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THE EFFECT OF LAND USE ON CHANNEL GEOMETRY AND SEDIMENT DISTRIBUTION IN GRAVEL MANTLED BEDROCK STREAMS, ILLINOIS RIVER WATERSHED, ARKANSAS

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ABSTRACT

Headwater stream morphology is a direct reflection of watershed characteristics and therefore can inform our understanding of anthropogenic influence on channel geometry and sediment dynamics. Little knowledge of the geomorphology of headwater streams in the Ozark Plateaus region of northwest Arkansas exists. The Illinois River watershed, in northwest Arkansas, is of critical interest within the region because of land use changes in the headwaters due to rapid population growth. A mixture of forest and agricultural (open pasture and poultry houses) land use dominates the watershed, but urban areas are rapidly expanding. These land use types: forest, agriculture and urban are an effective proxy for increasing anthropogenic disturbance. Analysis of longitudinal profile, cross-section and sediment distribution in streams from each land use type shows a strong trend of increasing slope and channel cross-sectional area with a greater degree of anthropogenic disturbance. Additionally, urban streams are characterized by the presence of exposed bedrock in the stream bed, while agricultural and forested streams are gravel mantled. These data have important implications for current and future stream management policies and practices regionally. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: channel geometry; sediment dynamics; bedrock streams; headwater streams

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INTRODUCTION

Anthropogenic activity has long been recognized as a controlling influence on stream morphology and bed material distribution by both geomorphologists and ecologists (Wolman, 1967; Leopold, 1968; Allan, 2004; Kang and Marsten, 2006; Poff *et al*., 2006; Urban *et al*., 2006; Levell and Chang, 2008). Stream morphology and ecology are an integration of geology, climate, habitat and disturbance regime over a range of spatial and temporal scales; hence identifying specific watershed responses to human action continues to be a challenge (Montgomery, 1999; Allan, 2004). We must strive to understand stream response within the context of the landscape processes, both natural and anthropogenic, on a continuum of spatial scales from stream reach to watershed to the wider physiographic region.

Understanding the direct and indirect effects of anthropogenic disturbance on stream systems is of critical importance for research and management. Urbanization of watersheds results in increased stream discharge, flow variability and increased sediment loads leading to habitat degradation (Allan, 2004; Chin, 2006; Poff *et al*., 2006). Wolman (1967) described three stages of river response to urbanization. The initial stage is a stream in dynamic equilibrium with the primarily agricultural or forested watershed. As development occurs the channel equilibrium is altered by a drastic increase in sediment due to land clearing. Once the development is complete with paved roads, culverts and sewers sediment load decreases and a new equilibrium or disequilibrium state evolves. Conversion of forest cover to agricultural land use can have similar results, but generally to a lesser degree (Montgomery, 1999; Allan, 2004; Poff *et al*., 2006). This general pattern has been observed globally in fluvial systems (Chin, 2006).

Headwater streams are particularly sensitive to anthropogenic disturbance and are likely to respond differently than higher order streams, because of the direct connection between watershed hill slopes, riparian zones and stream channels (Vannote *et al*., 1980; Frissell *et al*., 1986; Montgomery and Buffington, 1997; Liebault *et al*., 2005). The hierarchical nature of fluvial systems as described in the River Continuum Concept (Vannote *et al*., 1980) illustrates the natural upstream to downstream linear relationship of these systems, and dictates that stream characteristics at any individual point on a river are defined by all influences upstream. Distinguishing the effects of human versus natural disturbances is especially problematic in larger watersheds because stream morphology is an aggregate of all processes operating throughout the watershed. It follows that within the upper reaches differences in natural factors such as geology, hydrology and climate throughout an individual watershed are limited. Therefore, headwater streams are an

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ideal natural laboratory for studying system response to anthropogenic disturbance.

Existing knowledge of stream morphology in the Ozark Plateaus province varies widely in location, geographic extent and parameters measured; restricting our understanding of individual watersheds such as that of the Illinois River. The purpose of the research reported here is to relate geomorphic characteristics and sediment distribution within first and second order streams (headwater streams) in the Illinois River watershed to the dominant land use of the associated sub-watersheds. The basic conceptual model is that: forest land use has little to no anthropogenic disturbance; agricultural land use has moderate anthropogenic disturbance such as soil compaction from cattle grazing and heavy farm equipment; and urban land use has the maximum anthropogenic disturbance including active bank erosion control as well as paving and landscaping of the floodplain. Through a comparison of multiple headwater streams we constrain the range of expected morphology for the entire headwaters of the larger Illinois River watershed, and examine how this applies to the management concept of 'reference reaches' locally. The results have important implications for water quality and ecological health of headwater streams, as well as current and future stream restoration and protection projects.

