SPATIAL PATTERNS IN THE FLUVIAL SYSTEM:

COMPARISONS AMONG THREE EASTERN OKLAHOMA ECOREGIONS

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Morel. 2005 was the year of Team Blue Truck (Bryce and I) vs. Team White Truck (Dan, Mark, and James). I am not sure what the competition was, but if it was the dustiest truck then the Blue Truck won. Thanks for all your hard work. I hope all of you have some good memories….I sure do.

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CHAPTER 1

INTRODUCTION

Overview

This chapter introduces my doctorial dissertation study that partially fulfills the requirements for my graduation from Oklahoma State University. In doing so, I will: (1) introduce the multidisciplinary project from which my dissertation research developed; (2) explain the theoretical significance of this regional geomorphic stream study; (3) develop the main objectives of this study; (4) briefly introduce the role of ecoregions in scientific inquiry; and (5) provide an overview of the forthcoming chapters in the dissertation.

1. Aquatic habitat inventory of eastern Oklahoma streams

My dissertation stems from an interdisciplinary project designed to link geomorphology and aquatic habitat conditions to fish populations in selected eastern Oklahoma streams. The study was funded by the Oklahoma Department of Wildlife Conservation (F-55-R) as a Federal Aid Project, with William L. Fisher as PI and Richard A. Marston as Co-PI. The project was conducted from July 2002 to July 2005. Dan C. Dauwalter served on this research project as well, and developed a dissertation (Dauwalter, 2006) titled, “Relationships among geomorphology, habitat, and fishes in eastern Oklahoma streams: implications for stream restoration.”

2. Theoretical significance of using ecoregions in stream studies

No previous studies have been conducted that use ecoregions as a basis for comparisons of watershed morphology, upstream-to-downstream trends in channel morphology, and relative abundance of channel reach types. A study of this type provides a regional contribution to stream classification and management. Ecoregions are homogenous regions defined by similar geology, soil, land use, climate, and potential natural vegetation (Omernik, 1987). These ecoregion variables function to control and impact watershed morphology and the characteristics of stream reaches. The prior sentence will be validated in the upcoming chapters of this dissertation. For this reason, I propose that the ecoregions of Omernik should be the broad-scale measure by which organization of the fluvial hierarchy begins when classifying stream channels.

3. Objective of dissertation research

The main objective of this study is to evaluate whether ecoregions serve as an adequate spatial framework to explain variability in the characteristics of stream channels in eastern Oklahoma. Ecoregions provide a broad-level hierarchy by which the structuring of streams processes can be viewed. The Boston Mountains, Ozark Highlands, and Ouachita Mountains comprise the three eastern Oklahoma ecoregions used to evaluate patterns of channel variability on a regional level.

The next two lower scales in the fluvial hierarchy are the watershed and stream network (Frissell et al., 1986). Watershed morphology was compared among ecoregions. Morphometric analyses of watersheds integrate parameters of the stream networks (i.e., stream order and drainage density), so these two scales are combined in the understanding of how ecoregions influence watershed morphology and stream networks. Once these relationships were established, reach scale variables along the longitudinal profile of the stream were compared among ecoregions. At this point in the study it became apparent that certain conclusions could be drawn about how watersheds and stream channels were influenced attributes of ecological regions.

4. Ecoregions and the fluvial hierarchy

Ecoregions were originally developed to provide a geographic framework for ecosystem management (Omernik, 1987). Omernik (1987) stated that these geographic boundaries will allow managers, planners, and scientists to: (1) compare similarities and differences of land-water relationships; (2) establish water quality standards that are acceptable for a given region; (3) locate places to serve as monitoring, demonstration, and reference sites; (4) extrapolate from empirical data collected at other locations; and (5) predict the effect of change on land use and pollution controls. Omernik and Bailey (1997) reiterated the importance of ecoregions in providing a spatial framework for ecosystem assessment, research, inventory, monitoring, and management. Extrapolation of site specific data across an ecoregion allows for the attempted prediction of system function of locations where data have not been collected (Omernik and Bailey, 1997).

Ecoregions encompass large spatial areas that allow researchers to investigate geographic issues on multiple scales. For example, the organization of the fluvial system is often portrayed beginning with a region depicting similar characteristics (Frissell et al., 1986; Montgomery and Buffington, 1998). Kondolf et al. (2003) state that precipitation and vegetation leads to differences in processes and characteristics in stream channels. In addition to these variables, geology, soils, and land use lead to differences in processes and resultant forms in stream channels. Thus, ecoregions serve as a useful spatial framework to understand the characteristics of stream channels. For the purpose of this study, ecoregions provide a large-scale geographic unit in which the fluvial hierarchy is organized.

The majority of studies that incorporate ecoregions into the fluvial hierarchy are primarily focused on fish and macroinvertebrate interactions at this broad-level (Larsen et al., 1986; Rohm et al., 1987; Lyons, 1989; Newall and Magnuson, 1999; McCormick et al., 2000; Pan et al., 2000; Rabeni and Doisy, 2000; Dauwalter, 2006). The use of scale in ecological studies is an important concept for understanding the spatial and temporal implications habitat has on aquatic organisms (Parsons et al., 2004). Aquatic scientists widely accept that habitat (i.e., substrate, large woody debris, current, channel units, and temperature) is one of the major variables that dictates the richness and abundance of species, which is influenced by the characteristics of the ecoregion. Although ecoregions are not always the best predictor of aquatic assemblage distribution, they set a broad-scale parameter of geographic inquiry.

A study by Rohm et al., (1987) evaluated streams in six Arkansas ecoregions to assess the role of ecoregions on fish populations and species composition to habitat and water quality. Their results suggest that ecoregions tend to be good indicators for comparing fish populations and species abundance. They also found that the physical habitat of streams in the Arkansas Valley, Ozark Highlands, Boston Mountains, and Ouachita Mountains were more similar to each other than they were to the Mississippi Floodplain and South Central Plains ecoregions.

Geomorphologists also recognize the spatial and temporal implications of scale in the fluvial hierarchy. Geomorphologists are probably more concerned, however, with the processes occurring at and between scales in the hierarchy than aquatic scientists. I state this only because, by definition, geomorphology is the study of earth surface processes and resultant forms that occur through erosion and deposition (Vitek, 1989). For example, numerous geomorphic classifications at multiple spatial scales have been developed based on processes leading to a specific organization of river form (Kondolf, 2003). To my knowledge, geomorphic studies have not detailed the interconnectedness of ecoregion-watershed-stream network-longitudinal profile-reach classification for understanding how large-scale dynamics impact reach morphology. For this reason, a study was implemented to evaluate how stream morphology differed between ecoregions through a scale dependent fluvial hierarchy.

5. Dissertation chapters

This dissertation contains six chapters. Each chapter (besides this one and the conclusion) addresses a specific research question that will be prepared for submission to journals. This approach created a certain amount of overlap (i.e., study area and site selection sections) between the chapters. Because I have not selected the journals for these chapters, all the chapters are formatted following the guidelines of the journal *Geomorphology*.

Chapter 1 provides the reader with an overview of the dissertation. Chapter 2 is titled, “Morphometric Analysis of Watersheds in Three Eastern Oklahoma Ecoregions.” This chapter investigates whether watershed morphology differs among ecoregions and how stream channels are controlled by these differences. Chapter 3 is titled, “Upstream-to-Downstream Patterns in Channel Morphology: Three Eastern Oklahoma Ecoregions.” The chapter evaluates if the variables for stream channels (i.e., particle-size, bankfull width, width-depth ratio, gradient, and sinuosity) surveyed at the reach scale differ between ecoregions in an upstream-to-downstream direction. Chapter 4 is titled, “Watershed and Stream Reach Variability in Three Eastern Oklahoma Ecoregions.” This chapter evaluates the amount of variability that exists between and among watersheds and stream reaches of ecoregions. Chapter 5 is titled, “A Regional Perspective of Classifying Stream Channels in Eastern Oklahoma.” This chapter classifies stream channels using the Rosgen classification and investigates patterns among ecoregions. Chapter 6 is titled, “Conclusion.” In this chapter, final conclusions are drawn about the role ecoregions and scale play in understanding the characteristics of stream channels in eastern Oklahoma.

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CHAPTER 2

MORPHOMETRIC ANALYSIS OF WATERSHEDS IN THREE EASTERN OKLAHOMA ECOREGIONS

Abstract

An evaluation of how watershed morphology differs between ecoregions is currently lacking in the literature. For this reason, a study was conducted to decipher if watershed morphology was statistically significant among three ecoregions in eastern Oklahoma. In addition, conclusions were drawn about the characteristics of stream channels based on differences in watershed morphology. Ecoregions in this study include the Boston Mountains, Ozark Highlands, and the Ouachita Mountains of eastern Oklahoma. Morphometric variables measured among ecoregions were drainage density, circularity ratio, relief, relief ratio, and ruggedness number. Morphometric variables were attained using a combination of ArcView 3.3©, ArcGIS 9.1©, and digital elevation models from the USGS. Similar size watersheds of first, second, third, and fourth-order streams were compared between ecoregions. A Kruskil-Wallis non-parametric test was used to test for statistical differences at $\alpha = 0.05$. All of the analyses proved statistically significant within at least one of the orders. The Ozark Highlands have a relatively high drainage density despite having low relief watersheds. This information, when coupled with pre-existing studies of streams in the Missouri Ozark Highlands has helped explain the scour-fill gravel sequences and the unstable nature of streams in the Oklahoma Ozark Highlands. The morphometric analysis of watershed variables has improved the understanding of watershed dynamics and stream channel processes in these ecoregions. When conducted with in-channel surveys, morphometric analyses help researchers understand how the characteristics of watersheds impact stream channel morphology.

Keywords: Watershed morphology, Streams, Ecoregions, Oklahoma

1. Introduction

Watershed morphology is a function of resisting framework, driving forces, and time. The resisting framework involves the physical characteristics that provide resistance to the evolution of the: lithology, geologic structure, and vegetation. Driving forces are external variables that serve to weaken/strengthen or upset/reinforce the resisting framework that controls watershed morphology: climate and land use. Time is the period during which driving forces influence the resisting framework. The response of watershed morphology to changes in driving forces is often difficult to measure over geologic time.

Evidence exists that historical changes in driving forces have upset the controls on the watershed resisting framework, which has indirectly changed processes in stream channels. Researchers in the Missouri Ozarks have proposed that changes in land uses (i.e., driving force) during the period spanning the 1830s-1960s (i.e., time) are contributing to the increased amounts of gravel in the regional stream network. Originally logging was suspected as the gravel supplier to local streams (Kohler, 1984, Love, 1990). Jacobson and Primm (1997) proposed, however, that open-range grazing (1920-1960) of cattle and hogs concentrated in valleys destroyed the riparian zone (i.e., resisting framework) and promoted the headward migration of first-order channels. This headward extension increased the amount of gravel in the fluvial system. The increase in gravel has created a fluvial system that is currently aggrading in higher-order reaches (Jacobson, 1995). The Missouri Ozarks illustrate how changes in watershed morphology (i.e., lengthening of stream channels) are a function of resisting frameworks, driving forces, and time. As documented in the Missouri Ozarks, direct and indirect changes in watershed morphology have impacts on the characteristics of stream channels.

Streams are commonly organized into a hierarchical classification (Kondolf et al., 2003). Ecoregions represent the largest scale in the hierarchy and are defined by recurring patterns of geology, climate, land use, soils, and potential natural vegetation (Omernik, 1987). Nested within a homogeneous region are additional hierarchical levels that include watersheds, segments, reaches, channel units, and microhabitats (Frissell et al., 1986). The characteristics used to delineate ecoregions (i.e., geology, climate, land use, soils, and potential natural vegetation) are the same variables that control watershed morphology and the characteristics of stream channels.

This study evaluates how watershed morphology varies among three eastern Oklahoma ecoregions and deciphers whether differences in watershed morphology provides a good framework to characterize stream channels by ecoregion. The ability to link watershed morphology to the characteristics of stream channels could provide an additional resource for watershed management and planning.

2. Background

The term morphology is commonly described as the study of shape. Geomorphologists use the term and incorporate processes acting on the landscape that help define and alter landform shape with time. In a watershed context, morphometric analysis is used to investigate watershed geomorphology in a quantitative framework (Chorley et al., 1984). Horton (1932) set the stage for descriptive watershed analysis by introducing methods that helped explain functions of watersheds (Gregory and Walling, 1973). This quantitative morphometric analysis of watersheds was continued by a series of methodological and theoretical papers spanning more than a quarter century (Horton, 1945, Langbein, 1947, Strahler, 1952, Schumm, 1956, Strahler, 1958, Strahler, 1964). These papers helped establish how morphometric analyses could be used to differentiate geomorphological processes in contrasting regions.

Morisawa (1962) investigated whether the watersheds of Allegheny Plateau, Allegheny Mountains, and the Cumberland Plateau regions of the Appalachian Plateau were morphologically different. She found that by quantitatively assessing stream length, drainage density, slope, circularity, and relief ratio of watersheds that differences existed between the regions. The Cumberland and Allegheny Plateau are more similar to each other than either is to the Allegheny Mountains. Morisawa stated that these findings support separating each of the three regions into distinct geomorphic sections. Lewis (1969) used watershed characteristics to classify Indiana into contrasting morphometric regions.

More recent studies involve using morphometric analyses in process based studies and for environmental management implications. Jamieson et al. (2004) show that tectonic zones in the Indus Valley of Ladakh, north India, can be differentiated using morphometric analyses of longitudinal valleys. Watersheds draining one of the tectonic zones tend to be shorter, thinner, and have lower hypsometric integrals than the other two. These watersheds have been influenced by thrust propagation, which has lead to erosion and increased sediment to the main trunk river and elevated local base-level. Morphometric analyses have also been conducted on paleodrainages in the deserts of Kuwait to understand the genesis and hydrological implications of runoff in these drainages (Al-Sulaimi et al., 1997).

Potter at al. (1997) found in North Carolina that aquatic biodiversity is most at risk in agricultural lands draining watersheds with high circularity. Circular watersheds have short delivery times of maximum flow. This decreases the amount of time needed for pollutants to settle out of the water, which increases degradation of the stream and the overall biodiversity of aquatic macroinvertebrates. Relationships between morphometric variables, stream habitat, and fish abundance have been documented. In small Rocky Mountain streams, statistical evidence reports that basin relief, relief ratio, and a relatively low drainage density produces the best habitat for trout (Lanka et al., 1987). The authors conclude that measures of drainage basin morphology could be useful for predicting the best trout habitat in streams via simple morphometric calculations.

Watershed morphology influences the response of a flood hydrograph for a given basin. The shape and character of the flood hydrograph is dictated by the routing of water through the watershed (Ritter et al., 2002). Patton and Baker (1976) report that drainage density and stream frequency are good measures to predict peak discharge for watersheds in regions with unlike characteristics. Drainage density is an areal morphometric variable that is often a function of climate, lithology, and relief (Chorley et al., 1984). A comparison of arid watersheds to humid watersheds with similar lithology and slope shows that arid watersheds have greater drainage densities (Ritter et al., 2002). This occurs because less precipitation decreases vegetation, which accelerates overland flow and erosion potential in these regions. In regions with similar climate, lithology and relief are the dominant controls on drainage density. The circularity of the watershed also plays a dominant role in the characteristics of the flood hydrograph. Assuming watersheds have similar patterns of stream networks, circular watersheds will supply flow to the outlet more quickly than elongated watersheds. This is particularly true in watersheds with high relief ratios.

Morphometric variables used in quantitative watershed analysis are differentiated by measurement method. These include linear, areal, and relief/gradient measurements (Strahler, 1958). Linear measurements are based on properties of the stream network and perimeter of watershed. Some examples of linear measurements include stream order, bifurcation ratio, stream length, axial angle, and watershed length. Examples of areal measurements include drainage density, texture ratio, watershed circularity, and elongation ratio. Some examples of relief/gradient measurements include watershed relief, relief ratio, stream gradient, and valley gradient.

3. Study area

This study investigates three ecoregions in eastern Oklahoma as defined by Omernik (1987): Ozark Highlands, Boston Mountains, and Ouachita Mountains. These three ecoregions were selected because watershed morphology, stream habitat characteristics, and classification are of interest to the Department of Wildlife Conservation (ODWC). The ODWC recognizes that the management of these streams is influential to the overall health of the fisheries economy in this portion of the state (Fisher et al., 2002).

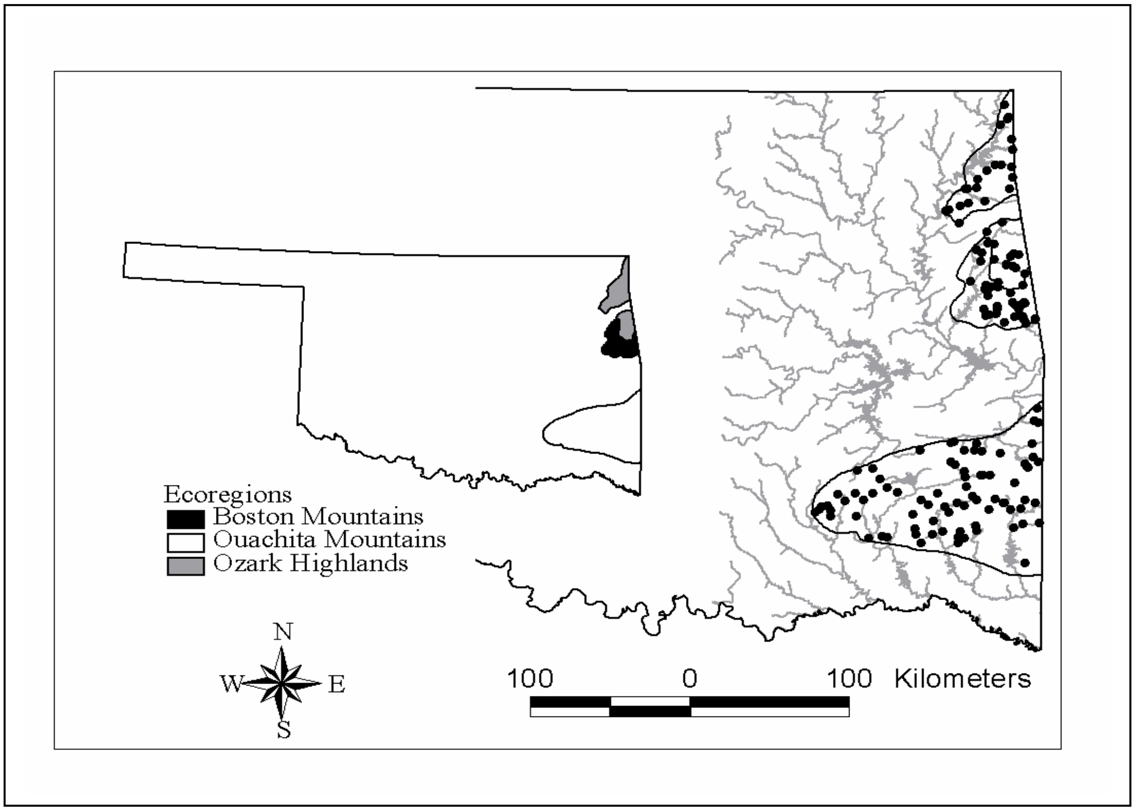

Fig. 2.1. Black dots represent study sites of first through fourth order watersheds used to decipher whether morphometric watershed variables are statistically different between ecoregions.

