Ecoregions and stream morphology in eastern Oklahoma

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1. Introduction

1.1. A regionalized landscape

The late-19th and early-20th centuries produced a series of works (e.g., Powell, 1895; Fenneman, 1931, 1938; Loomis, 1937; Atwood, 1940) in North America that constructed the landscape into distinct physiographic regions. For the most part, these regional delineations were determined by differences in geologic structure, altitude, relief, and topography (Thornbury, 1965). By the mid-20th century, however, the casual relationships of natural phenomena (i.e., physiography) had been elaborated on using a more detailed and systematic geomorphic analysis of landform origin. For example, the morphometric analyses of watersheds and stream networks (Horton, 1945; Strahler, 1950a,b, 1952, 1956; Schumm 1956; Hack, 1957; Melton, 1957; Morisawa 1962) set forth methods by which the quantitative understanding of landforms was possible (Strahler, 1968). In turn, fluvial geomorphologists, hydrologists, stream ecologists, and watershed managers now use statistical analyses that link similar landscapes to morphometric analyses, regional channel geometry, water quality, and aquatic assemblages (Larsen et al., 1986; Rohm et al., 1987; Lyons, 1989; Griffith et al., 1999; Marchant et al., 2000; Rabeni and Doisy, 2000; Cinotto, 2003; Dauwalter et al., 2007, 2008; Johnson and Fecko, 2008; Splinter et al., in press).
Montgomery (1999) argued that understanding how geomorphic processes relate to ecosystem function is necessary for ecosystem management with diverse physiographic regions. In addition to physiographic regions, regional boundaries have been set by ecological regions. Landscapes that constitute similarities in climate, geology, vegetation, soils, and land use comprise ecological regions. These regions encompass an area where a holistic approach to ecosystem management is focused (Bailey, 2002). The United States Bureau of Land Management, Fish and Wildlife Service, Forest Service, and National Parks Service have worked to implement ecological regions into their ecosystem management strategies (Bailey, 2002). The two most common delineations of ecological boundaries in the United States have been constructed by Bailey (1995) and Omernik (1987). Ecocoregion delineations of Bailey were developed primarily for application by the United States Forest Service and are based chiefly on climate and vegetation. Ecocoregions delineated by Omernik were originally developed by the U.S. Environmental Protection Agency for water quality management. The purpose of any ecocoregion delineation is to differentiate regions with contrasting ecosystem function (Omernik and Bailey, 1997). Considering the recent attempts to link ecology and geomorphology (Urban and Daniels, 2006; Renschler et al., 2007), the implementation of ecoregions in the fluvial hierarchy can be a useful way to help satisfy this linkage. For this reason, we completed a study that explained how the longitudinal patterns of channel morphology varied among Omernik’s ecoregions in eastern Oklahoma, USA.

The ultimate objective of this study was to establish whether trends in channel morphology (i.e., particle size, bankfull width, width/depth ratio, gradient, and sinuosity) differed among the Ozark Highlands, Boston Mountains, and Ouachita Mountains ecoregions. If differences exist among channel morphology by ecoregion, then the processes that dictate channel form are also different, which has implications for stream management and stream restoration.

1.2. Hierarchy in fluvial geomorphology and stream ecology

Studies in fluvial geomorphology are organized by a spatial framework. A hierarchical framework has been established that exhibits smaller scale components nested into larger scale components; the smaller scale component is influenced by the variables that constitute that next larger scale (Frisse1 et al., 1986; Kondolf et al., 2003). For example, a region with similar lithology, climate, geomorphology, and land use history would support similar channel characteristics (Kondolf et al., 2003). This hierarchical approach is widely accepted as a measure to assess the factors that influence stream morphology and the ecological characterization of rivers (Vannote et al., 1980; Lotspeich, 1980; Brussock et al., 1985; Biggs et al., 1990; Montgomery, 1999; Brierley and Fryirs, 2000; Thompson et al., 2004; Schmitt et al., 2007). A landscape that has been regionalized by both physical and biological components (i.e., ecoregions) provides a broad-scale hierarchy by which investigations into fluvial studies begin.

Interdisciplinary approaches to river science attempt to comprehend the relationship between biological and physical components (Parsons and Thoms, 2007). Fluvial geomorphologists are asked to decipher how the causal relationships of the holistic environment underpin processes associated with channel morphology and biotic function (Brierley and Fryirs, 2005; Parsons and Thoms, 2007). Phillips (2007) recently stated “landscapes are indeed shaped and controlled by deterministic, global laws, but the operation of these laws in specific geographical and historical contexts means that landforms and landscapes are often contingent, outcomes are clearly derived from the laws alone.” Whereas predicting channel morphology at a given point in space is difficult, the longitudinal trends in channel morphology might differ significantly among regions where biotic and abiotic components are interrelated.