Following Wolman's (1967) three stage model of channel response to urbanization, the streams selected for this study have reached a new persistent equilibrium/disequilibrium. We hypothesize that forested headwater streams with the least amount of anthropogenic impact will form multithread channels with greater sinuosity and width/depth ratios. As land use shifts from forest to agriculture to urban with an associated increase in anthropogenic impact, multithread channels will disappear, width/depth ratios will decrease and sinuosity will approach singularity.

SETTING

The Illinois River watershed is a critical catchment due to recent changes in demographics and land use. The river begins in northwest Arkansas and flows into Oklahoma where it is designated a scenic river finally emptying into Tenkiller Reservoir and the Arkansas River (Figure 1).

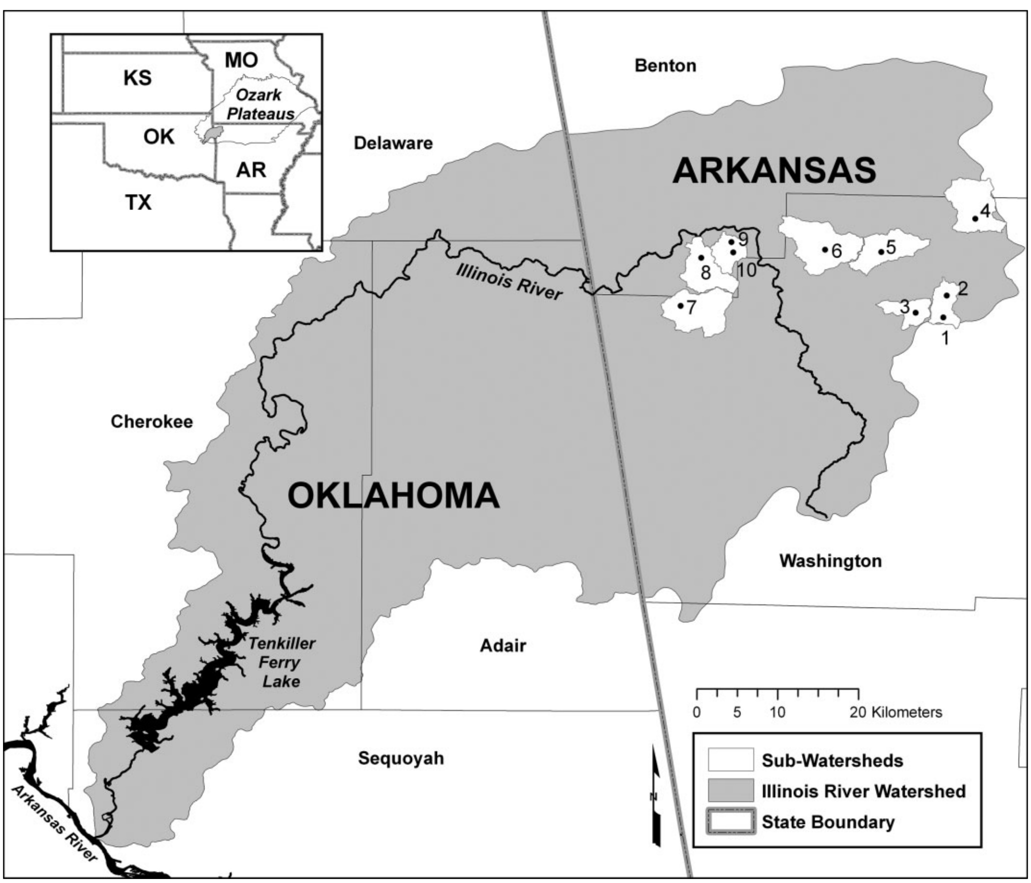

Figure 1. Geographic setting of the Illinois River watershed. Survey sites are numbered to correspond with data tables

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Northwest Arkansas has transitioned from a rural, family-farm-based agricultural economy to an urban, corporate agricultural economy, with an increase in population density of 47.76% from 66.87 persons km^{-2} in 1990 to 98.81 persons km^{-2} in 2000 (Center for Advanced Spatial Technologies, 2006; Ward, 2007). Such changes in land use practices are often reported to affect stream morphology (Dutnell, 2000; Panfil and Jacobson, 2001; Reuter *et al*., 2003; Keen-Zebert, 2007; Nickolotsky and Pavlowsky, 2007) as well as the ambient nutrient concentrations in streams regionally (Haggard *et al*., 2001; Petersen *et al*., 1998; Popova *et al*., 2006).