The Ozark Highlands ecoregion exists in parts of Kansas, Missouri, Arkansas, and Oklahoma. In Oklahoma the ecoregion encompasses 2,795 km^2 (Fig. 2.1). Woods et al. (2005) describes the region as being comprised of watersheds that are highly-to-moderately dissected. Lithology is mostly Mississippian-aged limestone or dolostone with interbedded chert. Mean annual precipitation is approximately 100-125 cm. Land use includes grazing, logging, poultry and livestock farming, and quarrying. Potential natural vegetation includes mainly oak-hickory forest and grassland. Soils orders on uplands consist of Ultisols, Alfisols, and Mollisols. Common soil series include Clarksville and Noark (Carter, 1997). Much of the native forest and prairie was removed during the logging boom at the turn of the 20th century.

The Boston Mountains ecoregion, to the south of the Ozark Highlands in Oklahoma (Fig. 2.1), encompasses 1,891km^2. Less dissection occurs in the Boston Mountains than the Ozark Highlands. Lithology includes Pennsylvanian-age sandstone, with minor amounts of Pennsylvanian and Mississippian-age limestone and shale. Mean annual precipitation is approximately 110-130 cm. Land use consists of forest and woodland, with flatter areas used for ranching and farming. The potential natural vegetation includes mostly oak-hickory forest (Woods et al., 2005). Soils orders on uplands consist of Ultisols, Inceptisols, and Entisols. Common soil series include Hector and Linker (Carter 1997).

The Ouachita Mountains ecoregion, south of the Boston Mountains and separated by the Arkansas Valley ecoregion (Fig. 2.1), encompasses 10,107 km^2 in Oklahoma. The region tends to be a mosaic of low mountains and high hills of folded Paleozoic rocks. Lithology varies throughout the ecoregion, including sandstone, shale, and novaculite. Maximum mean annual precipitation occurs on south-facing ridges, decreases to the east, and is 110-145 cm. Land use includes forestry, logging, ranching, woodland grazing, and recreation. The potential natural vegetation includes oak-hickory-pine forest (Woods et al., 2005). Soils orders consist of Ultisols, Alfisols, and Inceptisols. Common soil series include Clebit, Pirum, Neff, Tuskahoma, Wetsaw, and Wister (Carter 1997).

4. Methodology

4.1. Watershed selection

Watersheds for this study were selected based on a random point generator model that selected points on streams (1-4 order) in different basins by ecoregion (Fig. 2.1). The number of sites selected per ecoregion was attained using an area-weighted average based on the size of the ecoregion. This allowed for comparable sampling coverage across all three ecoregions. Watersheds that were not 90 percent confined to one ecoregion were not used in the analyses. Of the 149 watershed originally selected only 15 (10.1%) failed to meet the confinement criteria, the unconfined sites were not reselected for analysis.

4.2. Morphometric variables

Five variables were selected to determine whether watersheds were statistically significant between ecoregions: drainage density, circularity ratio, relief, relief ratio, and ruggedness number (Table 2.1). These variables were selected because they are thought to influence channel morphology and surface water hydrology along the longitudinal profile of streams. These variables were measured using tools in ArcView 3.3©, ArcGIS 9.1©, and Digital Elevation Models (DEMs) from the USGS National Elevation Dataset.

Drainage density was calculated by dividing the sum of stream lengths in the watershed by the watershed area (Horton, 1945). Circularity ratio is the area of the watershed divided by the area of a circle with the same perimeter as the basin (Miller, 1953). This variable expresses the overall shape of the watersheds. Relief is the highest elevation in the watershed minus the lowest elevation in the watershed. Relief ratio was calculated by dividing the total basin relief (outlet to summit of watershed) by the basin length (Schumm, 1956). The basin length used to calculate the relief ratio was a straight line from the watershed outlet to the summit, unless the straight line would have crossed the watershed boundary. Where this occurred, the line was bent along the channel and continued until the watershed and the valley were parallel. Ruggedness number is the basin relief multiplied by the drainage density. Watersheds draining first, second, third, and fourth order streams in the Boston Mountains is presented with morphometric variables to show differences in watersheds by size (Figure 2.2).

Table 2.1
Five morphometric variables used in the quantitative assessment of watershed differences by ecoregion. Table was modified from Strahler (1958).

Variable	Used or Defined	Calculated	Dimension
Drainage Density	Horton, 1945	$D = \frac{\Sigma \text{ stream length}}{\text{watershed area}}$	Areal
Circularity Ratio	Miller, 1953	$C = \frac{\text{area of watershed}}{\text{area of circle}}$	Areal
Relief	Strahler, 1952 Schumm, 1956	R = high elevation minus low elevation	Relief/Gradient
Relief Ratio	Schumm, 1956	$Rh = \frac{\text{watershed relief}}{\text{watershed length}}$	Relief/Gradient
Ruggedness Number	Morisawa, 1968	Rn = D*Basin Relief	Areal and Relief/Gradient

4.3. Statistical analysis

The Kruskal-Wallis One-Way ANOVA procedure was used to test for statistically significant differences among watersheds in the three ecoregions. The analytical software package used to perform the statistics was STATISTIX 8.0$^{\copyright}$. This nonparametric test makes no assumptions about how the underlying data is distributed (Rogerson, 2001). The test is employed to rank groups (i.e., ecoregions) using a pooled set of data from a watershed variables (e.g., drainage density). Ranks are assigned to each individual sample and replace the raw data by which they were originally ranked. Comparisons are evaluated by the mean ranks of the different groups at a given p-value to test for statistically significant differences among the groups. Significant differences among groups were tested at $\alpha = 0.05$.

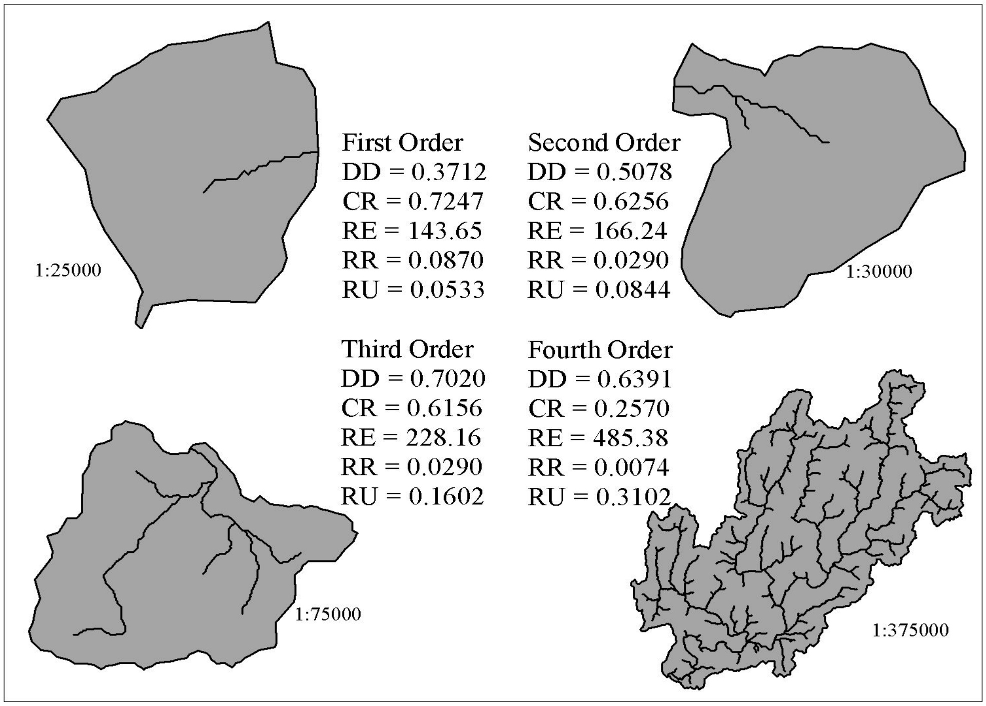

Fig. 2.2. Watersheds of contrasting stream orders (1-4) in the Boston Mountain ecoregion that portrays morphometric differences by watershed size. DD = drainage density, CR = circulatory ratio, RE = relief, RR = relief ratio, and RU = ruggedness number.

5. Results and discussion

5.1. Drainage density

Drainage density increases with stream order in two of the three ecoregions (Fig. 2.3). The Ozark Highlands is the exception. Watersheds of second-order streams in the Ozark Highlands have drainage densities slightly greater than watersheds of third-order streams (Table 2.2). The drainage density of the Ozark Highlands slightly decreases in watersheds of third-order streams and increases in watersheds of fourth-order streams. The greatest increase in drainage density occurs between watersheds of first and second-order streams. The amount of increase is greatest in the Ozark Highlands. The least amount of change in drainage density exists between watersheds of third and fourth-order streams (Table 2.2). The Boston Mountains have the lowest drainage density of the three ecoregions regardless of watershed size.

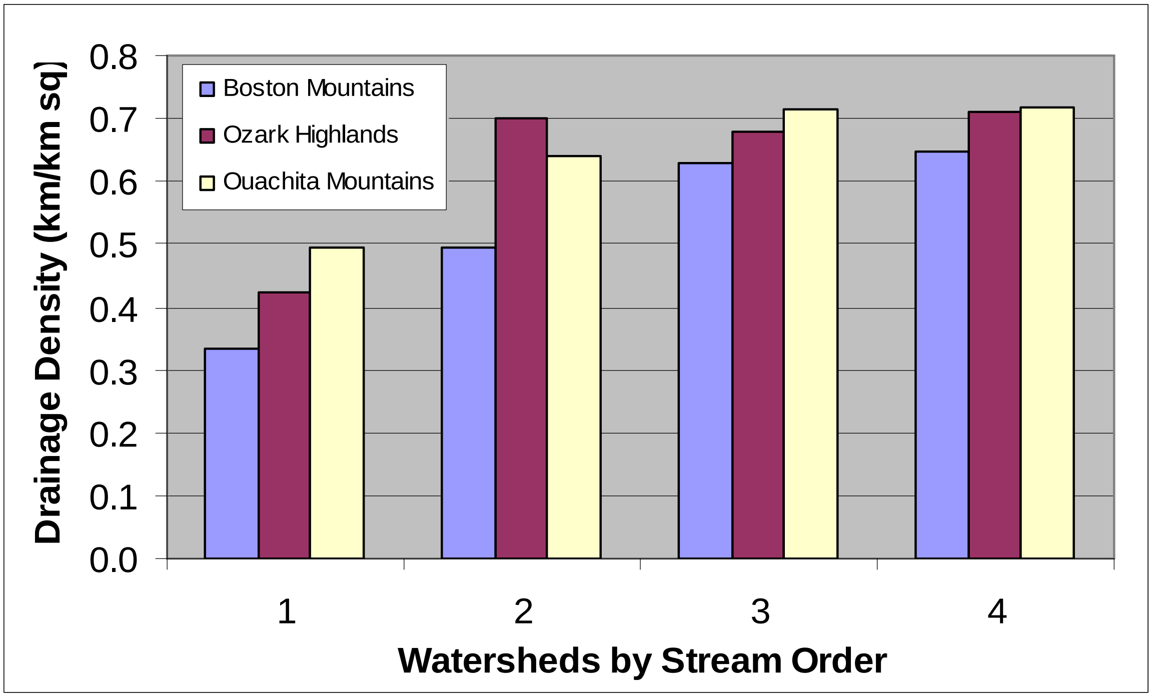

Fig. 2.3. Drainage density of watersheds by stream order.

No significant differences exist between ecoregions and drainage density of watersheds of first-order streams (Table 2.2). Drainage density in the Boston Mountains watersheds of second-order streams is statistically different from both the Ozark Highlands and the Ouachita Mountains similar size watersheds (Table 2.2). Drainage density in watersheds of third and fourth-order streams in the Boston Mountains is statistically significant from the Ouachita Mountains (Table 2.2). Little difference exists between the mean drainage density of the Ozark Highlands and Ouachita Mountains in watersheds of third and fourth-order streams (Fig. 2.3).

Table 2.2
Comparison of drainage density by order and ecoregion. The Kruskal-Wallis nonparametric statistical test was used to distinguish whether associations exist between order and ecoregion.

Ecoregion-Order[1]	Number	Mean	± 1 SD	Variance	SE Mean
Boston Mountains-1[a]	6	0.3335	0.2722	0.0741	0.1111
Ozark Highlands-1[a]	7	0.4218	0.2482	0.0616	0.0938
Ouachita Mountains-1[a]	19	0.4956	0.2645	0.0700	0.0607
Boston Mountains-2[b]	9	0.4929	0.0586	0.0034	0.0195
Ozark Highlands-2[a]	6	0.7002	0.1637	0.0268	0.0668
Ouachita Mountains-2[a]	22	0.6415	0.1334	0.0178	0.0285
Boston Mountains-3[b]	9	0.6281	0.0352	0.0012	0.0117
Ozark Highlands-3[ab]	7	0.6803	0.0775	0.0060	0.0293
Ouachita Mountains-3[a]	19	0.7131	0.1063	0.0113	0.0244
Boston Mountains-4[b]	7	0.6458	0.0158	0.0024	0.0059
Ozark Highlands-4[ab]	5	0.7120	0.0367	0.0013	0.0164
Ouachita Mountains-4[a]	18	0.7185	0.0550	0.0030	0.0130

[1] Similar superscripts in the ecoregion column (i.e., all [a] in first-order streams (1)) show no statistically significant differences between watersheds stratified by ecoregion. Where superscripts are different (i.e., [a] and [b]) between ecoregion and watershed order statistically significant difference exist. Superscripts [ab] are not statistically different from an ecoregion with a similar superscript.

Drainage density is often a function of relief. Watersheds with high relief have erosion potentials greater than watersheds with lower relief, which allow high relief streams to downcut and migrate upslope in a headward direction (Chorley et al., 1984). In the analysis of drainage density, this was not verified in all ecoregions. The highest drainage densities, regardless of order, occurred in the Ozark Highlands and the Ouachita Mountains. The direct relationship between watershed relief and drainage density holds true when examining the Ouachita Mountains. The Ozark Highlands, however, have a high drainage density with a much lower relief than either the Ouachita Mountains or the Boston Mountains (Fig. 2.5). Watersheds in the Boston Mountains have the lowest drainage density, but the second highest relief. These results suggest that another variable or combination of variables is responsible for controlling drainage density in the Ozark Highlands.

Previous studies have found that lithology plays a significant role in the drainage density of streams. Ray and Fisher (1960) found that stream networks developed in shale produced greater drainage densities than stream networks in granite. The Ozark Highlands are comprised of chert and limestone (e.g., cherty limestone), which differs in hardness and erosion potential from the sandstone and shale make-up of the Boston Mountains and the Ouachita Mountains.

The Ozark Highlands consist of well to excessively drained soils that form in colluvium and the underling clay residuum from cherty limestone. During high intensity rainfall, infiltration is low and sheet erosion is common. Where surface limestone has been dissolved, the headward migration of a stream channel has been intensified. The jointed and fractured limestone serves as a catalyst for rill development and the headward migration that produces stream channels. It can be proposed that the highly dissolvable cherty limestone of the Ozark Highlands exacerbates the initiation of stream channels and influences drainage densities in these watersheds.

In addition to lithology and underlying geologic structure, land use may play a role in the high drainage density of the Ozark Highlands. Studies in the Missouri Ozark Highlands report that land use change between the mid 1800s and mid 1900s influenced the headward migration of streams and indirectly increased the drainage density of these watersheds (Jacobson and Primm, 1997). The Missouri streams are not unlike those in encountered the Oklahoma Ozarks. The streams contain large amounts of gravel that is being redistributed throughout the system after mid-to-high magnitude floods (Jacobson, 1995). Jacobson and Primm (1997) propose that the increase in gravel resulted from the elaboration of the stream network. If the assumption is true and the gravel is coming from the initiation and elaboration of pre-existing channels, then the erosion from land use change probably plays a role in the high drainage density of the Oklahoma Ozark Highlands, which were extensively logged (Rice and Penfound, 1959) and later became open-range grazing land.

Land use change in the Boston Mountains and the Ouachita Mountains has also occurred. The drainage densities in these regions apparently have not been as impacted by land use changes as the Ozark Highlands. These differences may be attributed to the more resistant lithology and structure of the Boston Mountains and the Ouachita Mountains. Ridgetops of the Boston Mountains are primarily resistant sandstone with sideslopes of interbedded sandstone and shale (Woods et al., 2005). The Ouachita Mountains outcrops consist of sandstone, shale, and navaculite. Slopes are more resistant to erosion in the Boston Mountains and Ouachita Mountains and are not as impacted by land use change as the Ozark Highlands.

5.2. Circularity ratio

The circularity ratio in the Ozark Highlands and the Boston Mountains watersheds decreases as the size of the watersheds increase. A slight increase in the circularity ratio occurs in the Ouachita Mountains between watersheds of third and fourth-order streams (Fig. 2.4). The general trend, however, is that the circularity ratio decreases as watershed size increases. No statistically significant differences exist between ecoregions in watersheds of first, second, or third-order streams (Table 2.3). The circularity ratio is statistically significant only in watersheds of fourth-order streams between the less circular Boston Mountains and the more circular Ouachita Mountains (Table 2.3). Watersheds of first-order streams in the Boston Mountains are more circular than the Ozark Highlands and the Ouachita Mountains, but less circular in watersheds of fourth-order streams (Fig. 2.4).