The importance of interdisciplinary research between stream ecology and fluvial geomorphology has become increasingly apparent over the last quarter-century. Geomorphology plays a role in the functioning of ecosystems, while ecosystems influence geomorphic forms, processes, and associated stream management (Brierley and Fryirs, 2005; Urban and Daniels, 2006; Renschler et al., 2007). The importance of developing a stronger interdisciplinary approach between ecology and geomorphology was realized at 36th International Binghamton Symposium in 2005. The symposium “Geomorphology and Ecosystems,” brought researchers together to discuss the current and future status for bridging geomorphology and ecology (Renschler et al., 2007).

1.3. Omernik’s ecoregions

Ecoregions of the conterminous United States were established to help environmental managers comprehend landscape characteristics that influenced regional patterns of aquatic and terrestrial resources (Omernik, 1987). In addition, ecoregions provide a framework for comparative analysis of environmental problems (Loveland and Merchant, 2004a,b). Omernik’s ecoregions were delineated by similar associations of climate, soils, land use, topography, and potential natural vegetation. A short review of how Omernik’s maps were constructed follows; however, we suggest reading the original document (Omernik, 1987) for specifics.

A series of component maps were used to delineate ecoregions. These include: Major Land Uses (Anderson, 1970), Classes of Land-Surface Form (Hammond, 1970), Potential Natural Vegetation (Kuchler, 1970), and soil maps from multiple sources. Additional maps were used to verify the accuracy of the component maps. These include: Surficial Geology (Hunt, 1979), Physical Divisions (Fenneman, 1946), Land Resource Regions and Major Land Resource Areas of the United States (U.S. Department of Agriculture, 1981, Climates of the United States, (Baldwin, 1973) and Census of Agriculture (U.S. Bureau of the Census, 1969, 1974, 1978).

Omernik’s ecoregions are commonly 130,000 km², but range between 15,000 km² and 330,000 km². These ecoregions encompass watersheds of 500 km². Ecoregion boundaries were delineated after a rough draft of the region was sketched. Component maps were used via a map overlay process to delineate each ecoregion. Boundaries reflect the main condition that defined each ecoregion. The ecoregion boundaries of the Ozark Highlands, Boston Mountains, and Ouachita Mountains resemble physiographic boundaries describe by Fenneman (1938), Atwood (1940), and Hunt (1967). Fenneman (1938), however, included the Boston Mountains in his regionalized Ozark Plateaus. He did recognize the Boston Mountains as a “general denudation of the Ozark dome.”

Ecoregion boundaries are potentially better than geomorphic provinces for delineating the hierarchical structure of the fluvial system because of the greater number of variables used in the delineation and the lesser influence placed solely on geologic structure. In addition, most geomorphic boundaries do not incorporate land use variables for delineation. One hundred twenty Level III ecoregions exist in the United States according to Omernik (1987), which is twice the number of geomorphic provinces in Hunt (1974).

We selected Omernik (1987) ecoregions as an alternative to Bailey (1995) ecoregions to decipher whether the characteristics of stream channels differed among ecoregions. We did this because Omernik’s ecoregions were originally intended for surface water quality and management (Loveland and Merchant, 2004a,b) and are constantly being revised.

2. Longitudinal trends in channel morphology

Characteristics that define stream channel morphology (e.g., particle size, width, depth, gradient, and sinuosity) vary along the
longitudinal profile of the stream (Vannote et al., 1980; Rosgen, 1996). Variation in channel morphology occurs for different reasons. These include, but are not limited to, changes in discharge, sediment regime, climate, and local geology. Human modification of the landscape (i.e., logging, grazing, dam building, and urbanization) impacts the spatial and temporal changes of river systems and morphology. For this reason, it is difficult to develop a model that accurately predicts longitudinal changes in channel morphology among different regions; however, regional trends have been established (Brussock et al., 1985; Johnson and Fecko, 2008). Grant and Swanson (1995) reported that high gradient mountain streams greatly differ from lower gradient streams. High gradient mountain stream morphology is often influenced by external factors (e.g., landslides, alluvial fans, and bedrock outcrops), whereas lower gradient alluvial streams are more often impacted by flooding, riparian disturbance, and hard stabilization.

Particle size generally decreases along the longitudinal profile of the stream (Knighton, 1998). This downstream fining of particles is associated with the abrasion, hydraulic sorting, and weathering of the particles (Sambrook Smith and Ferguson, 1995; Knighton, 1998). In addition, a decrease in gradient lowers the transport capacity and competence of a stream to move bedload sediment, which reduces the frequency of larger particles in the downstream direction (Sambrook Smith and Ferguson, 1995). In gravel-bed streams the downstream fining of bed material does not always occur orderly because of the influence of tributaries, large woody debris, and colluvial deposits (Dawson, 1988; Rice and Church, 1996; Powell, 1998). Land use disturbance in the Missouri Ozark Highlands is responsible for increased sediment in select basins, which has led to increased sediment routing through the system (Jacobson and Gran, 1999).