The headwaters of the Illinois River in Arkansas flow across the lower Mississippian age Boone Formation, a cherty limestone that forms relatively low relief hills and valleys with high steep bluffs along streams on the Springfield Plateau (Stanton, 1993; King, 2001). The Springfield Plateau is one of the three erosional surfaces that comprise an asymmetrical dome in northwest Arkansas and southern Missouri called the Ozark Plateaus Geomorphic Province. The Boone Formation ranges from 30 to 147 m thick and is at the surface through the majority of the study area. Cherty regolith derived from the Boone Formation is present on hill slopes from 1 to 50 m thick throughout the watershed as well as accumulating in stream channels (Parse, 1995).

Surface hydrology in the Ozark Plateaus exhibits a dendritic drainage pattern, and first and second order streams dominate total stream length. The small meandering headwater streams regionally exhibit well-developed riffle and pool sequences (Brussock *et al*., 1985). Fractured mantled karst controls surface water and groundwater flow patterns and pathways, complicating the relationship between these flow paths, and strongly influencing stream hydrographs (Madole *et al*., 1991).

Characteristics of hydraulic geometry, longitudinal profile, cross-sectional geometry and planform are generally poorly understood in low-order streams and poorly documented for the Illinois River watershed in particular. Two recent projects focus on aspects of the relationship between watershed characteristics and land use–land cover (LULC) change in the headwaters of Illinois River watershed. LULC changes have led to channel widening as measured from aerial photography from 1941 to 2004 with the lower gradient headwater stream reaches in proximity to urban areas exhibiting the greatest degree of widening (Ward, 2007). This research illustrated historic change in geomorphic parameters that can be measured via remotely sensed data. Modern headwater stream morphology differences were documented through a paired watershed study of an urban stream and a rapidly urbanizing stream in Washington County (Keen-Zebert, 2007). These studies focused on channel evolution in response to long-term and short-term land use change. In contrast this study compares modern channel morphology in small watersheds with long-term (more than 10 years) consistent land use.

REGIONAL GEOMORPHIC RESPONSE TO LAND USE

The largest body of previous geomorphic research in the Ozark Plateaus region has focused on federally managed rivers including the Buffalo National River in Arkansas and the Ozark National Scenic Riverways in Missouri. The Ozark Geomorphology Project, active from 1992 to 1999, conducted by the Biological Resources Division of the United States Geological Survey (USGS), sought to describe how historic land use has affected modern stream morphology and habitat condition (McKenny *et al*., 1995; Jacobson and Primm, 1997; Jacobson and Gran, 1999; Jacobson and Pugh, 1997; Panfil and Jacobson, 2001). Land use practices since European settlement – logging, open grazing and clearing of riparian zones – has caused a non-point source disturbance leading to increases in gravel deposits within these watersheds. As a result of this anthropogenic disturbance gravel is transported by streams from small drainage basins and is deposited downstream in mid-size drainages. The gravel deposits are not uniform, travelling through the system in pulses and preferentially accumulating in specific areas, termed disturbance reaches. The disturbance reaches are characterized by rapid channel migration and shifting gravel bars with minimal vegetation (Jacobson and Gran, 1999). Unlike the Illinois River watershed, the watersheds studied for the Ozark Geomorphology Project have decreasing anthropogenic influence over time as federally protected lands.

METHODS

Site selection

Geographic Information System (GIS) analysis was used to identify watersheds with one dominant land use type, comprising greater than 50% forest, agriculture or urban. Data layers (Table I) for the Illinois River watershed were acquired from GeoStor, the state of Arkansas GIS data clearing house. The LULC layers were reclassified from eight land use types to four: urban, agriculture, forest and water (Table II). Per cent land use type was calculated for every 12-digit hydrologic unit code (HUC) within the Illinois River watershed in Benton and Washington counties, Arkansas. Fourteen headwater stream watersheds that meet the research goals were identified from the land use analysis; and the ten final field sites within eight watersheds were selected based on field verification of dominant land use type, suitability of site and land owner permission (Figure 1

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Table I. GIS data layers used for identification of study watersheds

Data layer	Description	Publisher
USGS watersheds	12-Digit hydrologic unit code (HUC) sub-watersheds for the Illinois River	Arkansas Natural Resources Conservation Service, 2005
Land use–land cover	Spring and Fall 2004 for Benton and Washington County, AR	Center for Advanced Spatial Technologies, 2005
USGS 1:24 000 quadrangle maps	Digital raster graphics for the Illinois River watershed	US Geological Survey, 2002

Table II. Land use reclassification from 2004 LULC data layers (Center for Advanced Spatial Technologies, 2005)

Original LULC designation	Reclassified designation
Urban – low density	Urban
Urban – high density	
Barren/bare soil	
Agriculture – crops	Agriculture
Agriculture – pasture	
Herbaceous/woody/scrub	Forest
Forest	
Water	Water

and Table III). All streams are perennial and free flowing with no dams or major diversions upstream from the survey sites. The watersheds were delineated using the ArcGIS (9.2) hydrology toolset.