The Ouachita Mountains have the least circular watersheds in first-order streams of the three ecoregions. This is most likely because of the elongated trellis stream network that is controlled by folded structures in many high gradient first-order streams. This pattern does not continue with watersheds of second-order streams. Circularity ratios of the dentritic stream networks (i.e., watersheds of second-order streams) in the Ozark Highlands are less than those in the Ouachita Mountains, which suggest that structure plays less of a role on circularity as the size of a watershed increases. The circularity ratio of the Boston Mountains shows the greatest amount of change from watersheds of first to fourth-order streams, while the Ouachita Mountains show the least.

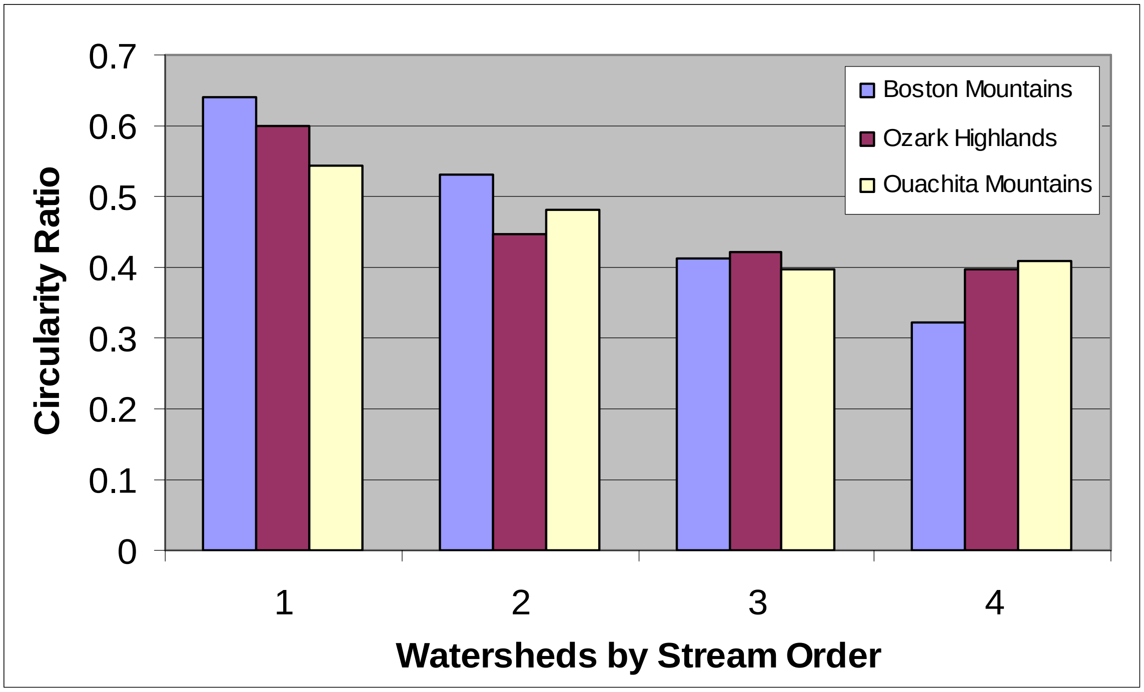

Fig. 2.4. Circularity ratio of watersheds by stream order.

Table 2.3
Comparison of circularity ratio by order and ecoregion. The Kruskal-Wallis nonparametric statistical test was used to distinguish whether associations exist between order and ecoregion.

Ecoregion[1]	Number	Mean	± 1 SD	Variance	SE Mean
Boston Mountains-1[a]	6	0.6395	0.0517	0.0026	0.0211
Ozark Highlands-1[a]	7	0.5989	0.1101	0.0121	0.0416
Ouachita Mountains-1[a]	19	0.5431	0.1444	0.0209	0.0331
Boston Mountains-2[a]	9	0.5311	0.0622	0.0038	0.0207
Ozark Highlands-2[a]	6	0.4473	0.0977	0.0095	0.0399
Ouachita Mountains-2[a]	22	0.4819	0.1071	0.0115	0.0228
Boston Mountains-3[a]	9	0.4115	0.0891	0.0079	0.0297
Ozark Highlands-3[a]	7	0.4226	0.1104	0.0122	0.0417
Ouachita Mountains-3[a]	19	0.3978	0.0972	0.0094	0.0223
Boston Mountains-4[b]	7	0.3206	0.0492	0.0024	0.0186
Ozark Highlands-4[ab]	5	0.3984	0.0516	0.0026	0.0231
Ouachita Mountains-4[a]	18	0.4091	0.0575	0.0033	0.0136

[1] See Table 2.2 for full explanation

More circular watersheds tend to concentrate overland flow to stream channels at a more consistent rate than non-circular watersheds. Stream channels draining circular watersheds achieve quicker peak flows during high precipitation events than less circular watersheds. Over time these peak flows can lead to a widening of the stream channel to accomodate these high magnitude flows. First-order streams in the Boston Mountains have wider bankfull widths and more circular watersheds than streams of similar size in the Ozark Highlands or Ouachita Mountains (Chapter 3). A direct relationship exists between bankfull width and circularity ratio in low-order streams of the Boston Mountains. The circularity ratio does not influence channel width in higher-order streams. Bankfull widths of higher-order streams are influenced more by increased drainage density, vegetation, bank cohesion, and the land use pattern adjacent to streambanks. In eastern Oklahoma, the high drainage density of the Ozark Highlands correlates to wide channels in lower reaches (Chapter 3). Trimble (2004) found that the bankfull width of forest streams were wider than grass streams in southwestern Wisconsin. In addition, grasslands that are heavily grazed tend to have bankfull widths wider than non-grazed riparian grasslands (Trimble, 2004).

5.3. Relief

Watershed relief is greatest in the Ouachita Mountains, followed by the Boston Mountains and the Ozark Highlands, respectively (Fig. 2.5). Watershed relief of first-order streams is statistically significant between the Ozark Highlands and the Ouachita Mountains (Table 2.4). Watersheds of second, third, and fourth-order streams in the Ozark Highlands are statistically different from the Boston Mountains and Ouachita

Mountains (Table 2.4). No statistically significant differences exist between the Boston Mountains and the Ouachita Mountains.

The low relief watersheds of the Ozark Highlands may help in understanding the current processes occurring in the stream channels in this region. Jacobson and Primm (1997) report that erosion was accelerated in the Missouri Ozarks because of changes and land use practices between 1830 and 1960. In Oklahoma, this too was a period of intensive land use change (Rice and Penfound, 1959). Accelerated erosion during this period probably occurred in Oklahoma Ozark Highland watersheds. If this is correct, the floodplains and pointbars probably serve as a storage location for these sediments. This would explain why the scour-erosion episodes occur of large pools in fourth-order streams of Baron Fork Creek that is occurring (personal communication, landowners). This sediment distribution has been described in the Missouri Ozarks (Jacobson, 1995).

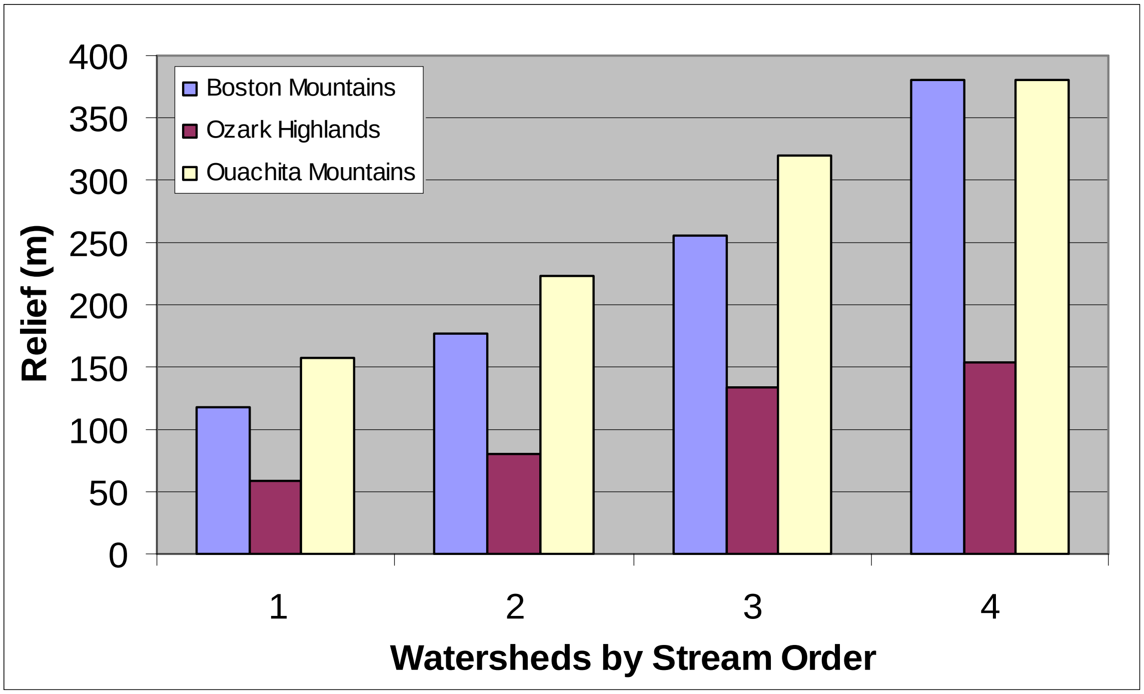

Fig. 2.5. Watershed relief by stream order shows large differences among ecoregions.

Table 2.4
Comparison of relief by order and ecoregion. The Kruskal-Wallis nonparametric statistical test was used to distinguish whether associations exist between order and ecoregion.

Ecoregion[1]	Number	Mean	± 1 SD	Variance	SE Mean
Boston Mountains-1[ab]	6	118.81	71.48	5109.00	29.18
Ozark Highlands-1[b]	7	58.77	23.37	545.91	8.83
Ouachita Mountains-1[a]	19	157.06	78.14	6105.90	17.93
Boston Mountains-2[a]	9	175.94	49.79	2479.40	16.60
Ozark Highlands-2[b]	6	79.64	20.26	410.60	8.27
Ouachita Mountains-2[a]	22	223.50	136.29	18575.00	29.06
Boston Mountains-3[a]	9	256.10	41.52	1724.00	13.84
Ozark Highlands-3[b]	7	134.29	41.24	1700.40	15.59
Ouachita Mountains-3[a]	19	320.20	124.83	15582.00	28.64
Boston Mountains-4[a]	7	379.88	76.37	5831.90	28.86
Ozark Highlands-4[b]	5	152.80	10.77	116.02	4.82
Ouachita Mountains-4[a]	18	379.41	181.26	32857.00	42.72

[1] See Table 2.2 for full explanation

Watershed relief in the Ozark Highlands is much less than in the Ouachita Mountains and the Boston Mountains (Fig. 2.5). The Ozark Highlands are more closely associated with plateau-like characteristics (i.e., Springfield Plateau) than the more mountainous Ouachita Mountains and Boston Mountains. The watersheds, however, tend to be moderately to highly dissected with well established stream networks. The maximum elevations in the Ozark Highlands are approximately 450 meters, while minimum elevations less than 120 meters in the valley bottoms (Woods et al., 2005). The Boston Mountains consist of low mountains and rolling hills with higher maximum and minimum elevations than the Ozark Highlands. Maximum elevations are approximately 520 meters, with minimum elevations of approximately 140 meters. The Ouachita Mountains have the largest range in high and low elevation among the ecoregions. This region of folded mountains and open hills has maximum elevations that exceed 800 meters, while low valley elevations are less than 20 meters (Woods et al., 2005). The northern boundary of the Ouachita Mountains consists of east to west trending watersheds that have the highest relief in the region.

5.4. Relief ratio

Watersheds of first and second-order streams in the Boston Mountains have higher relief ratios than the Ouachita Mountains (Fig. 2.6). Relief ratios in watersheds of third and fourth-order streams in the Ouachita Mountains exceed those of the Boston Mountains. The relief ratio of the Ozark Highlands is the lowest of the three ecoregions, which is a result of the overall low relief of the region. Less change exists in relief ratio by watershed size in the Ozark Highlands than the Boston Mountains or the Ouachita Mountains. The relief ratio of the Boston Mountains and the Ouachita Mountains are statistically different from the Ozark Highlands in watersheds of first and second-order streams (Table 2.5). In watersheds of third-order streams, the Ozark Highlands are statistically different from the Ouachita Mountains. No statistically significant differences exist among ecoregions and relief ratio in watersheds of fourth order streams (Table 2.5).

The relief ratio of the three ecoregions decreases as the size of the watershed increases. The Ozark Highlands decreases more slowly than either the Boston Mountains or the Ouachita Mountains. This relationship is influenced by the relatively low overall relief of the Ozark Highlands. The Boston Mountains have a higher relief ratio than the Ouachita Mountains in watersheds of first-order streams, but a lower relief. This means that the overall basin steepness of the Boston Mountains is greater than the Ouachita Mountains in watersheds of first and second-order streams. In watersheds of third and fourth-order streams, the Ouachita Mountains have steeper watersheds than the Boston Mountains. The low steepness of the Ozark Highlands watershed probably allowed for the extension and elaboration of pre-existing channel networks to advance in the headward direction. In doing so, the drainage density of the region was amplified.

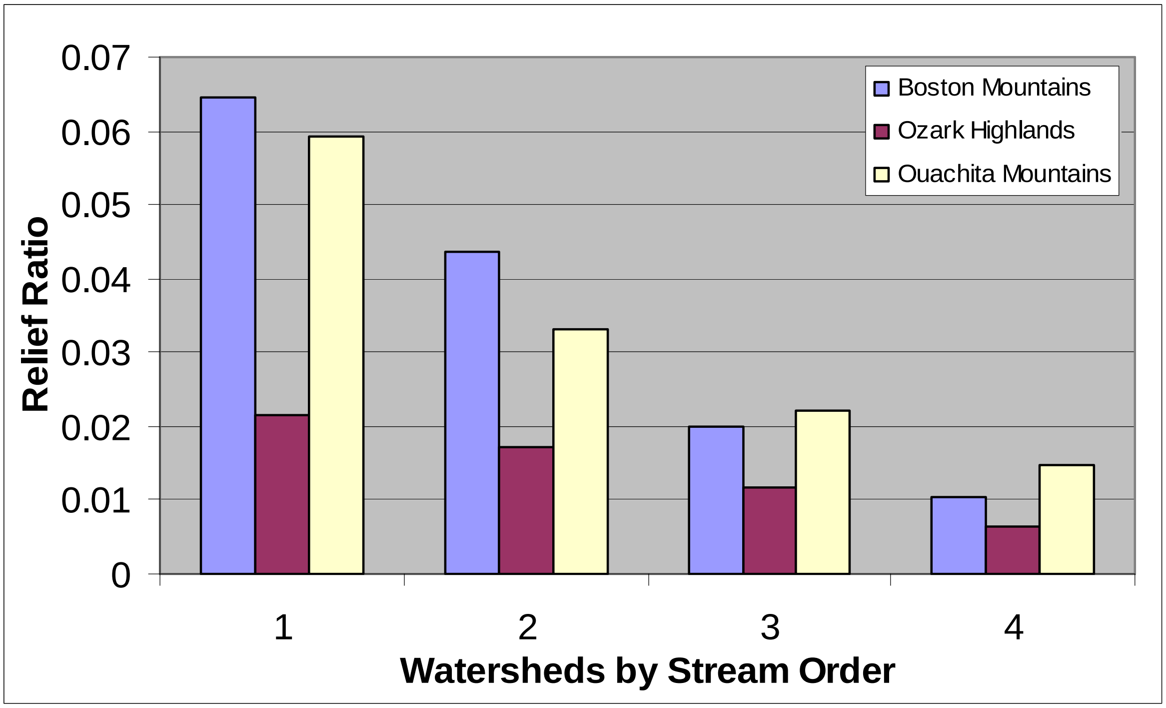

Fig. 2.6. Relief ratio decreases as watershed size increases. Large differences exist between the relief ratio of the Ozark Highlands and Boston Mountains and Ouachita Mountains.

Table 2.5
Comparison of relief ratio by order and ecoregion. The Kruskal-Wallis nonparametric statistical test was used to distinguish whether associations exist between order and ecoregion.

Ecoregion[1]	Number	Mean	± 1 SD	Variance	SE Mean
Boston Mountains-1^{a}	6	0.0646	0.0325	0.0010	0.0133
Ozark Highlands-1^{b}	7	0.0216	0.0097	0.0094	0.0036
Ouachita Mountains-1^{a}	19	0.0592	0.0424	0.0018	0.0097
Boston Mountains-2^{a}	9	0.0436	0.0190	0.0036	0.0063
Ozark Highlands-2^{b}	6	0.0171	0.0081	0.0066	0.0033
Ouachita Mountains-2^{a}	22	0.0332	0.0108	0.0015	0.0023
Boston Mountains-3^{ab}	9	0.0201	0.0097	0.00009	0.0032
Ozark Highlands-3^{b}	7	0.0116	0.0074	0.00005	0.0028
Ouachita Mountains-3^{a}	19	0.0222	0.0125	0.0001	0.0080
Boston Mountains-4^{a}	7	0.0103	0.0021	0.000004	0.00008
Ozark Highlands-4^{a}	5	0.0065	0.0035	0.00001	0.0016
Ouachita Mountains-4^{a}	18	0.0148	0.0114	0.0001	0.0027

[1] See Table 2.2 for full explanation

5.5. Ruggedness number

The ruggedness number increases as the size of the watershed increases. This occurs because drainage density and relief increase as the size of the watershed increases, both of which are multiplied together to get the ruggedness number. The Ouachita Mountains have the highest ruggedness number in all the watersheds, which is followed by the Boston Mountains and the Ozark Highlands, respectively (Fig. 2.7). No statistically significant differences exist between ecoregion and ruggedness number for watersheds of first or fourth-order streams. Statistically significant differences do exist between the Ouachita Mountains and the Ozark Highlands in watersheds of second and third-order streams (Table 2.6).

