.00–28 120.00	Tributary watershed grassland[a], tributary watershed land use[a]	Homer *et al*., 2007
Area of tributary forest cover (km^2)	30.89	0.00–340.00	Tributary watershed forest cover[a], tributary watershed land use[a]	Homer *et al*., 2007

Each model was evaluated at the local (LULC within bend series of interest), adjacent (LULC from adjacent bend series upstream from bend series of interest), and segment scale (LULC from one to five bend series upstream from bend series of interest). A global model was developed for each scale, which included all the variables at that scale.
[a]The model was also used to assess the density or area of sandbars in relation to variables from adjacent bend series upriver.
[b]The model was also used to assess the density or area of sandbars in relation to variables from segment scale (summation of variables from one to five bend series upriver).

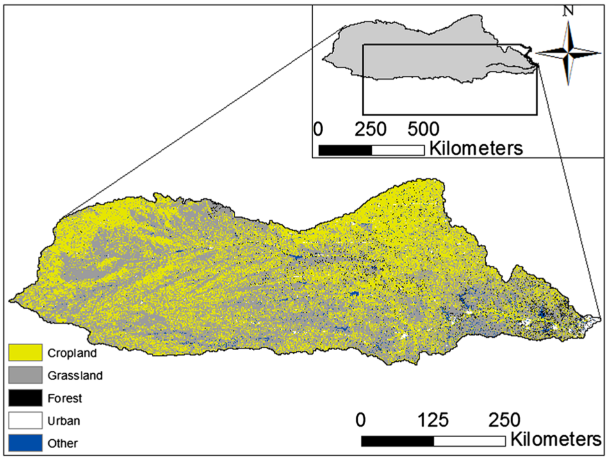

Figure 4. Land use–land cover within the Kansas River Basin from the 2001 National Land Cover Database. Land use–land cover that was not cropland, grassland, forest, or urban cover (e.g. water) is represented as the other category. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

slope of the entire Kansas River was used because the 1.64-m accuracy of the 30-m resolution digital elevation model (Gesh, 2007) prevented the calculation of reliable slope estimates for each bend series. Although slope can be assumed to be near zero for bend series directly above the three low-head obstructions at mean discharge, bankfull discharges submerge Tecumseh low-head dam and Johnson County weir and decrease the distance upstream of Bowersock Dam with a slope of zero, reducing bias in the slope used to calculate bankfull stream power of the associated bend series. Length and mean width (measured at the beginning, middle, and end) of a bend series were measured using the aerial photos previously described.

The number and area of sandbars within the Kansas River for each bend series were quantified in ArcGIS from the aerial photographs previously discussed. Although additional photographs at multiple discharges would have allowed assessment of sandbar habitat under various conditions, only one set of photographs taken under consistent discharges was available for analysis. Nevertheless, these photographs represent discharges that commonly occur and provide a proxy of the habitat frequently available. Sandbars were classified as an area of visible sediment surrounded by water or between the water surface and the most pronounced vegetated bank (Eitzmann and Paukert, 2010a; Figure 2). All measurements were standardized as the density (number per rkm) and mean area (m^2) of sandbars for each bend series.

Statistical analysis

An information theoretic approach was used to assess which subset of factors was likely the most influential on the density and size of sandbars within the Kansas River. This approach weights models (i.e. hypotheses) based on their likelihood of correctly approximating the data and the number of parameters included in the model (Burnham and Anderson, 2002). Models with greater likelihood are more likely to be correct; however, likelihood can be inflated by including more parameters; thus, models are penalized for each parameter included. In general, the best model will have the greatest likelihood relative to the number of parameters (Burnham and Anderson, 2002).