Survey methods

The study reaches were surveyed with standard methods (Harrelson *et al*., 1994; Simon and Castro, 2003) using a TRIMBLE 5600 DR Total Station. Reaches begin and end at the head of a riffle where identifiable, and are approximately 10 channel widths in length, including two or more meander bends. Elevation was recorded at channel centre, thalweg, water level and bankfull. Multiple cross-sections from active floodplain to active floodplain were measured at representative riffles, runs and pools within the longitudinal profile. Two additional cross-sections, one riffle and one pool, were measured at each site using a Northwest NRL200 Automatic Rotating Laser (machine accuracy of 0.635 cm over 30.5 m). All profile and cross-section measurements have a precision of approximately +/−2 cm.

Three pebble counts were conducted at each survey site. A longitudinal profile pebble count was conducted along the length of the survey reach within the bankfull channel using the modified Wolman method to decrease operator bias (Wolman, 1954; Harrelson *et al*., 1994; Bunte and Abt, 2001). Pebbles were measured using a gravelometer for sizes 2 mm to greater than 256 mm, equivalent to gravel and cobbles on the Wentworth scale (Church *et al*., 1987; Kondolf *et al*., 2003). Particles smaller than 2 mm were estimated as sand, silt or clay by rubbing the sediment between the forefinger and thumb. Any material deemed consolidated and *in situ* was identified as bedrock. Two cross-sectional pebble counts were conducted within the bankfull channel at a riffle and a pool or run corresponding with the second set of cross-section surveys.

All channel survey data were entered into the Reference Reach Spreadsheet in the STREAMS Modules to reduce channel survey data and to calculate bankfull dimensions, slope, sinuosity and sediment distribution (Mecklenburg and

Table III. Watershed area and per cent land use calculated from reclassified land use data layer

	Site # Figure 1	Watershed	Area (km^2)	% Urban	% Agriculture	% Forest	% Water
Urban	1, 2	Scull Creek	12.81	73.50	6.90	19.26	0.34
	3	Hamstring Creek	11.84	55.35	25.09	19.49	0.08
	4	Upper Spring Creek	28.30	67.70	20.16	11.97	0.18
Agriculture	5	Little Wildcat Creek	22.68	15.07	60.43	24.26	0.24
	6	Wildcat Creek	35.59	4.56	60.00	35.44	0.01
	7	Wedington Creek	29.92	2.26	58.96	38.65	0.13
Forest	8	Chambers Spring	21.80	1.17	33.65	65.08	0.10
	9, 10	Pedro Creek	12.05	0.63	9.30	90.06	0.00

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Ward, 2004). Bankfull flow, stream force and stream power value estimates were derived from the survey data to aid in the analysis and modelling of stream form and process. The STREAMS Modules is a Microsoft-Excel-based freeware program developed by the Ohio Department of Natural Resources and Ohio State University.

RESULTS

Site descriptions

Urban land use in the watersheds are dominated by single family dwellings, apartment complexes and businesses, while isolated wooded areas and pastures are scattered throughout (Table III). The Scull Creek Watershed, Sites 1 and 2, has greater than 73.5% urban land use. Site 1 has been managed as a city park since the 1940s and has three pedestrian bridges within the longitudinal profile. Site 2 is bounded by the University of Arkansas Agricultural Park, businesses and an apartment complex. There is a paved pedestrian path within the riparian zone. The Hamstring Creek watershed, Site 3, is the least developed of the urban sites with 55% urban land use. It flows through low-density suburban housing developments and horse pastures. The Upper Spring Creek watershed, Site 4, has 68% urban land use. The study site is directly upstream from a bridge and is bordered by a cemetery and low-density homes. This stream originates less than half a kilometre from the study site as a large cement culvert in a downtown business district.