Relief plays a larger role in the calculation of the ruggedness number than does drainage density because much larger values are associated with relief than drainage density. Drainage density does a much better job, however, of explaining the overall dissection of the Ozark Highlands than does the ruggedness number. The low relief of the Ozark Highlands biases the ruggedness number even through the drainage density of the Ozark Highlands is almost identical to that of the greater relief Ouachita Mountains, which has a much greater ruggedness number than the Ozark Highlands.

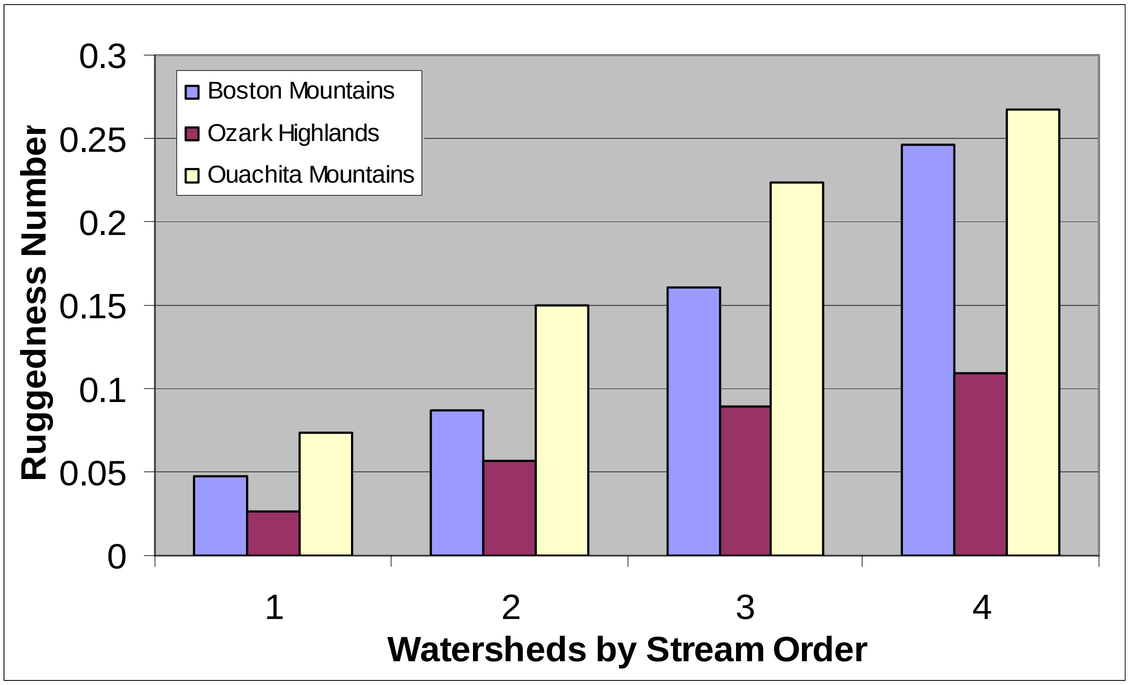

Fig. 2.7. Bar graph showing changes in ruggedness number with watershed size. The ruggedness number increases as order increases.

Table 2.6
Comparison of ruggedness number by order and ecoregion. The Kruskal-Wallis nonparametric statistical test was used to distinguish whether associations exist between order and ecoregion.

Ecoregion[1]	Number	Mean	± 1 SD	Variance	SE Mean
Boston Mountains-1[a]	6	0.0471	0.0516	0.0026	0.0211
Ozark Highlands-1[a]	7	0.0263	0.0214	0.0045	0.0080
Ouachita Mountains-1[a]	19	0.0732	0.0501	0.0025	0.0115
Boston Mountains-2[ab]	9	0.0868	0.0283	0.0008	0.0094
Ozark Highlands-2[b]	6	0.0562	0.0202	0.0004	0.0082
Ouachita Mountains-2[a]	22	0.1494	0.1097	0.0120	0.0234
Boston Mountains-3[ab]	9	0.1609	0.0267	0.0007	0.0089
Ozark Highlands-3[b]	7	0.0893	0.0210	0.0004	0.0079
Ouachita Mountains-3[a]	19	0.2242	0.0826	0.0068	0.0189
Boston Mountains-4[a]	7	0.2454	0.0489	0.0024	0.0185
Ozark Highlands-4[a]	5	0.1089	0.0103	0.0001	0.0046
Ouachita Mountains-4[a]	18	0.2669	0.1143	0.0131	0.0269

[1] See Table 2.2 for full explanation

6. Conclusion

Omernik and Bailey (1997) state that ecoregions are intended to provide a spatial framework for ecosystem assessment, research, inventory, monitoring, and management. In eastern Oklahoma, three ecoregions were used to test for differences in watershed morphology between regions with similar physical characteristics. All five morphometric variables examined in this study were statistically significant in some manner when stratified by order and ecoregion.

These results show that ecoregions are a useful spatial framework to evaluate watershed morphology on a large-scale. Characteristics of watershed morphology at the ecoregion scale allow for understanding current processes in stream channels in these regions. For example, drainage density in the Ozark Highlands is not a function of relief, but rather a function of lithology and fine-textured gravelly soils that decrease infiltration and accelerate erosion. In the Missouri Ozark Highlands, land use practices changed between 1830 and 1960 and accelerated erosion through the headward extension of pre-existing streams (Jacobson and Primm, 1997). This appears to have occurred in the Oklahoma Ozark Highlands as well. Evidence is supported by the high drainage density to low watersheds relief, and the influence of scour and deposition that occurs in higher-order streams of the region. Restoration of stream channels and applications of watershed management must consider that these streams are unstable and out of equilibrium. Stream restoration designs based on present channel form will not be successful if the processes that dictate channel morphology are different from those that explain the current stream reach morphology. Failure to understand these relationships will hinder the successful implementation of designs to restore the streams.

A demonstration of how and why watershed morphology differs by ecological region has been conducted. Although a certain amount of inherent variability exists between watersheds in like regions, enough similarities occur in the resisting framework and driving forces to suggest that ecoregions are good indicators for regional morphometric analyses. In addition, morphometric analyses help in understanding the characteristics of stream channels from upstream-to-downstream. Additional studies are needed to evaluate to what extent watershed morphology can be used to help predict the conditions of the stream channels at multiple spatial scales within a watershed.

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Appendix

[a] BM = Boston Mountains, OH = Ozark Highlands, OM = Ouachita Mountains. The number next to the region abbreviation is stream order

[b] ID = randomly selected points that serve a reaches (see page 100)

[c] DA = Drainage area above outlet

[d] DD = Drainage density (km/km^2)

[e] CR = Circularity Ratio

[f] RE = Relief (m)

[g] RR = Relief Ratio

[h] RN = Ruggedness Number

Region[a]	ID[b]	DA[c]	DD[d]	CR[e]	RE[f]	RR[g]	RN[h]
BM-1	0	2.53	0.371	0.725	143.645	0.087	0.053
BM-1	1	1.20	0.001	0.600	82.609	0.106	0.001
BM-1	2	1.31	0.036	0.643	76.741	0.050	0.003
BM-1	4	2.67	0.688	0.575	102.326	0.035	0.070
BM-1	6	2.98	0.539	0.658	251.566	0.085	0.136
BM-1	9	1.94	0.367	0.636	55.946	0.024	0.021
BM-2	10	6.06	0.494	0.463	86.485	0.030	0.043
BM-2	11	9.5	0.574	0.565	182.297	0.030	0.105
BM-2	12	19.32	0.536	0.482	269.132	0.031	0.144
BM-2	13	4.21	0.370	0.581	193.678	0.084	0.072
BM-2	15	8.16	0.446	0.461	175.013	0.041	0.078
BM-2	16	4.12	0.485	0.583	160.776	0.051	0.078
BM-2	17	14.00	0.492	0.472	210.041	0.028	0.103
BM-2	18	5.25	0.531	0.548	139.814	0.035	0.074
BM-2	19	3.67	0.508	0.626	166.239	0.062	0.084
BM-3	20	20.61	0.604	0.411	245.913	0.030	0.148
BM-3	21	21.85	0.702	0.616	228.163	0.029	0.160
BM-3	22	121.06	0.634	0.308	287.796	0.013	0.182
BM-3	23	144.95	0.607	0.383	265.542	0.011	0.161
BM-3	24	16.76	0.668	0.483	256.357	0.038	0.171
BM-3	25	40.83	0.596	0.373	164.687	0.011	0.098
BM-3	26	80.30	0.609	0.376	291.674	0.021	0.178
BM-3	27	88.24	0.624	0.373	302.516	0.017	0.189
BM-3	28	128.32	0.610	0.381	262.254	0.012	0.160
BM-4	30	205.74	0.661	0.356	345.327	0.012	0.228
BM-4	31	164.23	0.652	0.296	339.438	0.013	0.221
BM-4	32	237.92	0.655	0.369	355.591	0.011	0.233
BM-4	33	248.81	0.658	0.358	363.192	0.011	0.239
BM-4	35	587.46	0.639	0.257	485.380	0.007	0.310
BM-4	36	587.31	0.639	0.257	485.380	0.007	0.310

Region[a]	ID[b]	DA[c]	DD[d]	CR[e]	RE[f]	RR[g]	RN[h]
BM-4	37	223.29	0.616	0.351	284.839	0.010	0.175
OH-1	40	3.97	0.392	0.581	43.418	0.017	0.017
OH-1	42	3.92	0.579	0.475	107.434	0.027	0.062
OH-1	44	1.54	0.092	0.660	51.889	0.038	0.005
OH-1	46	6.81	0.637	0.538	61.036	0.010	0.039
OH-1	47	1.21	0.074	0.588	54.234	0.028	0.004
OH-1	48	4.55	0.667	0.538	59.091	0.015	0.039
OH-1	49	2.39	0.510	0.813	34.307	0.016	0.018
OH-2	50	16.18	0.616	0.535	51.636	0.006	0.032
OH-2	51	2.07	0.896	0.335	74.992	0.019	0.067
OH-2	53	11.12	0.795	0.420	101.263	0.014	0.081
OH-2	55	4.81	0.790	0.446	68.47	0.019	0.054
OH-2	57	3.50	0.434	0.587	76.466	0.031	0.033
OH-2	59	12.36	0.670	0.361	105.032	0.014	0.070
OH-3	60	80.41	0.590	0.214	141.136	0.005	0.083
OH-3	61	39.20	0.626	0.484	166.809	0.013	0.104
OH-3	63	21.58	0.617	0.467	204.452	0.027	0.126
OH-3	65	78.50	0.693	0.526	101.164	0.007	0.070
OH-3	67	14.65	0.816	0.448	86.815	0.010	0.071
OH-3	68	82.72	0.725	0.332	134.062	0.007	0.097
OH-3	69	19.71	0.696	0.488	105.584	0.013	0.073
OH-4	70	211.42	0.678	0.454	137.423	0.004	0.093
OH-4	71	291.75	0.668	0.345	163.576	0.004	0.109
OH-4	73	161.20	0.751	0.344	161.685	0.005	0.121
OH-4	75	33.87	0.733	0.438	154.070	0.013	0.113
OH-4	79	104.00	0.730	0.411	147.237	0.006	0.107
OM-1	80	2.40	0.416	0.519	290.76	0.107	0.121
OM-1	81	1.74	0.306	0.638	126.618	0.071	0.039
OM-1	82	5.52	0.614	0.579	109.036	0.022	0.067
OM-1	83	2.29	0.664	0.385	179.876	0.047	0.119

Region[a]	ID[b]	DA[c]	DD[d]	CR[e]	RE[f]	RR[g]	RN[h]
OM-1	84	1.23	0.066	0.678	209.759	0.122	0.014
OM-1	85	1.71	0.296	0.810	240.300	0.125	0.071
OM-1	87	3.35	0.722	0.413	137.013	0.033	0.099
OM-1	89	2.57	0.385	0.584	159.867	0.058	0.062
OM-2	90	7.72	0.574	0.445	136.277	0.025	0.078
OM-2	91	6.12	0.739	0.422	76.863	0.015	0.057
OM-2	92	13.94	0.652	0.427	130.15	0.018	0.085
OM-2	93	16.38	0.978	0.157	483.906	0.028	0.473
OM-2	94	13.23	0.619	0.464	390.003	0.041	0.241
OM-2	95	10.16	0.592	0.436	205.920	0.036	0.122
OM-2	96	10.17	0.571	0.554	245.889	0.042	0.140
OM-2	97	11.38	0.712	0.451	199.531	0.031	0.142
OM-2	98	19.85	0.622	0.370	552.775	0.047	0.344
OM-2	99	9.74	0.766	0.600	215.104	0.046	0.165
OM-3	101	34.26	0.920	0.369	208.242	0.012	0.192
OM-3	102	35.66	0.797	0.554	306.747	0.024	0.244
OM-3	103	12.17	0.768	0.446	256.292	0.039	0.197
OM-3	104	35.88	0.707	0.340	249.487	0.019	0.177
OM-3	105	49.04	0.776	0.409	378.477	0.024	0.294
OM-3	106	39.16	0.830	0.225	168.211	0.008	0.140
OM-3	107	34.97	0.701	0.408	441.500	0.032	0.310
OM-3	108	106.47	0.744	0.509	534.490	0.027	0.398
OM-3	109	99.79	0.756	0.301	363.797	0.010	0.275
OM-4	110	143.37	0.704	0.386	178.497	0.008	0.126
OM-4	111	293.58	0.765	0.397	298.105	0.005	0.228
OM-4	112	364.12	0.743	0.329	0.008	0.008	0.400
OM-4	113	157.83	0.773	0.454	256.372	0.008	0.198
OM-4	115	268.10	0.730	0.337	512.679	0.010	0.374
OM-4	116	78.06	0.683	0.374	161.424	0.015	0.110
OM-4	117	84.94	0.735	0.433	167.259	0.008	0.123

Region[a]	ID[b]	DA[c]	DD[d]	CR[e]	RE[f]	RR[g]	RN[h]
OM-4	118	155.32	0.797	0.438	216.283	0.005	0.172
OM-1	122	2.54	0.934	0.434	109.065	0.026	0.102
OM-1	123	2.54	0.480	0.578	45.863	0.019	0.022
OM-1	124	1.85	0.443	0.583	322.416	0.127	0.143
OM-1	125	10.24	0.974	0.226	130.720	0.011	0.127
OM-1	126	2.45	0.453	0.669	74.771	0.033	0.034
OM-1	128	8.35	0.737	0.376	248.258	0.032	0.183
OM-1	129	1.25	0.148	0.523	108.374	0.074	0.016
OM-2	130	3.27	0.585	0.454	101.517	0.027	0.059
OM-2	132	6.90	0.672	0.650	120.699	0.031	0.081
OM-2	133	21.59	0.610	0.467	479.049	0.042	0.292
OM-2	134	7.08	0.852	0.454	261.508	0.041	0.223
OM-2	136	3.16	0.355	0.486	123.296	0.044	0.044
OM-2	137	7.61	0.783	0.594	288.249	0.046	0.226
OM-2	138	4.66	0.563	0.438	74.813	0.019	0.042
OM-2	139	14.50	0.581	0.468	187.987	0.021	0.109
OM-2	140	8.04	0.506	0.602	148.560	0.032	0.075
OM-2	141	7.49	0.545	0.520	178.472	0.032	0.097
OM-3	142	61.98	0.627	0.405	213.739	0.010	0.134
OM-3	144	29.65	0.661	0.387	383.083	0.028	0.253
OM-3	145	78.56	0.427	0.236	546.753	0.023	0.233
OM-3	146	107.01	0.739	0.349	464.475	0.018	0.343
OM-3	148	34.95	0.638	0.540	150.424	0.012	0.096
OM-3	149	82.78	0.724	0.321	413.725	0.018	0.300
OM-3	150	65.96	0.717	0.387	276.151	0.015	0.198
OM-3	151	33.17	0.795	0.349	239.384	0.021	0.190
OM-4	152	68.03	0.734	0.447	159.484	0.010	0.117
OM-4	154	132.88	0.653	0.351	515.438	0.018	0.336
OM-4	155	116.33	0.654	0.489	588.489	0.024	0.385
OM-4	157	393.54	0.720	0.349	611.953	0.010	0.441

Region[a]	ID[b]	DA[c]	DD[d]	CR[e]	RE[f]	RR[g]	RN[h]
OM-4	158	75.74	0.612	0.451	653.876	0.046	0.400
OM-4	159	228.24	0.765	0.368	342.688	0.012	0.262
OM-4	160	68.95	0.719	0.492	335.727	0.022	0.242
OM-4	161	235.24	0.766	0.414	272.226	0.006	0.209
OM-1	162	1.21	0.021	0.782	210.651	0.132	0.004
OM-1	164	2.06	0.454	0.574	58.282	0.023	0.026
OM-1	165	3.10	0.594	0.546	135.476	0.037	0.080
OM-2	166	8.23	0.503	0.659	179.000	0.050	0.090
OM-3	167	11.73	0.654	0.465	355.520	0.062	0.200
OM-4	169	238.42	0.766	0.345	359.898	0.010	0.276
OM-1	911	2.85	0.710	0.423	87.037	0.026	0.062
OM-2	920	12.62	0.734	0.483	137.346	0.020	0.101
OM-3	930	15.11	0.661	0.557	133.340	0.020	0.088
OM-4	940	136.11	0.613	0.510	661.008	0.038	0.405

CHAPTER 3

UPSTREAM-TO-DOWNSTREAM PATTERNS IN CHANNEL MORPHOLOGY IN THREE EASTERN OKLAHOMA ECOREGIONS

Abstract

Ecoregions are delineated by similarities in geology, climate, soils, land use, and potential natural vegetation. These regions allow researchers to examine physical relationships on large spatial scales. Comparisons between ecoregions allow for understanding of how changes in the physical variables can be used to delineate regions that impact different processes at the ecoregion scale. For this reason, a study was designed to evaluate how the characteristics of stream channels differed from upstream-to-downstream between three ecoregions in eastern Oklahoma: Boston Mountains, Ozark Highlands, and Ouachita Mountains. One hundred and forty-nine reaches were surveyed in first- through fourth-order streams. Morphologic variables collected at each stream reach included particle-size, bankfull width, width-depth ratio, gradient, and sinuosity. Regression analysis was used to test for statistically significant differences (i.e., y-intercept and slope coefficients) between morphologic variables and ecoregions. Results show that statistically significant differences exist at $\alpha \leq 0.05$ between particle-size, bankfull width, and width-depth ratio. No statistically significant differences exist for gradient and sinuosity. Particle-size is smallest in the Ozark Highlands and largest in the

Ouachita Mountains. Bankfull width of the Ozark Highlands is statistically significant from the Boston Mountains and Ouachita Mountains. Width-depth ratios of the Boston Mountains and Ozark Highlands are not statistically significant. Significant differences exist, however, between the Boston Mountains and Ozark Highlands when compared individually to Ouachita Mountains. Findings of this study show that ecoregions afford a good spatial structure that can help in understanding the upstream-to-downstream trends of some variables of stream morphology surveyed at the reach scale. The hierarchy of the fluvial system begins within a broad, relatively homogenous setting that imparts control processes on stream function. Ecoregions provide an adequate regional division to begin a large-scale geomorphic study of processes in stream channels.