As discharge increases in the downstream direction, channels adjust to the increase of water volume and sediment supply in the stream system. In doing so, channels generally widen and deepen (Leopold and Maddock, 1953). Variation in cross-section geometry occurs, however, because of boundary composition, bank vegetation, and valley slope (Knighton, 1998). Sand bed channels with non-cohesive banks tend to be wider than channels with cohesive banks (Osterkamp and Hedman, 1982). This occurs because cohesive banks are harder to erode than non-cohesive banks, resulting in more confined channels. For example, some downstream reaches in the Driftless Area of southwestern Wisconsin are narrower than their upstream counterparts because a decrease in particle size occurs in bank material, which increased bank stability and narrowed the channel (Knox, 1987).

Trimble (2004), also working in the Driftless Area, reported that streams flowing through non-grazed grasslands had smaller width/depth ratios than streams flowing through forests. This occurred because instream large woody debris in the forested stream reaches increased water velocity through constriction, which facilitated erosion and the widening of the channel. Other studies report that channels lined with grass, however, are up to 30% wider than streams flowing through forests (Charlton et al., 1978). The protective role of riparian vegetation is difficult to quantify, but it is important for understanding channel morphology longitudinally (Knighton, 1998).

Bankfull channel width is used in the calculation of width/depth ratios. Bankfull width must be precisely defined in the field to accurately calculate the width/depth ratio of a stream. Establishing bankfull width in the field is a somewhat challenging task (Johnson and Heil, 1996). This is especially true where the channel bottom is narrow (i.e., entrenched) and the floodplain has not developed a series of stepped morphological surfaces (Knighton, 1998). Another problem in defining bankfull width is directly related to the many ways that are used to define bankfull (Leopold et al., 1964; Carlson, 1965; Williams, 1978; Gordon et al., 1992; Nash, 1994). Defining bankfull width accurately is important because bankfull estimates serve to help planners and geomorphologists in stream restoration designs (Johnson and Heil, 1996).

Bankfull channel width is linked to the discharge stage at which channel maintenance is most effective (Dunne and Leopold, 1978). This maintenance is affected by the cross-section geometry of the channel, transportability of bedload, forming and removal of channel bars, and altering meander bends in stream reaches. Events controlling channel maintenance may have a recurrence interval of ~1.5 years (Dunne and Leopold, 1978), although other studies have reported larger recurrence intervals (up to 25 years) for bankfull discharge (Williams, 1978; Nash, 1994; Petit and Paquet, 1997). Regardless, consistency in field verification of bankfull indicators is important when establishing bankfull width.

Along the longitudinal profile, gradient generally portrays a concave upward profile. Some of the controls on the degree of concavity include particle size, the influence of sediment from hillslopes, tectonic uplift, a decrease in base-level, and log-steps (Knighton, 1998; Montgomery and Buffington, 1998). Dams can also impact the concavity of channel gradient, especially if water release is sediment free and downstream scour occurs at the dam outlet. Headreach widths (i.e., 1st- and 2nd-order streams) may have steep gradients because they flow through bedrock lithologies with large particles that are resistant to erosion. Large particles cannot be abraded or sorted because stream discharge is below transport competency (Knighton, 1998). For most alluvial streams, gradient is generally a function of rock lithology, particle size, and discharge (Hack, 1957).

Sinuosity generally increases along the longitudinal profile in alluvial single thread streams. Upstream reaches with high gradients are often confined by valley walls or large bed material that decreases the ability of the stream to meander and transport sediment. As particle size decreases down-gradient, the bedload/total load ratio decreases, which allows streams to meander (Schumm, 1981, 1985). Changes in sinuosity throughout bedrock outcrops, riprap reaches, and dam construction, however, can alter the ability of channels to meander and may not accurately depict upstream-to-downstream changes along the channel. For example, sinuosity downstream of Jackson Lake Dam in Wyoming has fluctuated significantly in response to changes in maximum discharges and sediment delivery from tributaries over an 80-year period (Marston et al., 2005).

3. Study area

Ecoregions in eastern Oklahoma consist of the Central Irregular Plains, Ozark Highlands, Boston Mountains, Arkansas Valley, South Central Plains, and Ouachita Mountains (Omernik, 1987). The Ozark Highlands, Boston Mountains, and Ouachita Mountains (Fig. 1) were selected because they have high fisheries value and the Oklahoma Department of Wildlife Conservation (ODWC) has an active stream habitat management program, which uses procedures that incorporate the morphology, habitat, and classification of streams in these regions (Fisher et al., 2002, 2004; Dauwalter and Fisher, 2008). The ODWC recognizes that management of these streams is important to the overall well-being of the fisheries-related economy in eastern Oklahoma (Fisher et al., 2002; Dauwalter et al., 2007; Dauwalter and Fisher, 2008).