Competing hypotheses were developed *a priori* based on riparian and watershed factors influencing the density and size of sandbars in the Kansas River (Table I). Sixteen hypotheses were tested at three scales (local, adjacent and segment). Our first six hypotheses addressed the effect of riparian LULC on sandbar habitat, with the first focused on the proportion of cropland, the second on urban cover, the third on the proportion of forest, the fourth on the proportion of grassland, the fifth on both cropland and urban cover (altered LULC), and the sixth on all four. A natural LULC model was not considered because the natural (i.e. prairie) and altered (i.e. rangeland) LULC of grassland could not be separated. The influence of the contributing area of tributaries flowing into a bend series on a sandbar habitat was addressed in our seventh hypothesis. Our 8th through 13th hypotheses accounted for the influence of LULC in the watershed of contributing tributaries in a bend series, with the 8th focused on the area of a cropland, the 9th on the area of urban cover, the 10th on the area of a forest, the 11th on the area of a grassland, the 12th on altered LULC, and the 13th on cropland, urban cover, and forest (grassland was excluded from this model because of a positive correlation with cropland; variance inflation factor = 17). Our 14th hypothesis accounted for the proportion of discharge from major impoundments within a bend series. Our 15th hypothesis addressed the influence of bankfull stream power on sandbar habitat, and the 16th hypothesis was a global hypothesis that included all variables used in the models described previously. Our 17th hypothesis was a random model that compared the density and mean area of sandbars with a dataset of randomly generated numbers. We developed this approach to assess if other models performed better than random. The same hypotheses were considered at the adjacent and segment scale, except the hypothesis addressing discharge from major impoundments at both scales and the hypothesis considering bankfull stream power at the segment scale. Additionally, terms within these models were dropped from the global model.

Linear regression models were developed in R 2.13.2 (R Foundation for Statistical Computing, Vienna, Austria) and used to test each hypothesis. The mean sandbar area, bankfull stream power, contributing area of tributaries, and area of each LULC in the contributing watershed were

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$\log_e + 1$ transformed, and the proportion of urban cover in the riparian zone was arcsine square root transformed prior to the analysis to better meet normality assumptions. The proportion of urban cover in the riparian zone was transformed to the presence or absence for local and adjacent-scale analyses because urban riparian cover was absent from half of the bend series and failed to meet normality assumptions. The relative ability of each model to explain the proportion and density of sandbars was assessed using a second-order information criterion [Akaike information criterion $(AIC)_c$] because it is able to account for small sample sizes (Burnham and Anderson, 2002). Models with a ΔAIC_c of two or less were considered to perform the best given the data. Additionally, model averaging was conducted, following Burnham and Anderson (2002), to determine the relative importance of each parameter considered in the models.

RESULTS

A total of 597 sandbars were measured over the 44 bend series in the Kansas River, comprising a total area of 6.52 km^2, with a mean density of 10.04 sandbars per km^2 and a mean area of 0.18 km^2. Cropland, urban cover, grassland, and forest composed a mean of 33% (SE = 0.01), 10% (SE = 0.05), 18% (SE = 0.03), and 37% (SE = 0.06), of the riparian area, respectively. The mean area of cropland, urban cover, grassland, and forest within tributary watersheds was 446.00 km^2 (SE = 67.24), 13.50 km^2 (SE = 2.03), 773.31 km^2 (SE = 116.58), 30.89 km^2 (SE = 4.66) respectively (Table I).

The model that best explained the density of sandbars was the segment-scale tributary watershed LULC model (Table II), which predicted that the density of sandbars would increase with increased cropland and urban cover and decrease with increased forest within tributary watersheds. No other models had a ΔAIC_c less than two. Cropland, urban, and forest cover at the segment scale were ranked as the three most important variables considered in the models and had a relative importance of 0.96 (Table III); the next greatest relative importance (0.02) was for bankfull power at the adjacent scale. The top performing models examining the mean area of sandbars were tributary watershed altered LULC ($\Delta AIC_c = 0$) and tributary watershed LULC at the segment scale ($\Delta AIC_c = 1.05$; Table II). These models predicted that the mean size of

Table II. Top three models assessing the density and area of sandbars within the Kansas River, number of parameters in a model (*K*), second-order information criterion (AIC_c) scores, Akaike model weights (ω_i), log likelihood ($£(g_i|x)$), parameter estimates, and 95% confidence intervals (CI) of parameter estimates