Keywords: Geomorphology, Streams, Ecoregions, Oklahoma

1. Introduction

From the mid-nineteenth century to the mid-twentieth century qualitative or descriptive geomorphology (i.e., physiography) was largely regionally based. William Morris Davis defined the regional landscape based on the “cycle of erosion.” Landforms were either in a youthful, mature, or old-age stage of development (Davis, 1899). Regionalization of the landscape continued with the physiographic works of Fenneman (1931, 1938). The natural physiographic (i.e., geomorphic) regions of North America and Canada were produced by Hunt (1974). Eleven major divisions and 42 geomorphic provinces exist in North America and Canada. Boundaries of the 42 geomorphic provinces are mainly by geologic structure (Hunt, 1974). Less influential to the regionalization of geomorphic provinces are climate, vegetation, soils, and water.

According to Montgomery and Buffington (1998) the organization of the fluvial hierarchy begins with a regional boundary that is defined by geomorphic provinces. These geomorphic provinces consist of regions linked by similarities in physiographic, climatic, and geologic features. Montgomery and Buffington (1998) suggest that geomorphic provinces are too general to predict the characteristics of channel attributes. However, they note that streams in the Olympic Mountains geomorphic province have large quantities of woody debris that influence channel morphology. This suggests that the large-scale organization of the fluvial system by geomorphic province helps explain stream morphology at a broad-level classification only.

More recently, regional boundaries have been set by ecoregions (Omernik, 1987). Ecoregion boundaries were delineated by Omernik (1987) using geology, climate, land use, soils, and potential natural vegetation. Ecoregion boundaries are better than geomorphic boundaries for the hierarchical beginning of the fluvial system because of the increased amount of variables in the delineation and less influence placed on geologic structure. Geomorphic boundaries do not consider land use in variables for delineation. Chapter 2 of this dissertation shows that land use is an important variable in stream channel processes. One hundred and twenty Level III ecoregions exist in the United States, which is double the number of geomorphic provinces in Hunt (1974).

Ecoregions were originally designed as a spatial framework to evaluate surface water conditions (Loveland and Merchant, 2004). However, today ecoregions provide a framework for researchers to investigate and classify physical variables at multiple spatial scales. Ecoregions can be used to perform hierarchical investigations of stream surveys. This is because channel morphology is a function of the variables used in the construction of ecoregions. Comparing the morphology of stream channels between ecoregions helps explain the processes involved in developing channel characteristics in dissimilar biophysical environments. For this reason, ecoregions were used to portray differences in the characteristics of eastern Oklahoma stream channels surveyed at the reach scale. This was done by surveying eastern Oklahoma streams for particle-size, bankfull width, width-depth ratio, gradient, and sinuosity.

2. Background

Many of the characteristics that define stream channel morphology adjust channel form along the longitudinal profile of the stream. Adjustments in channel morphology occur for different reasons. These include, but are not limited to changes in discharge, sediment regime, local geology, and mass movements. Human modification of the landscape (i.e., logging, grazing, dam building, and stream channelization) impacts the spatial and temporal changes of river systems and morphology. For this reason, it is difficult to develop a model that accurately predicts upstream-to-downstream changes in channel morphology between different regions. Grant and Swanson (1995) point out that high gradient mountain streams greatly differ from lower gradient streams. High gradient mountain stream morphology is often influenced by external factors (i.e., landslides, alluvial fans, and bedrock outcrops), while lower gradient alluvial streams are seldom impacted by these external factors (Grant and Swanson, 1995). In lower gradient streams (i.e., eastern Oklahoma types) certain relationships in channel morphology often occur as stream size increases.

It is generally observed that particle-size decreases in the upstream-to-downstream direction (Knighton, 1998). Downstream fining of particle-sizes can occur by abrasion, hydraulic sorting, and weathering (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 down gradient direction (Sambrook Smith and Ferguson, 1995). This downstream fining of bed-material does not always occur in a systematic manner. Because of the influence of tributaries, large woody debris, and colluvial deposits particle-size in a gravel-bed stream is irregular (Dawson, 1988; Rice and Church, 1996; Powell, 1998).

As discharge increases in the downstream direction, channels adjust to the increase of water and sediment supply incorporated into 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, thus channels tend to be more confined. Knox (1987) proposed that channels narrow downstream in the Driftless Area of southwestern Wisconsin because a decrease in particle-size occurred in bank material, which increased bank stability and narrowed the channel.

Trimble (2004), also working in the Driftless Area, found that streams with riparian zones that had not been grazed had much smaller width-depth ratios than streams flowing through forests. This occurred because large woody debris incorporated to the stream increases velocity through constriction, which facilitates erosion and widening of the channel. Other studies report that channels lined with grass, however, are up to 30 percent wider than streams adjacent to forests (Charlton et al., 1978). The protective role of riparian vegetation is difficult to quantify, but important for understanding channel morphology longitudinally (Knighton, 1998).

Bankfull width is used in calculating width-depth ratios (Rosgen, 1996). 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 proves to be 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 numerous ways that have been implemented to help establish bankfull (Leopold et al., 1964; Carlston, 1965; Williams, 1978; Gordan et al., 1992; Nash, 1994). Defining bankfull width accurately is important when bankfull estimates serve to help planners and geomorphologists in restoration designs (Johnson and Heil, 1996).

Bankfull width of the channel is linked to the discharge stage at which channel maintenance is most effective (Dunne and Leopold, 1978). This maintenance includes the cross-section geometry of the channel, transportability of bed-load, forming and removal of channel bars, and altering meander bends in stream reaches. Events controlling channel maintenance have a recurrence interval of approximately 1.5 years (Dunne and Leopold, 1978). Other studies have argued for a much larger recurrence interval (1-25 years) for bankfull discharge (Williams, 1978; Nash, 1994). Regardless of viewpoint, consistency in field verification of bankfull indicators is important when establishing bankfull width.

The gradient of a stream decreases from upstream-to-downstream. Along the longitudinal profile, gradient generally portrays a concave upward profile. The controls on the degree of concavity are particle-size, influence of sediment via hillslopes, tectonic uplift, decrease in base-level, and log-steps (Knighton, 1998; Montgomery and Buffington, 1997). Dams can also impact the concavity of channel gradient, especially if water release is sediment free and downstream scour occurs at the outlet of the dam. Steep gradients in the upstream direction result from bedrock lithologies that are resistant to erosion. Large particles cannot be abraded or sorted because the capacity of the stream to move sediment is too weak (Knighton, 1998). For most alluvial streams, gradient is generally a function of rock lithology, particle-size, and discharge (Hack, 1957).

Sinuosity generally increases from upstream-to-downstream 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, sediment size and the bed load to total load ratio decreases, which allows streams to meander (Schumm, 1981, 1985). Changes in sinuosity throughout bedrock outcrops and riprap reaches, however, can alter the meanderability of the channel and may not accurately depict upstream-to-downstream changes along the channel. Marston et al. (2005) report that sinuosity downstream of

Jackson Lake Dam has fluctuated significantly in response to changes in maximum discharges and sediment delivery to tributaries.

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 were selected for study because stream morphology, stream habitat, and stream classification of these regions are of interest to the Department of Wildlife Conservation (ODWC). The ODWC recognizes that the management of these streams is influential to the overall wellbeing of the fisheries economy in this portion of the state (Fisher et al., 2002).

The Ozark Highlands exist in parts of Kansas, Missouri, Arkansas, and Oklahoma (Fig. 3.1). In Oklahoma the ecoregion encompasses 2,795 km^2. Woods et al. (2005) describes 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. Common soil series include Clarksville and Noark (Carter, 1997). Much of the native forest and prairie was removed during the logging boom at the turn of the century.

The Boston Mountains lie to the south of the Ozark Highlands in Oklahoma (Fig. 3.1). In Oklahoma, this ecoregion encompasses 1,891km^2. This region is not as dissected as the Ozark Highlands. 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 oak-hickory forest (Woods et al., 2005). Soils on uplands consist of Ultisols, Inceptisols, and Entisols. Common soil series include Hector and Linker (Carter 1997).

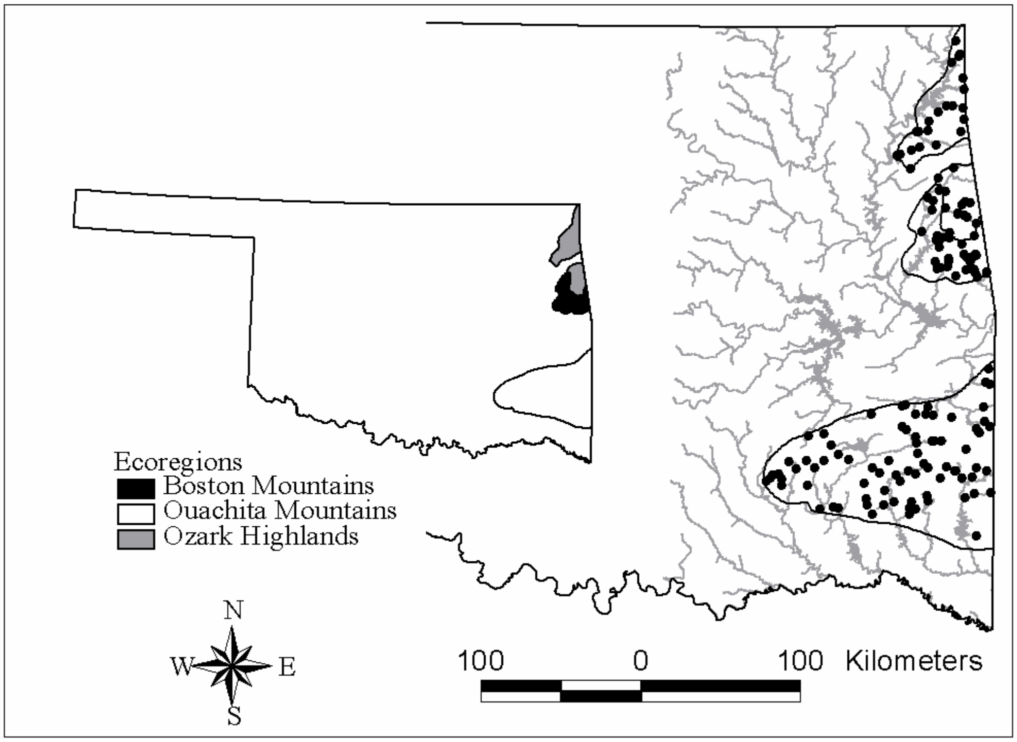

Fig. 3.1. Black dots represent first through fourth order stream reaches that were surveyed to determine channel morphology of eastern Oklahoma streams.

The Ouachita Mountains, south of the Boston Mountains, are separated by the Arkansas Valley ecoregion (Fig. 3.1). In Oklahoma, this ecoregion encompasses 10,100 km^2. The region tends to be 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 and decreases to the east. Land use consists of forestry, logging, ranching, woodland grazing, and recreation. The potential natural vegetation is oak-hickory-pine forest (Woods et al., 2005). Soils are Ultisols, Alfisols, and Inceptisols. Common soil series include Clebit, Pirum, Neff, Tuskahoma, Wetsaw, and Wister (Carter 1997).

4. Methodology

4.1. Site selection

A large-scale geomorphic study was conducted to determine how regional differences in climate, land use, geology, soils, and potential natural vegetation impact stream channel morphology from upstream-to-downstream in the Boston Mountains, Ozark Highlands, and Ouachita Mountains. A random point generator model in ArcView was applied to a stream network constructed using 30-meter DEMs (Fig. 3.1). The stream network was stratified into stream orders (1-4) for each ecoregion (Strahler, 1952). Points (i.e., reaches) were generated using a stratified random procedure based on ecoregion area, which suggested how many points per ecoregion were necessary for a stream sampling protocol that was equally weighted by region. 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 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) 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 (Rosgen, 1996). At each reach, three-to-four stream channel cross-sections were surveyed with a stadia rod and transit (Fig. 3.2). Two cross-sections were surveyed in pools and two in riffles. These 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 conducted accordingly. For example, if the reach was dry and 100 meters long, cross-sections would have been performed at 0, 25, 75, and 100 meters. Each cross-sectional transect was surveyed for particle-size, bankfull width, and width-depth ratio. In addition, the complete reach (i.e., upstream-to-downstream) was surveyed for gradient and sinuosity. Reach data were complied for particle-size, bankfull width, and width-depth ratio by averaging the data collected at each cross-section.

Fig. 3.2. Bryce Marston (tripod and level) and Dale Splinter (stadia rod) conducting a cross-sectional survey of a stream in the Ouachita Mountains ecoregion.

Particle-size analysis was conducted at each channel cross-section (Wolman, 1954). Particles were collected by walking along transects and picking-up the clast that lain under the toe of the measurer. The a, b, and c-axis of each particle were measured so that shape could be evaluated (Gordon et al., 1992). Particles were collected and measured from right-side bankfull (looking downstream) width to left-side bankfull width. Particles less than 2mm were classified as fines, while boulders were clasts bigger than 256 mm. Bedrock size was not measured, but counted as a percentage of the reach. In all, 100 particles (e.g., 53 clasts and 47 bedrock) were incorporated at each cross-section. The distribution of particles was entered in RIVERMorph 3.0©, which is used to create a particle-size frequency distribution. During data entry, fines were classified into the 2.0mm - 1.0mm fraction. Boulder size was not attained in the field. During data entry boulders were classified into the 256mm - 362mm fraction.

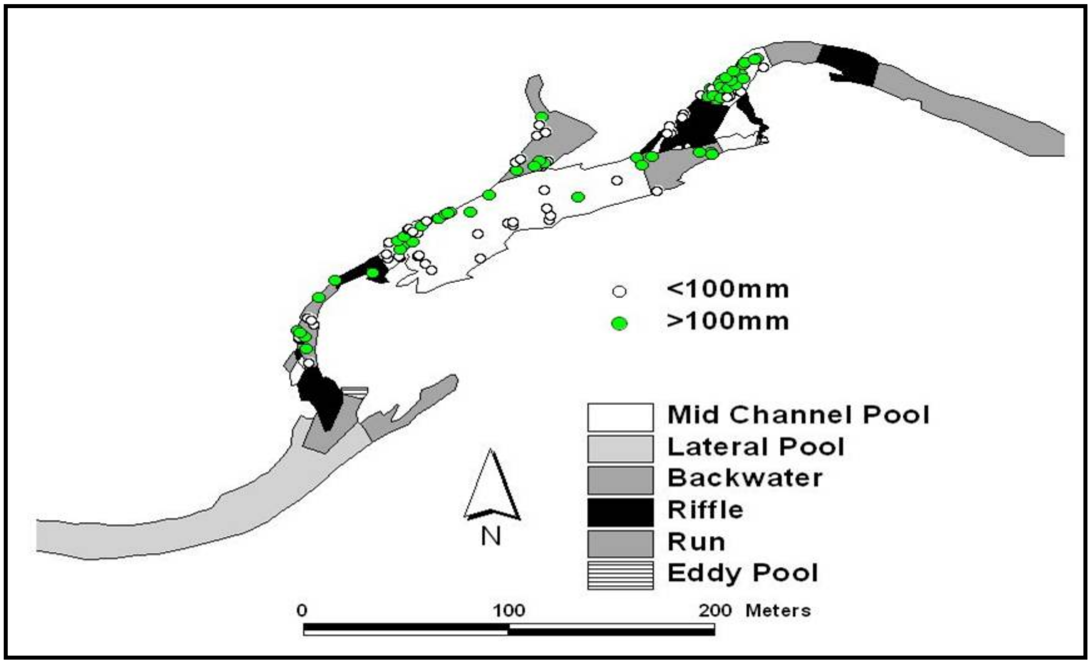

Fig. 3.3. Fourth-order Baron Fork stream depicting channel units of the reach. All reaches with channel units were mapped using a GPS and developed into maps using ArcView 3.3$^{\copyright}$. This map created by Dan Dauwalter.

Bankfull width was determined as the horizontal distance from right bank floodplain to left bank floodplain. Where no floodplain exists erodable boundaries, root zones, and soil development served as bankfull indicators. Width-depth ratio was calculated by dividing the bankfull width by the mean channel depth (Rosgen, 1996). Gradient was calculated by the elevation of water surface change divided by distance of change (Rosgen, 1996). All of the reaches were mapped with a Trimble GEOXT$^{\copyright}$ GPS receiver (Fig. 3.3) (Dauwalter et al., 2006). Sinuosity was calculated by dividing stream length by valley length, which allowed for calculating sinuosity in ArcView 3.3$^{\copyright}$.