The Ozark Highlands exist in parts of Kansas, Missouri, Arkansas, and Oklahoma. In Oklahoma, the ecoregion encompasses 2795 km². The eastern edge of the Ozark Highlands exists in eastern Oklahoma and incorporates part of the Springfield Plateau. Woods et al. (2005) described the region as being dominated by watersheds that are high to moderately dissected. Lithology consists of Mississippian-aged limestone with interbedded chert. Mean annual precipitation is 100–125 cm. Land use consists of grazing, logging, poultry and livestock farming, and quarrying. The potential natural vegetation consists of mainly oak–hickory forest and grassland. Soils on uplands consist of
Ultisols, Alfisols, and Mollisols. Mean watershed relief ranges from 59 m in 1st-order streams to 153 m in 4th-order streams (Splinter et al., in press). Much of the native forest and prairie was removed during the logging boom at the turn of the 20th century.

The Boston Mountains lie to the south of the Ozark Highlands in Oklahoma. In Oklahoma, the Boston Mountains ecoregion encompasses 1891 km². This region is a deeply dissected Plateau (Woods et al., 2005). Lithology consists of Pennsylvanian-age sandstone, with minor amounts of Pennsylvanian- and Mississippian-age limestone and shale. Mean annual precipitation is 110–130 cm. Land use consists of forest and woodland, with flatter areas used for ranching and farming. The potential natural vegetation consists mostly of oak–hickory forest (Woods et al., 2005). Soils on uplands consist of Ultisols, Inceptisols, and Entisols. Mean watershed relief ranges from 119 m in 1st-order streams to 380 m in 4th-order streams (Splinter et al., in press).

The Ouachita Mountains are separated from the Boston Mountains to the north by the Arkansas Valley ecoregion. In Oklahoma, the Ouachita Mountains ecoregion encompasses 10,100 km². Woods et al. (2005) describes the region as being a mosaic of low mountains and high hills of folded Paleozoic rocks. Lithology varies throughout the ecoregion with rock types of sandstone, shale, and novaculite. Mean annual precipitation (110–145 cm) is greatest on south-facing ridges. Land use consists of forestry, logging, ranching, woodland grazing, and recreation. The potential natural vegetation is oak–hickory–pine forest. Soils are Ultisols, Alfisols, and Inceptisols. Mean watershed relief ranges from 157 m in 1st-order streams to 380 m in 4th-order streams (Splinter et al., in press).

4. Methodology

4.1. Site selection

A random point generator model in ArcView 3.3© and ArcGIS 9.1© was applied to a stream network constructed for eastern Oklahoma using 30-m DEMs (Fig. 1). The stream network was stratified into stream orders (1–4) for each ecoregion. Points (i.e., reaches) were proportionally allocated to each ecoregion based on ecoregion area and distributed among stream orders within ecoregions. One hundred and forty-nine reaches were surveyed for particle size, bankfull width, width/depth ratio, channel gradient, and sinuosity. Thirty-five reaches were surveyed in the Boston Mountains, 34 in the Ozark Highlands, and 80 in the Ouachita Mountains. When access was denied by landowners or the reach was primarily disturbed (i.e., gravel mined, channelized, or no stream existed), the reach point was reselected. Point coordinates were downloaded into a Trimble GEOXT© Global Positioning System (GPS) receiver for exact navigation to the starting location of the reach.

4.2. Reach variables

Reaches were surveyed upstream of the randomly selected point unless restricted by access or affected by human disturbance. Reach length was calculated using 20 times bankfull width. At each reach, three to four stream channel cross-sections were surveyed with a stadia rod and transit. Two cross-sections were surveyed in pools and two in riffles when available. Cross-sections were placed perpendicular to the stream channel and across alternating pool and riffle sequences where bankfull indicators were well-established. When the stream was dry, the reach was divided into four equal sections, and four cross-sections were placed accordingly. Each cross-sectional transect was surveyed for particle size, bankfull width, and width/depth ratio. In addition, the reach (i.e., from upstream-to-downstream) was surveyed for gradient and sinuosity. Reach data were compiled for particle size, bankfull width, and width/depth ratio by averaging data collected at each cross-section. We believe that averaging bankfull width and the width/depth ratio of riffles and pools provided the best measure of the overall geometry of the reach because: (1) lumping takes the subjectivity out of identifying different types of pools (e.g., scour, mid-channel, bedrock, and log jams); and (2) the high amount of dry channels in small watersheds makes it difficult to accurately define riffles, especially in streams with fine-grained sediments and high distributions of large woody debris.