Model	K	AIC_c	ΔAIC_c	$£(g_i\|x)$	ω_i	Parameter	Beta	95% CI	
Sandbar density									
Tributary watershed land use–land cover	6	267.91	0.00	−128.02	0.96	Intercept	10.66	2.35	18.98
Segment scale						km^2 of cropland	4.19	2.71	5.67
						km^2 of urban cover	0.41	−2.02	2.83
						km^2 of forest	−5.93	−8.95	−2.91
Bankfull power	3	275.97	8.31	−134.68	0.02	Intercept	16.72	12.88	20.56
Adjacent scale						Bankfull power	−501.60	−747.70	−255.50
Tributary watershed in a grassland area	3	277.13	9.47	−135.26	0.01	Intercept	−7.55	−16.63	1.53
Segment scale						km^2 of grassland	2.52	1.22	3.82
Sandbar density with two influential observations removed									
Bankfull power	3	238.34	0.00	−115.85	0.48	Intercept	15.16	12.28	18.05
Adjacent scale						Bankfull power	−451.18	−633.69	−268.67
Bankfull power	3	239.63	1.29	−116.49	0.25	Intercept	14.33	11.65	17.01
Local scale						Bankfull power	−369.91	−525.85	−213.97
Tributary watershed in an urban area	3	242.33	3.99	−117.84	0.07	Intercept	12.99	10.62	15.37
Local scale						km^2 of urban cover	−2.55	−3.73	−1.37
Sandbar area									
Tributary watershed altered land use land cover	4	119.31	0.00	−55.13	0.41	Intercept	8.96	7.79	10.13
Segment scale						km^2 of cropland	0.30	0.06	0.55
						km^2 of urban cover	−0.46	−0.81	−0.11
Tributary watershed land use–land cover	6	120.36	1.05	−54.37	0.25	Intercept	8.41	6.91	9.91
Segment scale						km^2 of cropland	0.24	−0.03	0.51
						km^2 of urban cover	−0.62	−1.06	−0.18
						km^2 of forest	0.32	−0.23	0.86
Tributary urban cover	3	123.17	3.86	−58.28	0.06	Intercept	9.80	8.79	10.82
Segment scale						km^2 of urban cover	−0.18	−0.46	0.10

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Table III. Model-averaged relative importance (ω_i), beta estimates, and 95% confidence intervals (CI) of parameters and scale of the models a parameter was included in

Parameter	Scale	ω_i	Beta	95% CI	
Sandbar density					
Area of tributary cropland (km^2)	Segment	0.96	4.19	2.70	5.67
Area of tributary urban cover (km^2)	Segment	0.96	0.40	−2.03	2.82
Area of tributary forest cover (km^2)	Segment	0.96	−5.93	−8.95	−2.91
Sandbar density with two influential observations removed					
Bankfull power	Adjacent	0.48	−451.18	−633.69	−268.67
Bankfull power	Local	0.25	−369.91	−525.86	−213.95
Area of tributary urban cover (km^2)	Local	0.18	−2.51	−3.87	−1.15
Area of tributary cropland (km^2)	Local	0.12	1.16	−0.11	2.44
Sandbar area					
Area of tributary urban cover (km^2)	Segment	0.73	−0.50	−0.87	−0.12
Area of tributary cropland (km^2)	Segment	0.71	0.28	0.02	0.54
Area of tributary forest cover (km^2)	Segment	0.28	0.30	−0.23	0.84

Only parameters with a relative weight greater than 0.1 are shown.

sandbars would decrease with increases in urban cover and increase with cropland and forest in the tributary watersheds. Therefore, both the density of sandbars and the mean area of sandbars were best explained by LULC in tributaries at the segment and watershed scale. Urban, cropland, and forest cover at the segment scale were ranked as the three most important variables considered in the models examining sandbar area and had a relative importance of 0.73, 0.71, and 0.28 respectively (Table III). However, two observations were influential in models focused on sandbar density and tributary watershed LULC. These observations correspond to the first two bend series, which were influenced by the confluence of the Smoky Hill and Republican Rivers (Figure 1), the largest tributaries of the Kansas River, and had sandbar densities over 25 sandbars per km^2, whereas all others were less than 20 sandbars per km^2. The high density of sandbars in downstream bend series suggests that this confluence is geomorphologically significant (Benda *et al.*, 2004). Excluding these outliers from the analysis resulted in the models assessing bankfull stream power at the adjacent and local scales becoming the top performers ($\Delta AIC_c = 0$ and $\Delta AIC_c = 1.29$ respectively), and the model assessing tributary watershed LULC at the segment scale dropped to the sixth best model ($\Delta AIC_c = 4.76$; Table II). The parameters with the highest relative importance from this set of models were bankfull power at the adjacent and local scale and urban and cropland at the local scale (relative importance 0.48, 0.25, 0.18, 0.12 respectively; Table III).