4.*3 Statistical analysis*

Regression analysis with dummy variables was performed to evaluate whether the downstream trends in geomorphic variables were significantly different ($\alpha \leq 0.05$)

between ecoregions. Dummy variables are categorical variables (i.e., ecoregions) that take the value of value of zero or one in the regression. The Ouachita Mountains was used as the baseline region (i.e., omitted category) because this region consisted of the most sites and was deemed the most different from the other two regions. The independent variable in this study was drainage area above reach in kilometers (dakm^2). The dependent variables compared in separate regression equations were particle-size, bankfull width, width-depth ratio, gradient, and sinuosity. Both the independent variable and dependent variable were transformed using natural logs. Equation 1 was used to predict the dependent value for each of the 149 reaches:

$$\log(\hat{y}) = \beta_0 + \beta_1 BM + \beta_2 OH + \beta_3 \log(\mathrm{dakm}^2) + \beta_4 BM\log(\mathrm{dakm}^2) + \beta_5 OH\log(\mathrm{dakm}^2) \qquad (1)$$

Where:

$\log(\hat{y})$ = predicted value for dependent variable using regression equation
β_0 = Log of the baseline intercept
$\beta_1 BM$ = Log of the intercept * categorical variable (0, 1) of the BM
$\beta_2 OH$ = Log of the intercept * categorical variable (0, 1) of the OH
$\beta_3 \log(\mathrm{dakm}^2)$ = Log of the baseline slope * log of dakm^2
$\beta_4 BM\log(\mathrm{dakm}^2)$ = Slope * categorical variable (0, 1) of the BM * log of dakm^2
$\beta_5 OH\log(\mathrm{dakm}^2)$ = Slope * categorical variable (0, 1) of the OH * log of dakm^2

The predicted regression value for the Ouachita Mountains (i.e., baseline region) was attained when the Boston Mountains and Ozark Highlands were given 0 values in the regression equation, while the Ouachita Mountains received a value of 1 (Table 3.1). Predicted regression values for the reaches in the Boston Mountains were derived when the Ouachita Mountains and Ozark Highlands received a value of 0, while the Boston Mountains received a value of 1 (Table 3.1). The predicted regression equation for the Ozark Highlands was derived when the Boston Mountains and Ouachita Mountains received a value of 0, while the Ozark Highlands received a value of 1 (Table 3.1). For example, the predicted regression value for D16 particle-size (see page 16) for site 1 (0.93 $dakm^2$) in the Boston Mountains is calculated in equation 2 below:

$$\log(\hat{y}) = 2.316 + -1(1) + -0.62(0) + 0.079(0.18) + 0.173(0.18) + 0.048(0)(0.18) \qquad (2)$$

Predicted values were used to establish regression equations for each dependent variable of the regions. Once regression equations were attained, intercept and slope coefficients were compared to test for statistical differences between the dependent variables and ecoregions. The analytical software program STATA 8.0© was used to perform statistical analysis.

Table 3.1
Dummy variables assigned to each of the reaches within the three regions.

Region	Reaches[1]	BM	OH	OM
BM	0-38	1	0	0
OH	40-79	0	1	0
OM	80-940	0	0	1

[1] Numbering of OM reaches is not continuous from 80 through 940. A total of 80 reaches were surveyed in the region. The gap in numbering is attributed to the reselection of reaches that were impacted by human modification. See appendix for the complete numbering of reaches. Continuous numbering did occur in the BM and OH regions, however not all of the sites were surveyed.

5. Results and discussion

5.1 Particle-size

Upstream-to-downstream statistical trends in particle-size were evaluated for D16, D50, and D84. The D16, D50, and D84 were selected because these particle-sizes span the lower, middle, and upper frequency distribution of particles collected at each reach. All three size classes show particle-size increasing in the downstream direction (Figs. 3.4-3.6). Typically the largest particles occur in the Ouachita Mountains and the smallest particles occur in the Ozark Highlands. Statistically significant differences exist for y-intercept coefficients between the Boston Mountains and the Ouachita Mountains for D16 at $\alpha \leq 0.05$ (Table 3.2). The Boston Mountains (0.072) and Ozark Highlands (0.062) are not statistically significant (y-intercept coefficients) from the Ouachita Mountains when D50 comparisons were conducted (Table 3.3). The D84 comparison confirms statistically significant differences (y-intercept coefficients) between the Ozark Highlands and the Ouachita Mountains at $\alpha \leq 0.05$ (Table 3.4). Slopes of the regression show no significant differences in particle-size between ecoregions.

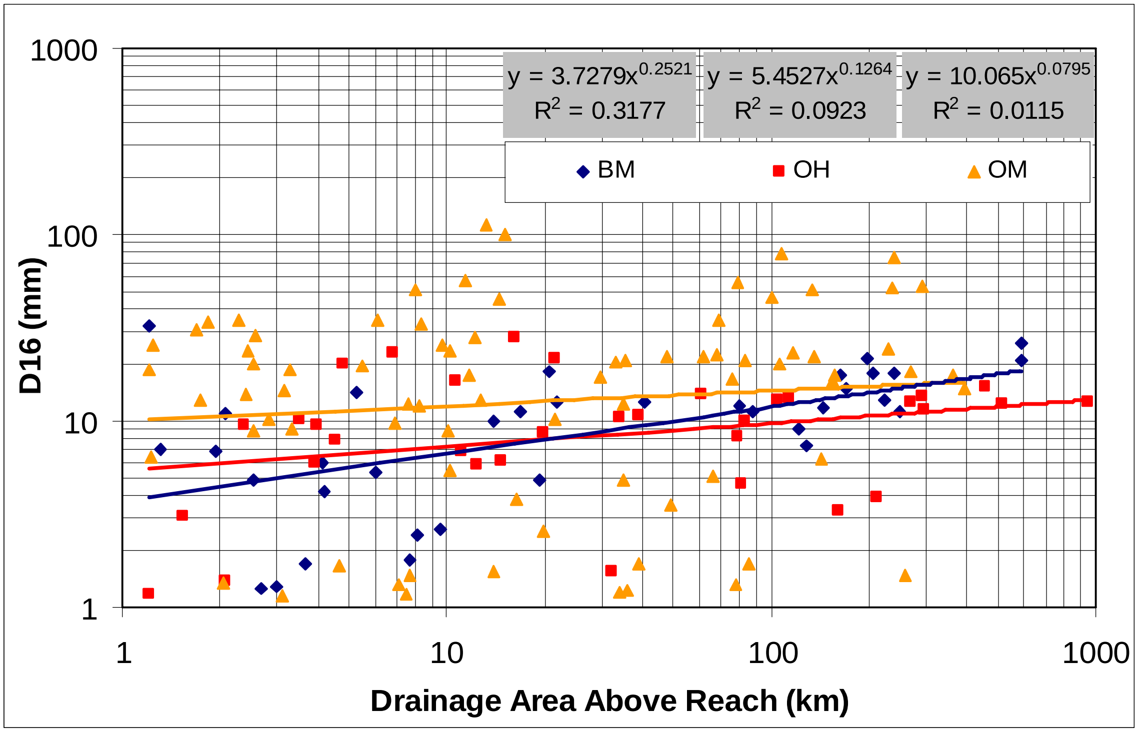

Fig. 3.4. Upstream-to-downstream trends in D16 particle-size for three eastern Oklahoma ecoregions.

Table 3.2
Particle-size frequency of D16 shows statistically significant differences ($\alpha = 0.05$) between the Boston Mountains ecoregion and Ouachita Mountains ecoregion using y-intercept coefficients.

Comparison[1]	Coefficients	Std Err	t	P>│t│[2]	Prob > F[3]
Intercept					
OM	2.316	0.229	10.13	0.000[a]	………..
BM	-1.000	0.407	-2.46	0.015[b]	………..
OH	-0.620	0.432	-1.43	0.154	………..
BM-OH	………….	………….	……..	………….	0.446
Slope					
OM	0.079	0.068	1.16	0.248	………..
BM	0.173	0.114	1.52	0.130	
OH	0.048	0.118	0.41	0.686	………..
BM-OH	………….	………….	……..	………….	0.344

[1] OM= Ouachita Mountains; BM = Boston Mountains; OH = Ozark Highlands;
BM-OH is the comparison between these two regions. OM is the constant variable.

[2] Significance levels, [a] = 0.01; [b] = 0.05;

[3] F test gives significance between BM-OH; same significance levels as row above.

Particle-size increases as drainage area above the reach increases in all three ecoregions. This pattern is not typical of particle-size distributions in the upstream-to-downstream direction (Knighton, 1998). It is generally observed that particle-size decreases from upstream-to-downstream due to abrasion and hydraulic sorting of particles. This suggests that other factors are responsible for the increase in particle-size in the downstream direction.

Streams in the Ozark Highlands have the smallest particle-sizes of the three ecoregions. The Ozark Highlands lithology 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 relatively constant, although slightly increasing particle-size in the upstream-to-downstream direction, suggests that the limestone is dissolved quickly upon entering the stream. The resultant chert is weathered and eroded through physical and chemical processes as it moves from upstream-to-downstream. The chert exposed through the dissolving of limestone retains a consistent particle-size from upstream-to-downstream because of its resistant nature to weathering. This does not explain, however, why particle-sizes tend to increase from upstream-to-downstream in this region.

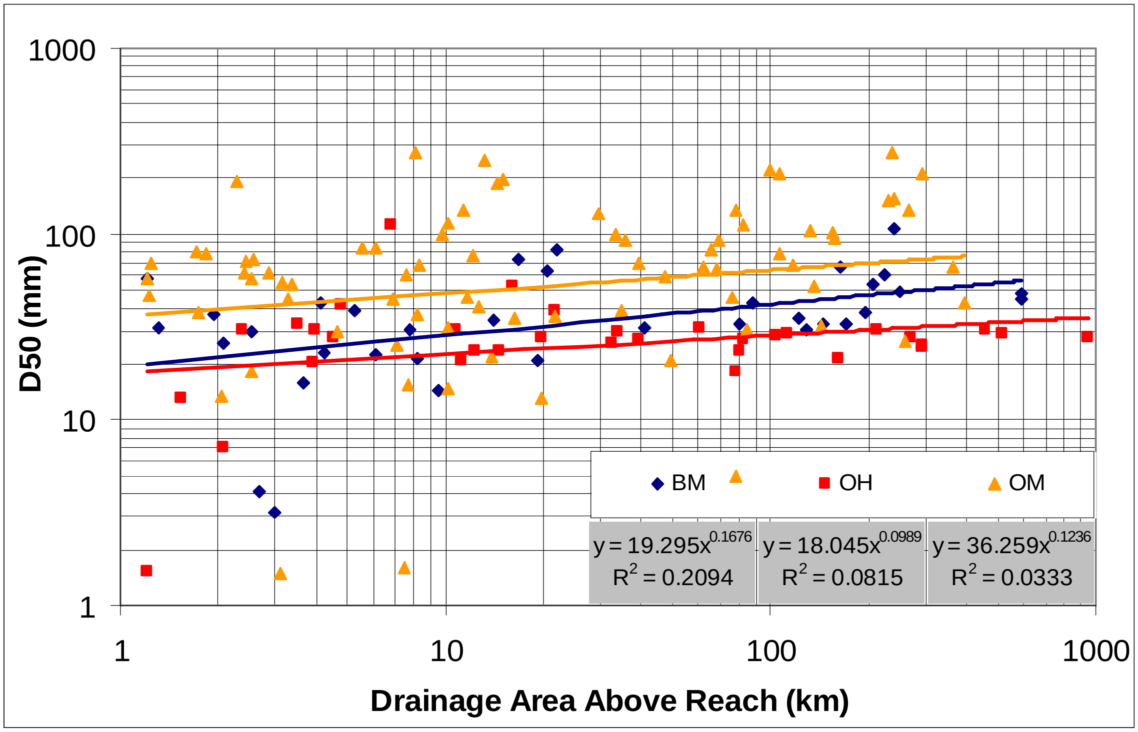

Fig. 3.5. Upstream-to-down trends in D50 particle-size for three eastern Oklahoma ecoregions.

Landowners in the Ozark Highlands report that streams are undergoing aggradation. Within the Baron Fork Creek watershed, accounts of pool depths decreasing have been reported (personal communication, local landowners). In addition, increases in large woody debris have also been reported (personal communication, local landowners). Reports of similar stream changes have been documented in the Missouri Ozark

Highlands (Jacobson, 1995). Increased amounts of sediment from land use change in the Missouri Ozark Highlands have caused streams to aggrade (Jacobson, 1995). It appears that streams in the Ozark Highlands are also undergoing this transformation. An untested hypothesis is proposed that may help explain why particle-sizes are increasing in the downstream direction in the Ozark Highlands.

Table 3.3
Particle-size frequency of D50 shows no statistically significant differences (α = 0.05) between the ecoregions.

Comparison[1]	Coefficients	Std Err	t	P>│t│[2]	Prob > F[3]
Intercept					
OM	3.619	0.204	17.74	0.000[a]	………..
BM	-0.659	0.363	-1.81	0.072	………..
OH	-0.726	0.385	-1.88	0.062	………..
BM-OH	………….	………….	……..	………….	0.881
Slope					
OM	0.116	0.061	1.92	0.057	………..
OH	0.051	0.102	0.50	0.615	………..
BM	-0.018	0.105	-0.17	0.867	………..
BM-OH	………….	………….	……..	………….	0.562

[1, 2, 3] See Table 3.2

The hypothesis is that stream aggradation is facilitating an increase in stream power on channel banks, which promotes erosion of coarse grain sediment in the banks. This sediment is incorporated into the channel and is only transported under high magnitude events. The relatively high drainage density of the Ozark Highlands to the low relief ratio promotes aggradation in lower watershed streams (Chapter 2). Combining aggradation and bank erosion along the downstream profile may be leading to an increase in particle-size from upstream-to-downstream.

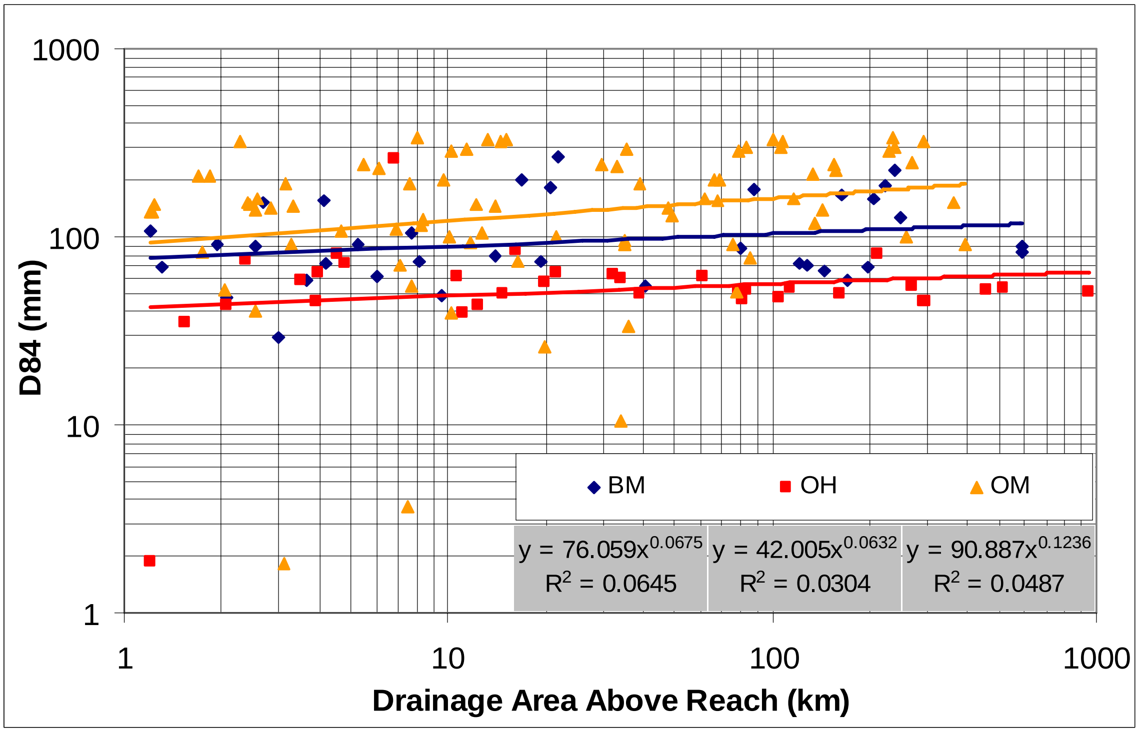

Fig. 3.6. Upstream-to-down trends in D84 particle-size for three eastern Oklahoma ecoregions.

Table 3.4
Particle-size frequency of D84 shows statistically significant differences ($\alpha = 0.05$) between the Ozark Highlands ecoregions and Ouachita Mountains ecoregion using y-intercept coefficients.

Comparison[1]	Coefficients	Std Err	t	P>|t|[2]	Prob > F[3]
Intercept					
OM	4.535	0.173	26.23	0.000[a]	……….
BM	-0.204	0.308	-0.66	0.509	……….
OH	-0.797	0.327	-2.44	0.016[b]	……….
BM-OH	………….	………….	…….	………….	0.117
Slope					
OM	0.117	0.051	2.28	0.024[b]	……….
BM	-0.050	0.086	-0.58	0.564	……….
OH	-0.054	0.089	-0.61	0.544	……….
BM-OH	………….	………….	…….	………….	0.966

[1, 2, 3] See Table 3.2

The second largest particle-sizes occur in the Boston Mountains. Particle-sizes in Boston Mountain streams are larger than those in the Ozark Highlands streams because the higher watershed relief supplies larger particles to the fluvial system. In addition, the lithology of the Boston Mountains is primarily sandstone, which weathers and abrades at a slower rate than the cherty limestone of the Ozark Highlands. The increase in particle-size in the downstream direction is attributed to: (1) the influence of tributaries; (2) streambank erosion in the downstream direction; and (3) the steep side-slopes adjacent to the channel contribute coarse-grained material (Figs. 3.7 and 3.8).

Fig. 3.7. A source for particle-size increase in the downstream direction is bank erosion. This third-order Little Lee Creek reach (Site 27) drains an 88 km^2 watershed.

The largest particles occur in the Ouachita Mountains. This region has the highest watershed relief of all the ecoregions in this study. Steep side-slopes and bedrock outcrops are common, which produce large particles in the streams of this region (Fig. 3.9). Particle-size increases in the downstream direction because of these local sources of large sediment delivered to these streams. Resistant lithologies prohibit the weathering and abrasion of sediment. Large sediment is seldom moved in these locations because of a lack of stream power and thus streams remain relatively stable. Streams of high gradient (i.e., first-order) tend to be less stable and show characteristics of channels with split, multiple, or undefinable banks (Fig. 3.10). The erosive capability on high energy streams often make them difficult to study in the field because they lack definable banks and often have vegetation growing in the channel.

Fig. 3.8. Steep sided-slopes influence particle-size in the downstream direction. A fourth-order reach of Little Lee Creek (Site 32) draining a 237 km^2 watershed.