Fig. 1. Randomly selected stream reaches (with ID) by stream order in three ecoregions in eastern Oklahoma, USA.
Particle size analysis was conducted at each channel cross-section (Wolman, 1954). Particles were collected along transects and picking clast under the toe of the measurer. Particles were collected and measured from right-side bankfull (looking downstream) width to left-side bankfull width. In some instances, measuring particles out of the wetted portion of the pool or rifle occurred. When bankfull width surpassed the wetted width, bar deposits were measured. This technique led to sampling in a non-homogeneous population (Kondolf, 1997). For this reason, we did not try to separate pool from rifle transect particle sizes. Rather, our goal was to examine the sediment sizes flowing within the channel, not compare differences in particle size between riffles and pools. We understand that this method probably increased our residual scatter within each ecoregion; however, regardless of sampling scheme, particle size can have lateral variability (Bunte and Abt, 2001). The particle size results, however, provide a good quantitative representation of changes occurring along the longitudinal profile of streams by ecoregion, which is better than a simpler qualitative assessment of particle size.

Particles \(<2\) mm were classified as fines, and boulders were clasts \(\geq256\) mm. Bedrock size was not measured, but counted as a percentage of the reach. In all, 100 units of measure (i.e., sand through bedrock) were collected at each cross-section. The distribution of particles was entered into the software program RIVERMorph 3.0©, which is used to create a particle size frequency distribution.
During data entry, fines were classified into the 2.0–1.0 mm fraction; and boulders, which were not measured in the field, were classified into the 256–362 mm fraction.

Bankfull width was determined as the horizontal distance from right bank floodplain to left bank floodplain. At each transect, bankfull was identified by: (i) differentiating the modern floodplain from low terraces; (ii) defining breaks in coarse and fine sediment deposition; and (iii) utilizing the differences in vegetation along the channel. Where no obvious floodplain existed, erodable boundaries, root zones, and soil development served as bankfull indicators. Width/depth ratio was calculated by dividing bankfull width by the mean channel depth. Mean channel depth was calculated by dividing bankfull area by bankfull width. Gradient was calculated by dividing the elevation of water surface change from upstream-to-downstream by reach length. Water surface elevation was surveyed using a level and stadia rod from the top to the bottom of the reach. Reach length was obtained in the field using a tape measure or upstream and downstream GPS boundaries. Sinuosity was calculated by dividing stream length by valley length. Valley length was attained using upstream and downstream GPS boundaries.

4.3. Statistical analysis

Regression analysis was used to evaluate whether longitudinal trends in geomorphic variables differed among ecoregions. Ecoregions were modeled as dummy variables. Dummy variables are categorical variables (i.e., ecoregions) that take the value of zero or one in the regression. The Ouachita Mountains (OM) were used as the baseline region because it had the most sites and was expected to differ most from the Ozark Highlands (OH) and Boston Mountains (BM). The independent variable was drainage area (km²) above the reach. The dependent variables, compared in separate regression equations, were particle size, bankfull width, width/depth ratio, gradient, and sinuosity. Drainage area (A; km²) and the dependent variables were transformed using natural logs prior to analysis. The fitted model is portrayed in Eq. (1):

\[
\log(\bar{y}) = \beta_0 + \beta_1 A_{\text{BM}} + \beta_2 A_{\text{OH}} + \beta_3 \log A
\]

where \(\bar{y}\) is the predicted value for the dependent variable; \(A_{\text{BM}}\) and \(A_{\text{OH}}\) is the categorical variable (0,1) of the BM and OH, respectively, and \(\beta_0\) to \(\beta_3\) are constants.

Parameter estimates were used to interpret differences in channel morphology among ecoregions and differences in the rate at which channel morphology changed with drainage area. The interactions were evaluated to determine if channel morphology in an ecoregion \(\beta_3 A_{BM}\log A\) or \(\beta_3 A_{OH}\log A\) changed at a different rate with drainage area than it did in the baseline ecoregion \(\beta_3 A_{OM}\log A\), where \(A_{OM}\) is the categorical variable of the OM). Intercepts were interpreted as consistent differences between ecoregions \((\beta_1 A_{BM}\) or \(\beta_1 A_{OH}\)) and the baseline ecoregion \(\beta_0\) regardless of drainage area. The analytical software program STATA 8.0® was used to perform statistical analysis. Type I error rate was set at \(\alpha = 0.05\).

The predicted regression value for the Ouachita Mountains (i.e., baseline region) was obtained when the Boston Mountains and Ozark Highlands were given 0 values in the regression equation and the Ouachita Mountains received a value of 1 (Table 1). Predicted regression values for the reaches in the Boston Mountains were obtained when the Ouachita Mountains and Ozark Highlands received a value of 0 and the Boston Mountains received a value of 1 (Table 1). The predicted regression equation for the Ozark Highlands was obtained when the Ouachita Mountains and Ouachita Mountains received a value of 0 and the Boston Mountains received a value of 1 (Table 1).
received a value of 0 and the Ozark Highlands received a value of 1 (Table 1). For example, the predicted regression value for $D_{98}$ particle size (mm) for reach 1 (1.20 km$^2$) in the Boston Mountains is calculated as:

$$\log(y) = 2.316 + -1(1) + -0.62(0) + 0.079(0.18)$$

$$+ 0.173(0.18) + 0.048(0.18)$$

Each dependent variable (i.e., $D_{16}$, $D_{50}$, $D_{94}$, bankfull width, width/depth ratio, gradient, and sinuosity) had a predicted regression value calculated for each reach. These predicted regression values were plotted for each dependent variable by ecoregion. Y-intercepts and slope coefficients for each regression were compared among ecoregions to test for statistical differences. Summary statistics, by stream order and ecoregion, are given in Table 2.