Agricultural land use includes pastures, hay fields and large corporate poultry houses. Little Wildcat Creek watershed, Site 5, has 69% agricultural land use. There are small family farms on both sides of the streams. Directly upstream of the study site the landowners maintain a spring house with pipes across the stream used for a commercial bottled water company. Site 6 in the Wildcat Creek watershed flows through a wholesale plant nursery and horse pasture. A low-water bridge bisects the longitudinal profile. Wedington Creek watershed, Site 7, flows through pasture and hayfields. Both Sites 5 and 7 are located on family farms that have maintained the same ownership for at least two generations. In all these watersheds there are occasional small low-density housing developments that reflect urban sprawl locally.

The area designated as forested land use in the study area is managed by the state and federal governments as a recreation area for hunting, hiking, mountain biking and horseback riding. The Chambers Spring watershed, Site 8, is 65% forested land use, but originates outside the forest on agricultural land. Controlled burns were scheduled for this watershed during the period of study, but were not carried out. The Pedro Creek watershed, Sites 9 and 10, is 90% forested land use. Both streams are paralleled by a gravel road in their valleys.

Profiles

Longitudinal profile data provide context for the cross-sectional data and bed material assessment. Profiles exhibit low slopes and sinuosities with some variation across land use types (Table III), indicating the uniformity of geology within the watershed. Headwater streams are often associated with steeper gradients, but the slopes in this watershed were gentle and uniform at all study sites. Mean slope was the same for forest and agricultural land use, but increased under urban land use. Reach sinuosity (stream reach length/straight line length of survey) ranges between 1.0 and 1.2 with a mean of 1.1 for urban and agricultural sites. Forested sites have increased sinuosity, ranging from 1.3 to 2.2, with a mean of 1.87. Stream sinuosity of headwater stream segments (from stream initiation to the confluence with the larger) as measured from the 1:24 000 USGS digital raster graphic ranges from 1.08 to 1.44, with no statistically significant relationship to land use.

Visual differences are readily apparent at forested sites; specifically ephemeral side channels were present with comparable width to the main channel. Also, the forested channels have overgrown meander bends with gravel bar deposits on the inside of the bend. Conversely, urban and agricultural sites are characterized by relatively straight channels for long distances with minimal meander bends of a larger wavelength and smaller frequency. Overall a distinct pattern of riffle/pool spacing in the forested streams does not emerge, but pools do exist. Urban and agricultural streams have a gentler longitudinal thalweg profile with minimal pool development as compared to forested streams.

Cross-sections

The cross-sectional geometry of all sites is highly variable within reaches regardless of land use (Figure 2A). Single factor analysis of variance for both the cross-sectional area and the width to depth ratio data shows no statistically significant difference at the 95% confidence level, but there are some apparent trends in the data. Forested streams have the largest range of width to depth ratio values followed by urban streams; and mean cross-sectional area decreased from 14.4 in urban sites to 7.8 in forested sites (Table IV). The trend in increasing area with increasing anthropogenic disturbance is reflected in the mean maximum depth: urban = 1.5 m, agriculture = 1.3 m and forest = 1.0 m.

Forested streams have gravel deposits within the bankfull channel parallel to the banks. These channel margin bars are approximately half a metre higher than the channel bed, 3.1–7.4 m wide, and occupy 20–50% of the bankfull channel

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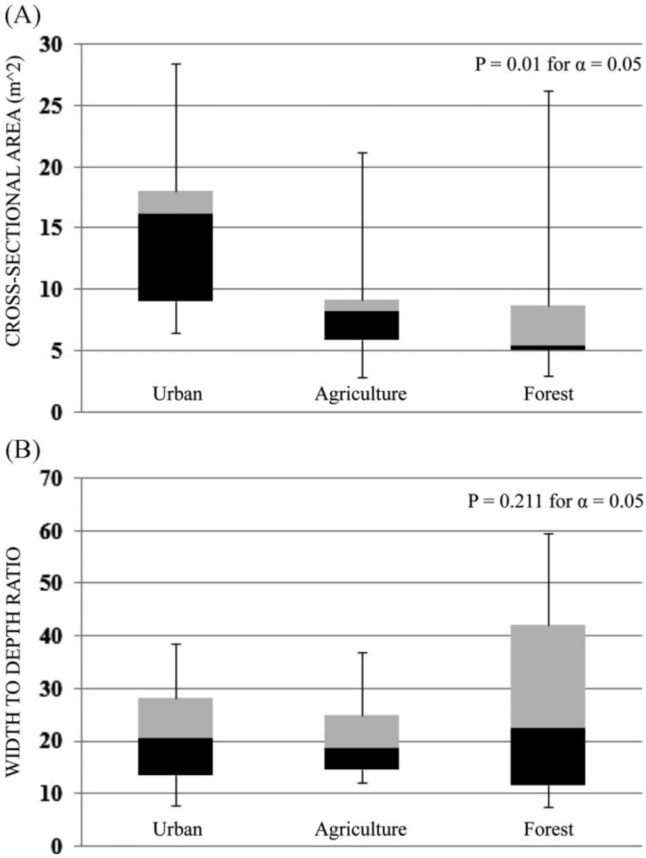