Fig. 3.9. Fourth-order reach (Glover River-Site 169) representing side-slope and bedrock as sources for large particle-size values.

Fig. 3.10. A first-order reach (Unnamed-Site 82) that is unstable. Stream flow is not confined by streambanks. This type of wide and expansive channel is not uncommon in first-order channels of the Ouachita Mountains that comprise high gradients.

5.2. Bankfull channel width

Bankfull channel width increases in the upstream-to-downstream direction in all ecoregions (Fig. 3.11). Bankfull channel width normally increases downstream due to the influence of tributaries supplying water and sediment that scours the banks and makes them wider from upstream-to-downstream. Upstream-to-downstream trends show that the bankfull width of streams in the Ozark Highlands increases more than streams in the Boston Mountains or the Ouachita Mountains. The statistically significant differences in the y-intercept and slope coefficients ($\alpha \leq 0.01$) between the Ozark Highlands and the Ouachita Mountains support evidence for contrasting stream sizes between the regions (Table 3.5). In addition, statistically significant differences exist between the Boston Mountains and the Ozark Highlands y-intercept coefficients ($\alpha \leq 0.01$) and nearly statistically significant slope coefficients (0.075) of the regressions (Table 3.5).

Bankfull channel width is greatest in the Boston Mountains from upstream-to-downstream (Fig. 3.11). In upper watersheds, bankfull channel width is the smallest in the Ozark Highlands. As drainage area increases, bankfull width of streams in the Ozark Highlands increases in size similar to the bankfull width of streams in the Ouachita Mountains (Fig. 3.11).

A contradiction exists in the role of regional drainage density on bankfull channel width in this study. Bankfull channel width has been reported as a function of drainage density, which suggests that the widest bankfull channel widths should be in watersheds with the highest drainage densities. However, in this study the highest drainage densities are in the Ozark Highlands and the Ouachita Mountains and the lowest drainage densities are in the Boston Mountains (Chapter 2). An inverse relationship between bankfull channel width and drainage density occurs in all three ecoregions. This suggests that other variables besides drainage density are responsible for the observed bankfull channel widths between the ecoregions.

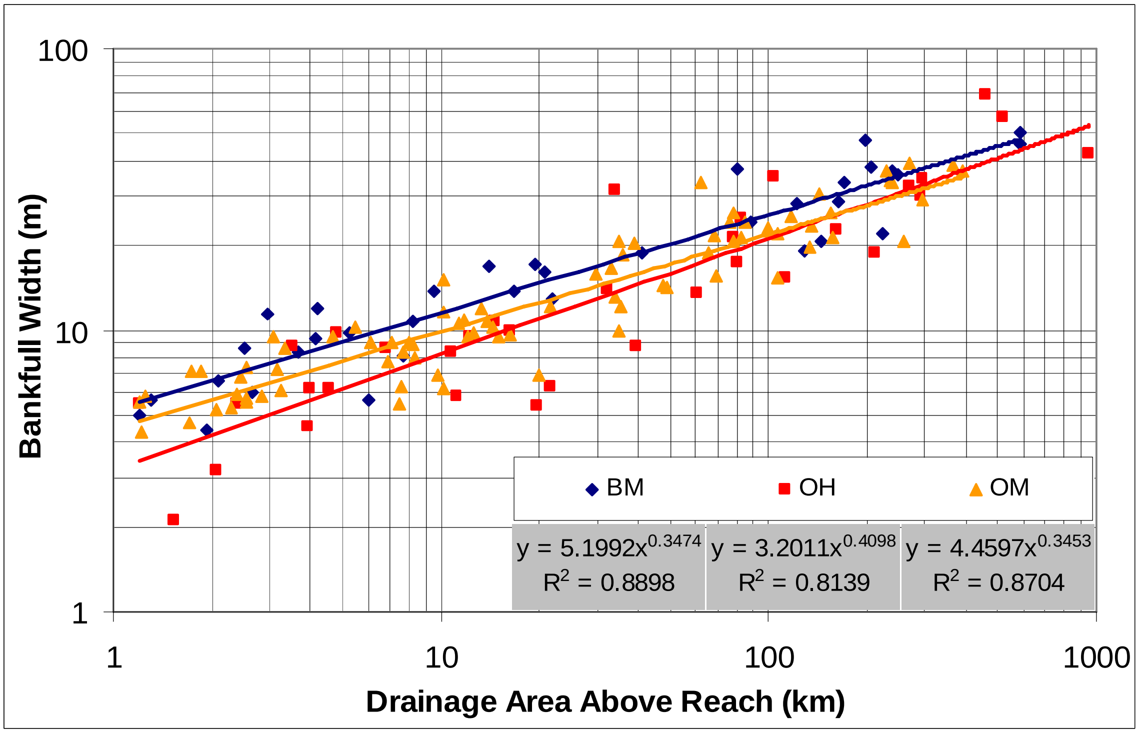

Fig. 3.11. Streams in the Boston Mountains generally have the greatest bankfull width, while streams in the Ozark Highlands have the smallest bankfull width in upper watersheds and transition to fairly wide channels downstream.

Table 3.5
Bankfull channel width shows statistically significant differences ($\alpha \leq 0.01$) between the Ozark Highlands ecoregions and Ouachita Mountains ecoregion using y-intercept and slope coefficients. An F-test reports statistically significant differences between the Boston Mountains and Ozark Highlands using y-intercept ($\alpha \leq 0.01$) coefficients.

Comparison[1]	Coefficients	Std Err	t	$P>\|t\|$[2]	Prob > F[3]
Intercept					
OM	1.561	0.060	25.95	0.000[a]	………..
BM	0.880	0.107	0.82	0.413	………..
OH	-0.397	0.114	-3.49	0.001[a]	………..
BM-OH	………….	………….	……..	………….	0.000[a]
Slope					
OM	0.330	0.018	18.46	0.000[a]	………..
BM	0.018	0.030	0.59	0.555	………..
OH	0.080	0.031	2.59	0.010	………..
BM-OH	………….	………….	……..	………….	0.075[c]

[1, 2, 3] See Table 3.2

Bankfull channel widths in the upper watersheds of the Ozark Highlands are smaller than either the Boston Mountains or the Ouachita Mountains (Fig. 3.11). This is probably a function of the lower watershed relief of the region and the jointed and fractured limestone bedrock that allows rainfall runoff to be reduced because of infiltration under non-disturbance (i.e., logging) events (Chapter 2). This decreases overland flow off the hillslopes and reduces water in the stream channels. Many of the streams surveyed in the upper watersheds of the Ozark Highlands were dry and were flowing only after rainfall events. For example, 10 of 15 first and second-order streams were completely dry and two more were intermittent. This leads to smaller bankfull channel widths in these upper watersheds. The relatively high drainage density and tributary stream input in the middle to lower watersheds in the Ozark Highlands function to increase bankfull channel width downstream. This is represented by the regression line of the slope in Fig. 3.11, which depicts how bankfull channel width increases with respect to stream size in the Ozark Highlands.

In upper watersheds, the bankfull channel width of streams in the Boston Mountains and the 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 in these regions. In addition, the highest circularity ratio (i.e., most circular basins) of upper watersheds occurred in the Boston Mountains, which increases the rate at which peak discharge enters those stream channels (Chapter 2).

5.3. Width-depth ratio

The width-depth ratio of streams increases in the downstream direction in all three ecoregions. This is an expected result considering that channels must get wider and deeper downstream to carry increased amounts of water and sediment supplied by tributaries (Leopold and Maddock, 1953, Rosgen, 1996). Streams in the Ouachita Mountains show the least amount of increase as drainage area above of the reach increases (Fig. 3.12). The Boston Mountains and Ozark Highlands have slope coefficients that are statistically different ($\alpha \leq 0.01$) from the Ouachita Mountains (Table 3.6). The lowest width-depth ratios exist in upper watershed streams of the Ozark Highlands. These low width-depth ratios are replaced by much higher width-depth ratios in lower watersheds (Fig. 3.12).

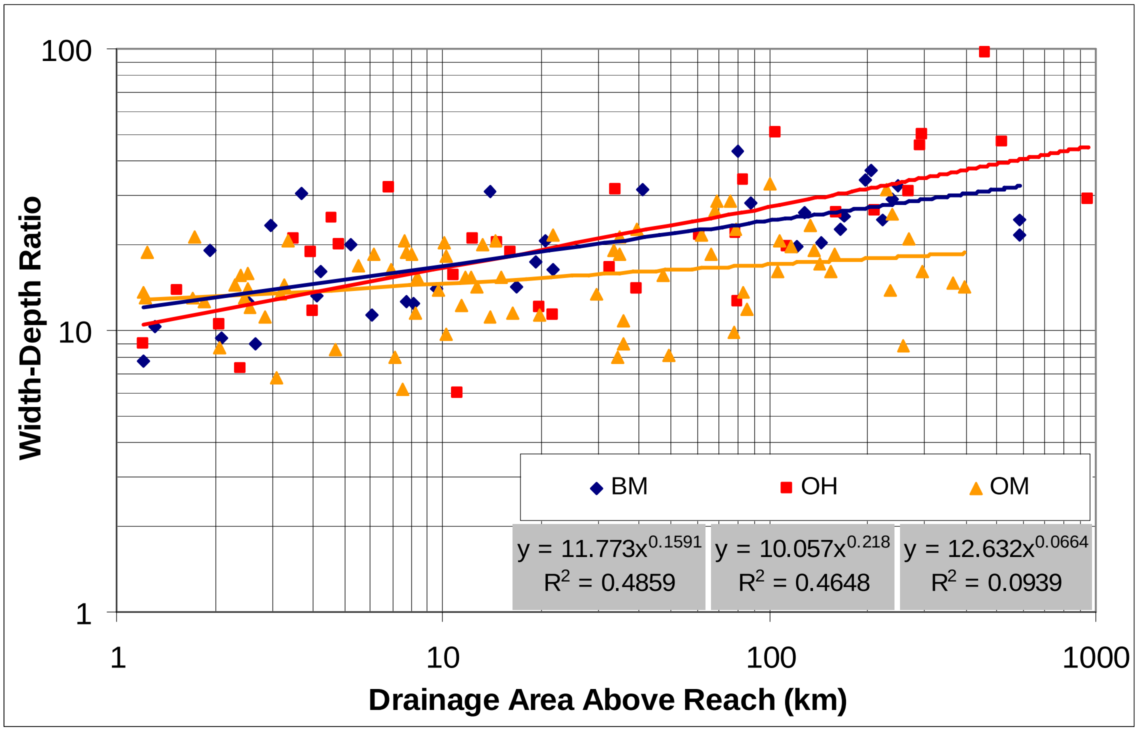

Fig. 3.12. Width-depth ratio increases with watershed size in all ecoregions. Streams in the Ozark Highlands have the lowest width-depth ratios in upper watersheds, but rapidly progress to the highest width-depth ratios. Streams in the Ouachita Mountains show little change in width-depth ratio from upstream-to-downstream.

The low width-depth ratios of streams in Ozark Highlands upper watersheds are a function of little streamflow except under rainfall events. This lack of streamflow produces channels that are narrow and shallow. Upper watershed bankfull channel widths in the Boston Mountains and Ouachita Mountains tend to be wider and deeper than those in the Ozark Highlands. As the drainage area increases in the Ozark Highlands, a considerable increase occurs in width-depth ratio. The relatively high drainage density and transport capacity of gravel helps establish high width-depth ratios in the Ozark Highlands. During high flow events, gravel is transported from streams in the upper watersheds and deposited downstream. The 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. 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 occur in the Ozark Highlands.

Table 3.6
Slope coefficients of the Boston Mountains and Ozark Highlands are statistically different from the Ouachita Mountains at $\alpha \leq 0.01$.

Comparison[1]	Coefficients	Std Err	t	$P>\|t\|$[2]	Prob > F[3]
Intercept					
OM	2.561	0.807	31.72	0.000[a]	………..
BM	-0.095	0.144	-0.66	0.508	………..
OH	-0.253	0.153	-1.66	0.100	………..
BM-OH	………….	………….	……..	………….	0.372
Slope					
OM	0.059	0.024	2.47	0.015[b]	………..
BM	0.100	0.040	2.48	0.014[a]	………..
OH	0.159	0.041	3.82	0.000[a]	………..
BM-OH	………….	………….	……..	………….	0.210

[1, 2, 3] See Table 3.2

Streams in the Ouachita Mountains have the most consistent width-depth ratios in the upstream-to-downstream (Fig. 3.12). 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. The increase in particle-size and bedrock outcrops in the downstream direction 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 Ouachita Mountains than those in the Ozark Highlands. Streams in the Boston Mountains have substrate 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 as what occurs in the streams in the Ouachita Mountains.

5.4. Gradient

Stream gradient in all ecoregions decreases in the downstream direction. No statistically significant differences exist in gradient between ecoregions (Table 3.7). Regressions and scatter plots illustrate that gradient variability is greatest in the Ouachita Mountains and least in the Boston Mountains (Fig. 3.13). The high amount of gradient variability in the Ouachita Mountains results from an ecoregion that tends to have more regional variability than the other two ecoregions. The Ouachita Mountains encompasses a landscape that is defined by hills and mountains with high relief in its interior and low gradient flats at the base of hills and lowlands in its western edge. In addition, some higher-order stream reaches in the Ouachita Mountains were dominated by a single large pool and a few additional channel units. Other higher-order streams in the Ouachita Mountains had a series of riffle-run-pool sequences, which increased reach slope. This contrast in channel unit type led to a large range in gradient of high-order streams. No correlation exists between watershed relief and stream gradient between ecoregions.

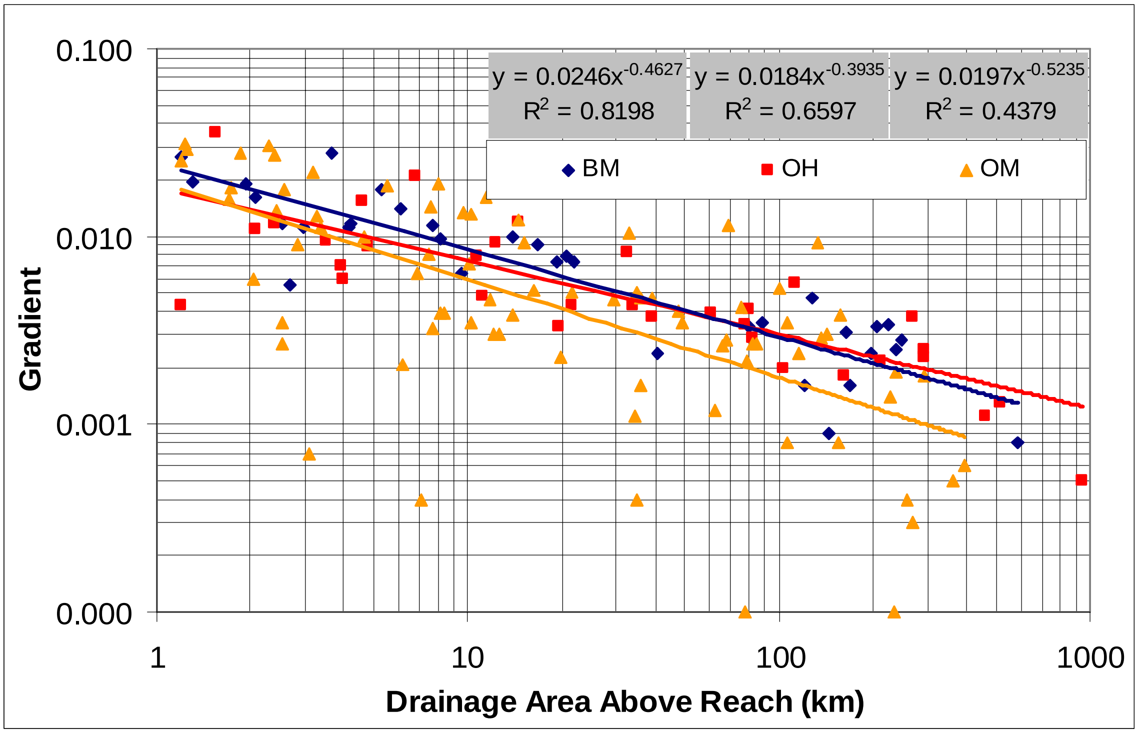

Fig. 3.13. Stream gradient decreases with increasing watershed size in all ecoregions. The greatest amount of change exists in the Ouachita Mountains, while the least amount exists in the Boston Mountains.

Table 3.7.
Comparisons between ecoregions with y-intercept and slope coefficients from regression analysis report no statistically significant differences in gradient.

Comparison[1]	Coefficients	Std Err	t	P>|t|[2]	Prob > F[3]
Intercept					
OM	-4.131	0.053	-8.57	0.000[a]	………..
BM	0.427	0.312	1.37	0.174	………..
OH	0.138	0.332	0.42	0.678	………..
BM-OH	………….	………….	……..	………….	0.450
Slope					
OM	-0.453	0.176	-23.47	0.000[a]	………..
BM	-0.010	0.088	-0.11	0.910	………..
OH	0.059	0.091	0.65	0.514	………..
BM-OH	………….	………….	……..	………….	0.497

[1, 2, 3] See Table 3.2

5.5. Sinuosity

No definite pattern or statistical differences exists in sinuosity between the ecoregions (Fig. 3.14; Table 3.8). The classification of channel patterns classification (Schumm, 1981) shows that meandering streams generally have small sediment size. Typically, the particle-size of stream channels decreases from upstream-to-downstream, which would suggest that sinuosity increases downstream. Particle-size in the Ozark Highlands, Boston Mountains, and Ouachita Mountains increases or remains the same, however, from upstream-to-downstream. Thus, sinuosity remains relatively constant from upstream-to-downstream in all ecoregions. The majority of stream reaches surveyed have sinuosities less than 1.5, which implies that these reaches are generally straight.