5. Results and discussion

5.1. Particle size

The $D_{16}$, $D_{50}$, and $D_{94}$ particle sizes were selected for analysis because they span the lower, middle, and upper frequency distribution of particle size. Although not always statistically different in terms of the y-intercept, the largest particles occur in the Ouachita Mountains (Table 2) and the smallest particles in the Ozark Highlands (Figs. 2 and 3). The y-intercept coefficients for $D_{16}$ regression models differed between the Boston Mountains and the Ouachita Mountains ($\alpha \leq 0.015$ (Table 3)). $D_{50}$ did not differ among ecoregions (Table 4); however, $D_{94}$ y-intercept coefficients differed between the Ozark Highlands and the Ouachita Mountains ($\alpha \leq 0.016$ (Table 5)). The $D_{94}$ comparison provided statistical validation that small streams of the Ozark Highlands (gravel bed) are quite different from small Ouachita Mountain streams (cobble bed). Slopes of the particle size regression did not differ among ecoregions. The rate of change in particle size from upstream-to-downstream was constant in all ecoregions.

In general, streams in the Ozark Highlands had the smallest particle sizes of the three ecoregions (Fig. 2). Lithology of the Ozark Highlands is predominantly cherty limestone and sandstone. The cherty limestone of the Ozark Highlands impacts the particle size distributions found in these streams. Limestone is easily weathered and dissolvable in streams, which exposes the more resistant chert nodules. The resultant chert is difficult to weather through physical and chemical processes as it moves from upstream-to-downstream. Chert exposed through the dissolution of limestone retains a fairly consistent particle size along the longitudinal profile.

Landowners in the Ozark Highlands of eastern Oklahoma report that streams are undergoing aggradation. Within the Baron Fork Creek watershed, local landowners gave us personal accounts of pool depth decreasing. In addition, increases in large woody debris are occurring in the streams. Studies of similar stream changes have been documented in the Missouri Ozark Highlands (Jacobson, 1995; Jacobson and Primm, 1997; Jacobson and Gran, 1999). Increased amounts of sediment from land use change, predominantly grazing, in the Missouri Ozark Highlands have caused streams to aggrade (Jacobson, 1995). Streams in the eastern Oklahoma Ozark Highlands are also undergoing this transformation.

Summary statistics (Table 2) report that the Boston Mountain streams have the second largest particle sizes, while the Ouachita Mountain streams have the largest particle sizes. Particle sizes in Boston Mountain streams are larger than those in the Ozark Highland because the Boston Mountains have a higher watershed relief, which has the potential to supply larger particles to the fluvial system (Splinter et al., in press). The sandstone lithology of the Boston Mountains is more resistant to weathering and abrasion, which makes erosion of the sandstone difficult in this fluvial system. Boulder size particles are common in Ouachita Mountain streams (Smithson and Johnston, 1999; Marion and Weirich, 2003). This region has the highest watershed relief of all the ecoregions in this study (Splinter et al., in press). Steep V sideslopes and bedrock outcrops are common, which result in large particles in the streams of this region (Fig. 2). Particle size increased in the downstream direction ($D_{95}$) because of the local geologic setting of steep sideslopes and bedrock outcrops. Resistant sandstone and novaculate prohibit the weathering and abrasion of sediment. Large sediment is seldom moved in these locations because of a lack of stream power and streams remain relatively stable.

5.2. Bankfull channel width

It is well understood that bankfull channel width increases downstream with the addition of tributaries associated with increased drainage area (Leopold et al., 1964). In turn, bankfull...
channel width has been correlated with increased drainage area in ecoregions of the conterminous United States (Faustini et al., 2009). Bankfull width of the Ozark Highlands increased approximately 49 m along its longitudinal profile, whereas the Boston Mountains and Ouachita Mountains widened 43 m and 33 m, respectively (Fig. 4). Y-intercept ($\alpha \leq 0.001$) and slope coefficients ($\alpha \leq 0.010$) between the Ozark Highlands and the Ouachita Mountains and y-intercept coefficients between the Boston Mountains and Ozark Highlands differed ($\alpha \leq 0.000$), providing evidence for contrasting stream sizes among regions (Table 6). The widest predicted bankfull widths are in the Boston Mountains (Fig. 4). Although no y-intercept or slope difference existed between the Boston Mountains and Ouachita Mountains, a difference existed between the Ozark Highlands and the other two ecoregions (Table 6).