Figure 2. Statistical analysis of bankfull cross-sectional geometry. A) Comparison of cross-sectional area, and B) Comparison of width-depth ratios. Black boxes represent the 25th to 50th percentile, grey boxes represent 50th to 75th percentile and whiskers denote the lowest and highest values

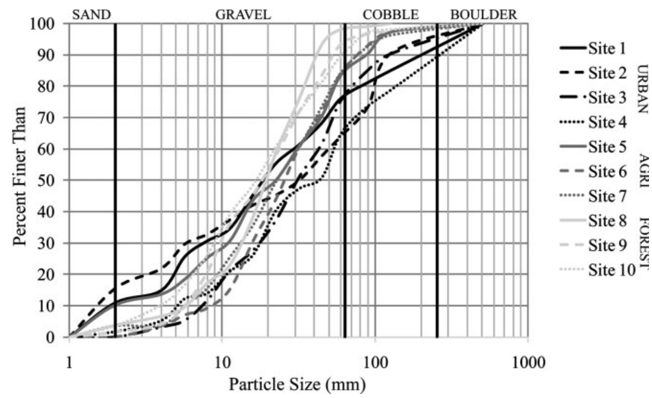

Figure 3. Sand to boulder particle size distribution within longitudinal profile by land use type

width. Ephemeral channels cut through these deposits accommodating moderately increased flow velocities. Agricultural streams and forested streams have similar bankfull widths (mean of 13 and 12 m, respectively), but in the agricultural streams there are fewer channel margin bars and the channel edges are steeper. Urban streams are significantly wider (mean of 17 m) and moderately deeper with no channel margin bars.

Sediment distribution

The gravel, cobble and boulder fraction of the bed material is dominated by chert in all the study streams, but there are distinct differences in size distribution based on land use type. Three distinct bed material patterns emerge from the pebble count data (Figures 3 and 4). Urban stream reaches contain 3–59% exposed bedrock within the bankfull channel, and a greater amount of <2 mm fraction resulting in a bimodal distribution of bed materials. Agricultural streams exhibit less than 1% exposed bedrock, and no bedrock is exposed in forested reaches. Analysis of the sediment size fractions of the bed material (Figure 3) show forested reaches are dominated by medium to coarse gravels (8–45 mm) and agricultural reaches are dominated by coarse gravel to small cobbles (16–90 mm). There is a general coarsing of bed material as anthropogenic disturbance increases. Grain size designations are a modified Wenworth

Table IV. Summary of stream survey data means and estimated values for bankfull flow and stream power from STREAMS Modules

LULC	Longitudinal profile		Bankfull dimensions						Bankfull flow estimates		Forces and power estimates	
	Slope (%)	Sinuosity	Area (m^2)	Width (m)	Mean depth (m)	Maximum depth (m)	Hydraulic radius (m)	Width/depth ratio	Velocity ($m\,s^{-1}$)	Discharge (cm)	Shear stress ($N\,m^{-2}$)	Unit stream power ($W\,m^{-2}$)
Urban	1.17	1.1	14.4	17.0	0.9	1.5	0.8	22.6	3	46	95	334
Agriculture	0.71	1.1	10.1	13.7	0.7	1.3	0.7	19.6	2	19	45	103
Forest	0.69	1.9	7.8	13.8	0.6	1.0	0.5	28.3	2	14	37	85

Equations: Velocity is calculated from Manning's equation and used to determine estimated discharge.
$v = (1/n)R^{2/3}S^{1/2}$ where v is velocity, n is the roughness coefficient, R is the hydraulic radius and S is the channel slope.
$\tau_0 = \gamma_w RS$ where τ_0 is shear stress and γ_w is specific weight of water.
$\omega = \gamma_w QS/w$ where Q is discharge and w is channel width.

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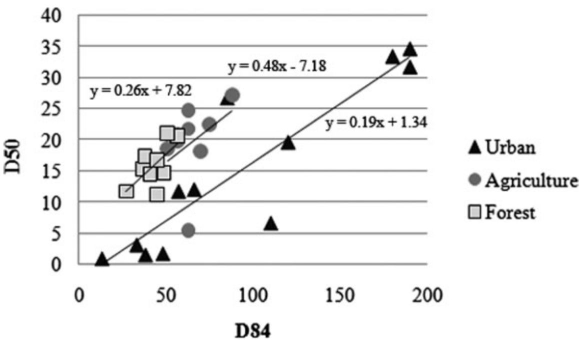

Figure 4. Comparison of D_{50} (mean particle size) to D_{84} (84% finer than) for cumulative pebble counts

scale as described by Church *et al*. (1987) and Kondolf *et al*. (2003).