DISCUSSION

Land use and land cover within tributary watersheds at the segment scale were the most influential of the variables predicting sandbar density and area and suggest that sandbars within the Kansas River are correlated with sediment conveyance and/or supply from tributaries to the mainstem. The positive correlation between agriculture and sandbar size and density likely stems from increased erosion associated with agriculture (Knighton, 1998). Sediment eroded from cropland is an unnatural source that is detrimental to tributary streams and fishes (Burcher *et al.*, 2007), and we suggest that restoration efforts avoid increasing sediment supply from cropland. Additionally, sandbar size and density were correlated with urban cover within tributary watersheds; however, urban cover only composes 3% of the Kansas River basin, primarily near the Kansas River. Although these areas may be within tributary watersheds, they are often near the riparian zone of the Kansas River and may incorporate unmeasured factors (e.g. channelization) with more localized influences. Lastly, decreases in sandbar density with increased forest within tributary watersheds likely stems from large woody debris stabilizing sediments (Keller and Swanson, 1979; Abbe and Montgomery, 1996). Forest cover within tributary corridors of the Kansas River basin has increased following fire suppression and other anthropogenic alterations (Knight *et al.*, 1994) and may increase sediment storage within these streams. However, our analysis only highlights these LULCs as being influential and not the mechanisms behind their influence. Future studies incorporating specifics on sediment supply and conveyance in relation to LULC within tributary watersheds would allow a process-based understanding of how LULC impacts sandbar formation.

With the two influential observations removed from the sandbar density analysis, bankfull stream power at the adjacent and local scales was also important in

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determining sandbar densities. Given that the relationship between bankfull stream power and channel morphology has been well documented (Knighton, 1998), the strong performance of the bankfull stream power models is not surprising. Lower densities of sandbars in bend series with higher bankfull stream power likely stem from higher sediment transport rates associated with increased stream power.

The value of the information theoretic approach is relative to the models developed. Variables that were not measured may explain variation in the response variables, particularly when there are complex interactions among multiple mechanisms and multiple spatial scales. Our study focused on LULC, and other variables not measured in this study may also further explain sandbar size and density in the Kansas River. In this study, we were unable to include in-stream alterations that may be influential on sandbar habitat (e.g. sand dredging and channelization) because the resolution of the aerial photos was not fine enough to allow these factors to be accurately quantified. Reductions in sandbars and alterations to channel morphology have been documented where sediment load was reduced through dredging (Kondolf, 1997), which in the Kansas River, is a major source of sediment loss that may influence channel morphology (Fischer *et al*., 2012). Channelization structures also are intermittently present throughout the Kansas River, which constrict flow to a narrowed main channel (Pinter *et al*., 2010) and may reduce sediment availability and deposition through reducing lateral channel migration and artificially increasing bankfull stream power. Channelization structures may also create favourable hydraulic situations for the persistence of some sandbars (Tracy-Smith *et al*., 2012). Furthermore, the bend series with the greatest proportion of urban riparian cover were in the downstream-most sections of the river, which are also subject to dredging, channelization, and backwater from the Missouri River, which together may have confounded the influence of riparian urban cover. Future studies may benefit by incorporating the influence of in-stream alterations on sandbar habitat.

The influence of large impoundments in Kansas River tributaries was not evident, and the proportion of discharge from major impoundments was not included as a variable in any of the top models. This is a surprising finding given that prior studies of Great Plains rivers have shown that dams cause reductions in sediment load for several hundred rkm, although these effects do diminish with distance from the dam (Williams and Wolman, 1984). The dam influence may be counteracted by sediment introduced from agricultural soil erosion or from bank and bed erosion, or dam influences may be expressed as changes in grain-size distributions, which were not captured in our analysis.

Rivers are complex systems, where interactions among multiple variables give rise to unique and intricate dynamics (Hynes, 1975; Poole, 2002). Our methods helped parse down a number of variables and identify those that were influential on sandbar habitat. In particular, LULC within tributary watersheds appears to be influential on sandbar size within the Kansas River, and consideration of processes within tributary watersheds could improve the success of large river restoration projects. Additionally, given the strong performance of segment-scale models, the effect of LULC within a tributary's watershed on the size of sandbars in the mainstem may not be seen for several kilometres downstream. However, the relationship between LULC within tributary watersheds and sandbar densities was more ambiguous and appears to be driven by bend series at the head of the Kansas River, which had substantially higher densities of sandbars. Nevertheless, taking the current state of the landscape into context is of value when considering habitat within large river systems, as is understanding the role of landscape processes on run-off and sediment delivery (Beechie *et al*., 2010).

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