Bankfull channel widths in 1st- and 2nd-order streams of the Ozark Highlands were narrower than the Boston Mountains and the Ouachita Mountains (Fig. 4). This is probably a function of the lower watershed relief of the region and the jointed and fractured limestone...
bedrock (i.e. karst topography) that allows rainfall runoff to be reduced because of higher infiltration rates (Splinter et al., in press). Low-order streams surveyed in the Ozark Highlands were dry and flowing only after rainfall events. Ten of 15 1st- and 2nd-order streams were completely dry and two were intermittent, which probably leads to narrower bankfull channel widths in low-order reaches (Fig. 3). In addition, a rapid increase in drainage density exists in medium and larger watersheds in the Ozark Highlands which functions to increase bankfull channel width downstream (via tributaries) then in other ecoregions (Splinter et al., in press). The slope of the regression line in Fig. 4 depicts how bankfull channel width increases with stream size in the Ozark Highlands than in the other ecoregions.

The wider bankfull channel width in smaller watersheds of the Boston Mountains and Ouachita Mountains is probably a function of the higher watershed relief in these regions. Overland flow in these higher relief watersheds collects in streams and is more readily available for sediment transport and erosion of stream banks, which widen the bankfull channel width of the streams.

5.3. Width/depth ratio

The width/depth ratio of streams increased in the downstream direction in all three ecoregions. The Boston Mountains and Ozark Highlands have slope coefficients different ($\alpha \leq 0.05$) from the Ouachita Mountains (Table 7), which signifies a greater rate of change downstream in the Ozark Highlands and Boston Mountains. The lowest width/depth ratios (although y-intercept coefficients are not different from the other ecoregions) occurred in low-order streams of the Ozark Highlands and transitioned into the highest values downstream (Table 7; Fig. 4).

The low width/depth ratios of streams in small Ozark Highland watersheds are the result of little streamflow except during rainfall events. A lack of streamflow produces channels that are narrow and shallow. As the drainage area increased in the Ozark Highlands, a considerable increase occurred in width/depth ratio. The relatively high drainage density and transport capacity of gravel helps establish high width/depth ratios in the Ozark Highlands. Splinter et al. (in press) showed that drainage density increased dramatically from 1st to 2nd-order streams in the Ozark Highlands.

Stream studies in the adjacent Missouri Ozarks show that land use change led to the headward extension of the stream network into unchanneled upland valleys (Jacobson, 1995). In turn, gravel was added to the system and is currently being routed during higher flow events (Jacobson and Primm, 1997; Jacobson and Gran, 1999). Remshardt and Fisher (2008) reported that high flow events (between 1999 and 2000) along a section of Baron Creek (Oklahoma Ozark Highlands) altered the cross-sectional profile between 62% and 93%. We believe that during high flow events, gravel is being

![Fig. 4. Longitudinal trends in bankfull width and width/depth ratio. Width/depth ratio changes only slightly longitudinally in the Ouachita Mountains when compared to the Ozark Highlands and Boston Mountains. This reflects the regions large substrate and structural controls.](image-url)
transported from streams in the upper watersheds and deposited downstream. Higher-order streams in the Ozark Highlands are aggrading, which causes high magnitude flood events to accelerate erosion on the stream banks. Aggradation of the streambed decreases mean depth. This coupled with increasing channel width supports streams with high width/depth ratios (Schumm, 1960). Evidence for aggradation comes from communication with landowners in the region who recall past periods when the pools were much deeper. Five of the six highest width/depth ratios conducted in this study occurred in the Ozark Highlands.

Streams in the Ouachita Mountains have the most consistent width/depth ratios from upstream-to-downstream of all the ecoregions (Fig. 4). The width/depth ratios of these streams are controlled by large substrate and bedrock outcrops. Streams cannot downcut through the large substrate and are forced to laterally migrate or remain confined by local geology even in large streams. The large particle size and bedrock outcrops serve to retard increases in the width/depth ratio from those observed in streams of the Boston Mountains and Ozark Highlands. The width/depth ratios of streams in the Boston Mountains are more similar with those in the Ozark Highlands than those in the Ouachita Mountains. Streams in the Boston Mountains generally have substrate particles larger than the Ozark Highlands and smaller than the Ouachita Mountains. The larger substrate, along with bedrock, influences the width/depth ratio of streams in the Boston Mountains, but not to the extent it does in the streams in the Ouachita Mountains.