Although two significant flood events occurred (April 2008 and September 2008) during collection of field data, no observable changes in gravel distribution were observed in the urban or agricultural stream channels. New gravel deposits were observed in ephemeral drainages and the stream channels in the two forested watersheds. Two survey markers attached to 30.5 cm rebar were washed away or covered by gravel. No new gravel deposits were observed in urban reaches supporting the hypothesis that new gravel inputs are minimal.

Large woody debris was not measured in this study, but it is important to note it can have a strong effect on the deposition of sediment locally (Bunte and Abt, 2001). Woody debris was observed at all three forested sites, and noticeably absent at both agricultural and urban survey sites.

DISCUSSION

The profile and cross-sectional characteristics of streams in the study area suggest planform and longitudinal characteristics are controlled by both land use and regional geology. All reach slopes are lower than might be expected for headwater streams, because of the dissected nature of the Springfield Plateau. Most perennial streams including headwater streams flow along the valley floor with minimal slope. Reach slopes for forested and agricultural watersheds are less than 1%, while urban reaches have a significantly greater slope. This is interpreted to be tied to the gravel distribution in these reaches. Unlike forested and agricultural watersheds, urban reaches have exposed bedrock. It is inferred that the slope of the urban reaches is controlled by bedrock, while slope in the other reaches is controlled to a greater degree by the distribution of gravel covering the bedrock.

Urban and agricultural reaches have similar reach sinuosity, while forested reaches have a significantly greater sinuosity. This suggests that anthropogenic activity in agricultural and urban areas is affecting sinuosity. Observed disturbances at the agricultural sites include vegetation clearing up to the channel edge, cattle grazing and removal of gravel with heavy equipment. Within urban reaches floodplains are landscaped and small drainage structures channelize runoff into the streams. In this study forested reaches are interpreted as being the least disturbed and therefore more stable; as disturbance increases in agricultural and urban reaches sinuosity decreases. The Ozark Geomorphology Project (Jacobson and Pugh, 1998; Jacobson and Gran, 1999) noted the opposite trend in which disturbed reaches rather than stable reaches exhibit increased sinuosity. Disturbance reaches migrate laterally at rates of several channel widths per decade, while stable reaches migrate less than a channel width per decade. A distinct difference is that stable and disturbed reaches, as described in the Ozark Geomorphology Project, were identified in the same stream not different streams as in this study. Furthermore, the increased sinuosity within disturbance reaches was attributed to greater channel roughness which promotes flow divergence and lateral channel migration. In this study forested and agricultural reaches have greater channel roughness due to the gravel bed; while in urban reaches (disturbed streams) the exposed bedrock decreases channel roughness. Roughness is a very complex characteristic of natural channels, but generally greater channel roughness promotes increased sinuosity (Leopold *et al*., 1992; Jacobson and Gran, 1999). It follows that forested streams in this study should have the greatest sinuosity. The lower sinuosity value in agricultural streams can be attributed to the anthropogenic alterations of the floodplain. These results parallel the prevailing theory that a primary result of anthropogenic disturbance is channel straightening (Chin, 2006).

In headwater streams, the coarsest bed material should be found in the pools, on the riffle crests and at the upstream head of the bars. According to standard geomorphic theory these are also the points of greatest shear stress (Knighton, 1998; Bunte and Abt, 2001). Gravel is scoured from the riffles in streams when the sediment supply is less than transport capacity of the streams (Bunte and Abt, 2001). This relationship exists in urban reaches within the study area. Gravel is noticeably absent from the riffle crests at three of the four urban sites. Comparing stream depth in urban reaches to forested reaches it is possible up to a half metre of sediment has been eroded from the urban reaches.