5.4. Gradient

Stream gradient was not statistically different among ecoregions (Table 8). The gradient variability was greatest in the Ouachita Mountains and least variable in the Boston Mountains (Fig. 5). The high variability in the Ouachita Mountains resulted from having more regional variability than the Ozark Highlands or Boston Mountains (Splinter, 2006). The Ouachita Mountains encompass a landscape that is defined by hills and mountains with high relief in its interior and low gradient flats at the base of hills, in floodplains of large rivers, and in the lowlands at the region’s western edge (Woods et al., 2005). In addition, some larger stream reaches in the Ouachita Mountains consisted of a single large pool with a very low slope. Other large streams in the Ouachita Mountains had a series of riffle-run-pool sequences that increased reach slope. This contrast in channel unit frequency and type led to a large range in gradient of high-order streams.

5.5. Sinuosity

Sinuosity was not significantly different among ecoregions (Table 9). No longitudinal pattern in sinuosity was evident among ecoregions (Fig. 5). When compared along the longitudinal profile of a stream, sinuosity remained the same. In part, sinuosity increases

### Table 6

| Comparison  | Coefficients | SE  | t    | P>|t| | Prob>F |
|-------------|--------------|-----|------|-----|--------|
| Intercept   | 1.561        | 0.060 | 25.95 | 0.000|
| BM vs. OM   | 0.080        | 0.107 | 0.82  | 0.413|
| OH vs. OM   | −0.397       | 0.114 | −3.49 | 0.001|
| BM vs. OH   | 0.000        |       |       |      |
| Slope       | 0.330        | 0.018 | 18.46 | 0.000|
| BM vs. OM   | 0.018        | 0.030 | 0.59  | 0.555|
| OH vs. OM   | 0.080        | 0.031 | 2.59  | 0.010|
| BM vs. OH   | 0.075        |       |       |      |

* See Table 3.

### Table 7

| Comparison  | Coefficients | SE  | t    | P>|t| | Prob>F |
|-------------|--------------|-----|------|-----|--------|
| Intercept   | 2.561        | 0.060 | 31.72 | 0.000|
| BM vs. OM   | −0.095       | 0.144 | −0.66 | 0.508|
| OH vs. OM   | −0.253       | 0.153 | −1.66 | 0.100|
| BM vs. OH   | 0.372        |       |       |      |
| Slope       | 0.059        | 0.024 | 2.47  | 0.015|
| BM vs. OM   | 0.100        | 0.040 | 2.48  | 0.014|
| OH vs. OM   | 0.159        | 0.041 | 3.82  | 0.000|
| BM vs. OH   | 0.210        |       |       |      |

* See Table 3.
where localized bank erosion occurred and a redistribution of energy in the water column developed (Knighton, 1998; Ritter et al., 2002). Schumm (1981) classified streams with the highest sinuosity as those primarily having small sediment size. In the Ozark Highlands, Boston Mountains, and Ouachita Mountains, particle size is most often gravel or cobble. Sediment movement is primarily bedload. The majority of stream reaches surveyed had a sinuosity <1.5, which indicates generally straight reaches.

6. Conclusion

This study investigated how longitudinal patterns in channel morphology differed among ecoregions. The results showed that longitudinal patterns differed for three (particle size ($D_{50}$ and $D_{90}$), bankfull width, and width/depth ratio) of the five variables tested. Variables not found to be statistically significant were gradient and sinuosity. Our findings are similar to other studies that have shown using broad-scale variables (geology, topography, climate, land use, vegetation, and soils) provide a spatial organization by which the characteristics of stream channels can be classified and studied (Brussock et al., 1985; Cohen et al., 1998; Montgomery, 1999; Snelder et al., 2004). We recommend using ecoregions to study the longitudinal characteristics of stream morphology for the following reasons: (1) regional curves can be characterized for the region; (2) disturbance reaches can be quickly identified once the regional curve is developed, and (3) ecoregions provide fluvial geomorphologists and stream ecologists a regional picture that portrays broad-scale variables that influence the physical and biological aspects of streams.

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References

Jackson, R.B., 1995. Spatial controls on patterns of land-use induced stream disturbance at the drainage basin scale – an example from gravel-bed streams

Table 9

Comparison of sinuosity among ecoregions using slope and y-intercept coefficients.

| Comparison | Coefficients | SE | t | P>|t| | Prob>F |
|------------|--------------|----|---|--------|--------|
| Intercept  |              |    |   |        |        |
| OM, baseline | 0.141        | 0.033 | 4.24 | 0.000  |        |
| BM vs. OM  | −0.047       | 0.060 | −0.80 | 0.427  |        |
| OH vs. OM  | −0.026       | 0.063 | −0.41 | 0.684  |        |
| BM vs. OH  |              |    |   |        | 0.767  |

Slope

| OM, baseline | −0.002      | 0.010 | −0.20 | 0.843  |        |
| BM vs. OM    | 0.011       | 0.017 | 0.76  | 0.451  |        |
| OH vs. OM    | 0.010       | 0.017 | 0.56  | 0.578  | 0.877  |

a See Table 3.