Additionally these data suggest urban streams in the study area are decoupled from source gravels. Historic trends in valley bottom land use change from forested to cleared agricultural areas in the Ozarks has resulted in decreased erosional resistance (Jacobson and Primm, 1997; Ward, 2007). Jacobson and Primm hypothesized that gravel is

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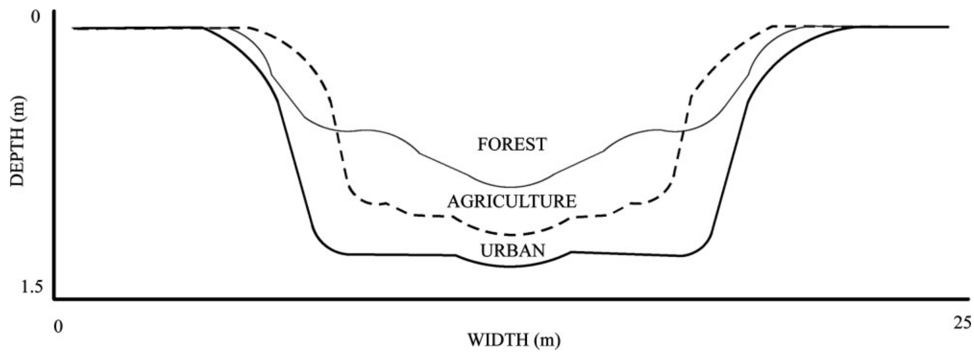

Figure 5. Generalized conceptual model of cross-sectional geometry adjustments to anthropogenic disturbance in the Illinois River watershed

removed from first and second order valleys and then deposited downstream. This study illustrates a more complex relationship between anthropogenic influence and gravel distribution. Gravel fills the stream beds in both agricultural and forested watersheds, and following Jacobson and Primm (1997) the current gravel deposits are a result of land use change in the valley bottoms over the past century. Gravel is being evacuated from urban watersheds, and we suggest there are minimal new inputs of gravel to these streams resulting in a significant increase in exposed bedrock at the channel base.

The relationship between bankfull cross-sectional area and the distribution of bed materials is useful in developing a conceptual model for headwater stream channel response to land use within the watershed (Figure 5). Forested streams have a small low flow channel surrounded by wide gravel deposits within the bankfull channel creating a step pattern. As anthropogenic disturbance increases, the gravel deposits are mobilized and shifted downstream. This is exemplified by the agricultural streams which have similar bankfull width to forested streams, but a wider low flow channel and coarser grained bed materials. In urban channels with the greatest anthropogenic disturbance, the gravels are preferentially evacuated from the riffles, little to no new gravel is washed into the stream and the stream has eroded to bedrock. As a result, the stream erosive power is distributed laterally widening the channel; corresponding with the observed increase in bankfull width or agricultural and urban reaches. These results are consistent with the observed effects of urbanization globally (Wolman, 1967; Chin, 2006).

Coarse sediment moves discontinuously through a watershed depending on the competency of flow and the capacity of the stream channel (Knighton, 1998). Estimated velocities are similar for all channel reaches, but discharge is significantly greater for urban reaches reflected by the greater channel area. Calculated shear stress and unit stream power values for the urban streams (Table IV) in the study are approximately three times that of the forested values. The increase in discharge and unit stream power with increasing anthropogenic disturbance results in increasing stream competency from forested to agricultural to urban watersheds. The redistribution of gravel downstream and the calculated increased discharge creates a positive feedback loop in the urban watersheds. Ultimately if anthropogenic disturbance increases past a threshold in the watershed, these streams could become bedrock streams devoid of all gravel.

CONCLUSIONS

This study adds to the growing body of research that suggests the need to look at watershed scale processes and controls even within the same physiographic province. Several stream restoration projects have been initiated along urban streams in the Illinois River watershed, based on Rosgen's (1994; 1996) theories of Natural Channel Design, in which reference reaches are inferred from channel appearance of 'undisturbed' reaches in the watershed. Applying values of width, depth, slope and sinuosity from a reference reach to a project reach requires the state of dynamic equilibrium and channel forming discharge be equivalent (Shields *et al.*, 2003). This is problematic because it does not account for the observed differences in sediment distribution and inferred sediment sources between land use types. Without reintroducing gravel to the urban streams and providing a source of gravel replenishment, an urban channel engineered to fit the geometry of a forested (undisturbed) reach will more than likely fail over time. Any stream management or restoration projects should include standards for riparian zones and meander belts that allow for the greatest variability in sinuosity, which is approximately two in the headwaters of the Illinois River. Application of reference reach concept must be within the context of the complexities of both natural and anthropogenic influences on watersheds.

The urban reaches in the headwaters of the Illinois River watershed also represent a new stage in our land use history and therefore we should be concerned with how the lack of

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gravel will propagate downstream. The next steps in this research are to determine how far the gravel has moved downstream, estimate the volume of gravel removed, and determine the major gravel sources in the agricultural and forested watersheds. This research illustrates how through a careful analysis of stream geometry and sediment distribution we can strive to separate anthopogenic-induced changes from naturally-induced changes in fluvial systems.

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