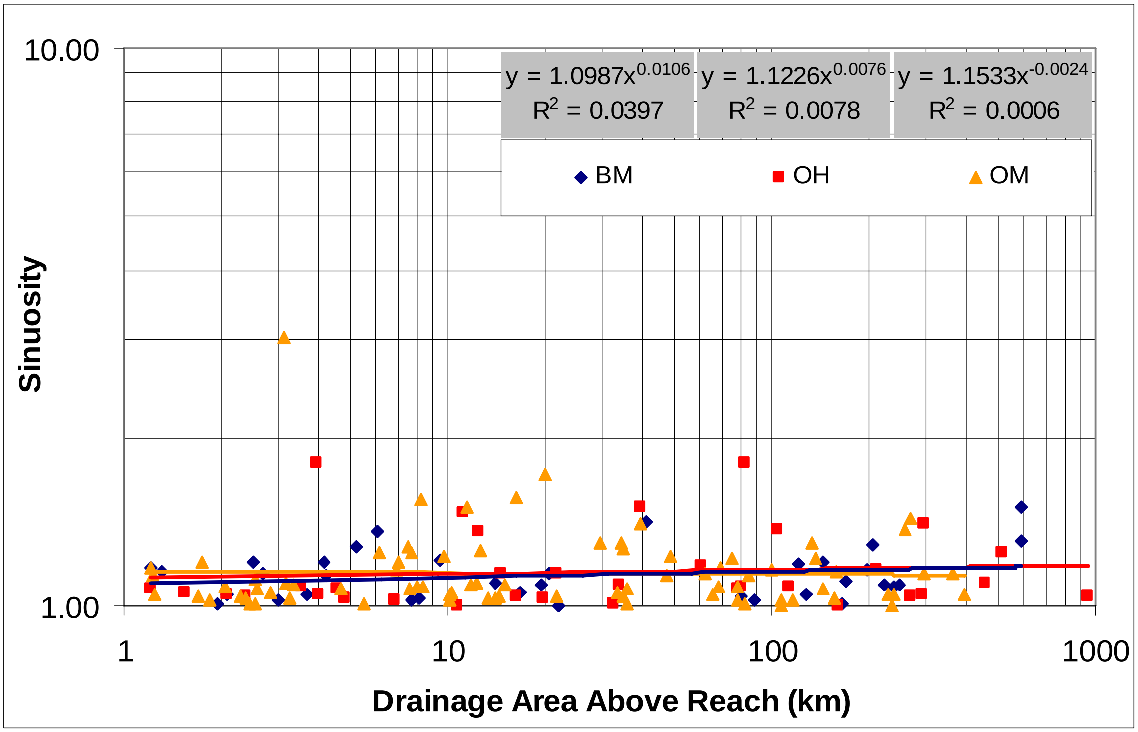

Fig. 3.14. Stream sinuosity changes very little in the upstream-to-downstream direction regardless of ecoregion.

The distributions of streams with sinuosity greater than 1.5 include one in the Boston Mountains, three in Ozark Highlands, and two in the Ouachita Mountains. The Ozark Highlands have the greatest proportion of meandering stream reaches, which is in part dictated by the relatively small particles in the region. The Boston Mountains and Ouachita Mountains have the largest particles and lowest proportion of meandering stream channels. Sinuosity values greater than 1.5 occur most often in first and second-order streams. The greatest sinuosity (3.04) occurred in a first-order sand-bed stream in the Ouachita Mountains.

Table 3.8
Comparisons between ecoregions with y-intercept and slope coefficients from regression analysis report no statistically significant differences in sinuosity.

Comparison[1]	Coefficients	Std Err	t	P>|t|[2]	Prob > F[3]
Intercept					
OM	0.141	0.033	4.24	0.000[a]	………..
BM	-0.047	0.060	-0.80	0.427	………..
OH	-0.026	0.063	-0.41	0.684	………..
BM-OH	………….	………….	……..	………….	0.767
Slope					
OM	-0.002	0.010	-0.20	0.843	………..
BM	0.013	0.017	0.76	0.451	………..
OH	0.010	0.017	0.56	0.578	………..
BM-OH	………….	………….	……..	………….	0.877

[1, 2, 3] See Table 3.2

6. Conclusion

This study is the first to investigate how upstream-to-downstream patterns differ between ecoregions. The results show that upstream-to-downstream patterns differ for three of the five variables used to test for statistical differences between regions. Variables that were not found to be statistically significant (i.e., gradient and sinuosity) between ecoregions still provide insight to understand upstream-to-downstream changes, or lack thereof, of channel patterns. These finding support the notion that ecoregions provide a useful spatial organization by which stream channel patterns can be classified and studied. This approach to studying the upstream-to-downstream patterns in stream morphology can be utilized to help understand variables at the reach scale in a regional setting. Ecoregions provide an adequate spatial framework for understanding upstream-to-downstream patterns in stream morphology.

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Appendix

[a] ID = points (i.e., reaches) that were randomly selected for surveying. Sites 0-38 are in the Boston Mountains, 40-79 are in the Ozark Highlands, and 80-940 are in the Ouachita Mountains. See page 100 for site locations

[b] Order = Strahler stream order

[c] DA = drainage area above reach

[d] LAT = latitude; LONG = longitude. Both are portrayed in decimal degrees

[e] D16, D50, and D84 are particle-size frequency distributions

[f] BFW = bankfull channel width

[g] WDR = width-depth ratio

ID[a]	Order[b]	DA[c]	LAT[d]	LONG[d]	D16[e]	D50[e]	D84[e]	BFW[f]	WDR[g]	Gradient	Sinuosity
0	1	2.53	-94.64354	35.71506	4.80	30.08	88.11	8.61	12.72	0.0118	1.20
1	1	1.20	-94.85530	36.02027	32.36	58.11	107.79	5.00	7.84	0.0267	1.17
2	1	1.31	-94.81802	35.75762	7.06	30.95	68.89	5.69	10.34	0.0194	1.15
3	1	2.09	-94.74459	35.83849	10.92	25.74	47.57	6.62	9.45	0.0162	1.05
4	1	2.67	-94.94045	35.84572	1.27	4.12	150.30	6.05	8.95	0.0055	1.14
6	1	2.98	-94.80967	35.64384	1.31	3.21	28.97	11.38	23.61	0.0112	1.02
9	1	1.94	-94.55515	35.89084	6.95	36.81	92.06	4.42	19.13	0.0192	1.01
10	2	6.06	-94.81345	36.07630	5.36	22.72	61.95	5.63	11.38	0.0140	1.36
11	2	9.50	-94.74744	35.80812	2.60	14.47	48.12	13.87	14.16	0.0063	1.21
12	2	19.32	-94.57024	35.71684	4.78	20.79	73.56	17.19	17.58	0.0073	1.09
13	2	4.21	-94.83536	35.63805	4.20	23.09	72.89	11.90	16.09	0.0116	1.13
14	2	7.73	-94.66156	35.77397	1.79	30.74	104.08	8.07	12.59	0.0115	1.02
15	2	8.16	-94.79221	35.80762	2.45	21.35	74.33	10.72	12.45	0.0097	1.03
16	2	4.12	-94.70297	35.59857	5.93	42.91	154.18	9.36	13.33	0.0111	1.20
17	2	14.00	-94.81778	35.79874	9.96	34.54	79.57	17.00	31.20	0.0099	1.10
18	2	5.25	-94.89644	36.03782	14.28	38.61	91.21	9.72	20.06	0.0178	1.28
19	2	3.67	-94.85094	35.67705	1.70	15.92	58.93	8.39	30.89	0.0274	1.05
20	3	20.61	-94.62303	35.69727	18.49	63.98	184.53	16.01	20.69	0.0079	1.14

ID[a]	Order[b]	DA[c]	LAT[d]	LONG[d]	D16[e]	D50[e]	D84[e]	BFW[f]	WDR[g]	Gradient	Sinuosity
21	3	21.85	-94.63589	35.63297	12.65	81.48	267.21	12.86	16.39	0.0073	1.00
22	3	121.06	-94.57034	35.81904	9.19	35.42	71.75	28.10	19.82	0.0016	1.19
23	3	144.95	-94.75490	35.67674	11.83	32.93	65.39	20.57	20.44	0.0009	1.20
24	3	16.76	-94.56256	35.71146	11.29	72.85	200.39	13.82	14.21	0.0090	1.06
25	3	40.83	-94.86758	35.96605	12.59	31.31	54.19	18.70	31.51	0.0024	1.41
26	3	80.30	-94.59154	35.69705	12.17	32.50	86.24	37.16	42.92	0.0033	1.04
27	3	88.24	-94.60218	35.67725	11.25	42.34	179.74	24.31	28.15	0.0035	1.02
28	3	128.32	-94.75724	35.69692	7.44	30.40	70.25	19.26	26.29	0.0047	1.05
29	4	170.15	-94.83056	35.81959	14.98	32.89	58.74	33.64	25.34	0.0016	1.11
30	4	205.74	-94.57278	35.63194	17.88	53.89	157.97	38.07	37.06	0.0033	1.29
31	4	164.23	-94.58648	35.63346	17.65	66.32	167.82	28.51	22.81	0.0031	1.01
32	4	237.92	-94.56733	35.61029	17.86	105.45	226.65	36.57	29.48	0.0025	1.08
33	4	248.81	-94.5590	35.59066	11.27	48.67	126.81	35.73	32.71	0.0028	1.09
35	4	587.46	-94.48830	35.61308	25.95	48.06	89.76	50.42	24.73	0.0008	1.51
36	4	587.31	-94.48750	35.61415	21.36	44.20	82.92	46.07	21.73	0.0008	1.31
37	4	223.29	-94.75965	35.64778	12.84	60.66	188.88	22.14	24.63	0.0034	1.09
38	4	196.58	-94.84116	35.80009	21.47	37.92	68.95	47.40	34.04	0.0024	1.16
40	1	3.97	-94.88598	36.41099	9.46	30.38	63.68	6.17	11.75	0.0070	1.05
42	1	3.92	-94.95372	36.40384	6.01	20.28	45.72	4.58	18.87	0.0060	1.80

ID[a]	Order[b]	DA[c]	LAT[d]	LONG[d]	D16[e]	D50[e]	D84[e]	BFW[f]	WDR[g]	Gradient	Sinuosity
44	1	1.54	-94.81055	36.51458	3.11	13.14	35.11	2.11	13.81	0.0362	1.06
46	1	6.81	-94.68353	36.90687	23.34	110.86	258.83	8.68	32.14	0.0211	1.02
47	1	1.21	-94.71122	36.79092	1.17	1.53	1.89	5.50	9.01	0.0043	1.07
48	1	4.55	-94.60535	36.00001	7.98	27.97	81.01	6.26	25.14	0.0156	1.07
49	1	2.39	-94.65626	36.83539	9.44	30.47	75.18	5.51	7.33	0.0116	1.04
50	2	16.18	-94.63495	36.46854	27.79	53.11	85.75	9.97	19.00	0.0194	1.04
51	2	2.07	-95.01182	36.19942	1.39	7.02	43.65	3.18	10.55	0.0110	1.05
53	2	11.12	-95.00170	36.30319	6.87	20.95	39.10	5.81	5.98	0.0048	1.47
54	2	32.44	-95.10445	36.27189	1.55	25.66	62.45	14.01	16.75	0.0082	1.01
55	2	4.81	-94.63504	36.70382	20.47	41.49	72.51	9.76	20.29	0.0088	1.03
57	2	3.50	-94.77190	36.07118	10.31	32.78	58.81	8.80	21.04	0.0094	1.08
58	2	10.72	-94.81833	36.14605	16.26	30.57	61.05	8.39	15.61	0.0078	1.00
59	2	12.36	-94.82840	36.33027	5.76	23.60	43.45	9.54	20.95	0.0092	1.36
60	3	80.41	-94.75773	36.54725	4.56	23.59	46.09	17.49	12.54	0.0041	1.08
61	3	39.20	-94.61952	35.92193	10.68	27.19	49.64	8.79	14.08	0.0037	1.51
62	3	112.92	-94.94842	36.31639	13.23	29.40	53.29	15.26	19.72	0.0057	1.08
63	3	21.58	-94.68628	35.94180	21.87	38.74	64.16	6.30	11.40	0.0043	1.14
65	3	78.50	-94.65368	36.40151	8.22	17.97	50.80	21.47	22.07	0.0034	1.07
66	3	60.74	-95.08177	36.27940	13.81	31.44	61.35	13.60	21.63	0.0039	1.18

ID[a]	Order[b]	DA[c]	LAT[d]	LONG[d]	D16[e]	D50[e]	D84[e]	BFW[f]	WDR[g]	Gradient	Sinuosity
67	3	14.65	-94.63616	36.01049	6.07	23.66	49.34	10.80	20.33	0.0120	1.14
68	3	82.72	-94.63648	36.53683	10.10	26.84	52.51	25.06	34.30	0.0029	1.80
69	3	19.71	-94.87849	36.46510	8.59	27.98	56.69	5.42	12.07	0.0033	1.03
70	4	211.42	-94.66073	36.82370	3.89	30.25	81.69	18.83	26.69	0.0022	1.16
71	4	291.75	-94.62682	36.63993	13.66	24.69	45.07	29.91	45.28	0.0023	1.05
72	4	951.31	-94.96892	36.40561	12.64	28.08	51.02	42.47	29.10	0.0005	1.04
73	4	161.20	-94.71296	36.54542	3.29	21.41	50.18	22.69	26.14	0.0018	1.00
74	4	517.58	-94.67419	35.95203	12.26	29.45	53.97	57.33	47.02	0.0013	1.25
75	4	33.87	-94.65153	35.99318	10.42	29.74	59.91	31.74	31.40	0.0043	1.09
76	4	269.30	-95.09272	36.28158	12.65	27.59	54.13	32.44	31.19	0.0037	1.04
77	4	294.38	-94.70740	36.20017	11.45	25.37	45.64	34.58	49.72	0.0025	1.40
78	4	457.78	-94.64427	35.93715	15.10	30.67	51.79	68.30	96.87	0.0011	1.10
79	4	104.00	-94.76873	35.97538	12.98	28.74	47.84	35.01	50.16	0.0020	1.37
80	1	2.40	-94.57958	34.52939	13.95	61.45	152.71	5.97	15.66	0.0268	1.03
81	1	1.745.52	-94.58001	34.74567	12.90	37.33	83.91	7.19	21.41	0.0180	1.20
82	1	2.29	-95.92151	34.47240	19.58	83.66	243.96	10.24	16.87	0.0185	1.01
83	1	1.23	-94.98258	34.61418	34.37	193.31	321.22	5.32	14.44	0.0301	1.04
84	1	1.71	-95.18664	34.57554	6.37	46.41	136.77	4.36	13.09	0.0315	1.13
85	1	1.71	-94.99938	34.83407	30.70	80.18	209.87	4.69	13.09	0.0158	1.04

ID[a]	Order[b]	DA[c]	LAT[d]	LONG[d]	D16[e]	D50[e]	D84[e]	BFW[f]	WDR[g]	Gradient	Sinuosity
87	1	3.35	-95.15161	34.34595	9.12	53.21	144.13	8.64	20.92	0.0111	1.09
89	1	2.57	-95.73351	34.71476	28.96	73.56	157.58	7.42	12.11	0.0178	1.07
90	2	7.72	-95.56557	34.31396	1.49	15.55	54.24	8.32	19.04	0.0032	1.25
91	2	6.12	-95.92042	34.44025	34.44	84.33	230.61	9.09	18.53	0.0021	1.25
92	2	13.94	-95.63197	34.72684	1.55	22.05	143.66	10.65	11.10	0.0038	1.03
93	2	16.38	-94.99204	34.67145	3.85	35.54	73.69	9.69	11.44	0.0052	1.56
94	2	13.23	-95.08970	34.76629	113.09	250.44	330.19	11.91	20.13	0.0204	1.03
95	2	10.16	-94.90979	34.86934	8.91	31.30	99.92	15.23	20.46	0.0071	1.05
96	2	10.17	-95.29962	34.53662	23.77	113.04	288.03	11.53	18.47	0.0132	1.02
97	2	11.38	-95.04329	34.30511	56.62	134.74	289.73	10.64	12.32	0.0163	1.51
98	2	19.85	-94.52452	34.86628	2.54	12.92	26.22	6.97	11.29	0.0023	1.72
99	2	9.74	-94.83362	34.47081	25.40	100.04	200.92	6.92	13.89	0.0135	1.23
101	3	34.26	-95.69514	34.53428	1.22	1.67	10.39	13.07	8.06	0.0011	1.30
102	3	35.66	-95.10972	34.45655	21.25	93.01	289.73	12.23	8.91	0.0016	1.01
103	3	12.18	-94.78945	34.53411	27.91	76.88	150.06	9.49	15.46	0.0030	1.10
104	3	35.88	-95.57950	34.66099	1.25	1.78	33.82	18.44	10.76	0.0047	1.07
105	3	49.04	-94.99794	34.70761	3.58	20.76	130.52	14.18	8.12	0.0035	1.23
106	3	39.16	-95.33595	34.32561	1.73	68.97	191.99	20.49	22.83	0.0047	1.40
107	3	3.50	-95.05764	34.74878	4.85	39.04	94.77	9.86	18.51	0.0050	1.27

ID[a]	Order[b]	DA[c]	LAT[d]	LONG[d]	D16[e]	D50[e]	D84[e]	BFW[f]	WDR[g]	Gradient	Sinuosity
108	3	106.47	-94.87671	34.82241	20.42	78.34	296.59	15.30	16.11	0.0008	1.00
109	3	99.79	-95.24859	34.50612	46.14	220.53	325.09	23.02	33.13	0.0053	1.16
110	4	143.37	-95.81969	34.53030	6.31	31.82	139.37	30.57	17.15	0.0030	1.07
111	4	293.58	-94.66045	34.36284	52.77	210.48	322.41	29.36	16.22	0.0018	1.14
112	4	364.12	-95.13331	34.49273	17.48	65.71	150.88	38.63	14.79	0.0005	1.14
113	4	157.83	-94.48306	34.38923	17.59	94.07	225.27	21.17	18.55	0.0038	1.15
114	4	258.85	-95.65696	34.30347	1.48	26.45	100.74	20.71	8.87	0.0004	1.37
115	4	268.10	-95.04749	34.51771	18.33	134.83	250.14	38.90	21.03	0.0003	1.44
116	4	78.06	-95.87362	34.57229	1.32	4.97	51.08	26.06	9.91	0.0001	1.08
117	4	84.94	-96.03013	34.46042	1.73	30.53	78.12	24.29	11.94	0.0027	1.13
118	4	155.32	-95.22181	34.32450	16.43	101.10	241.03	26.05	16.25	0.0008	1.03
122	1	2.54	-95.94325	34.50242	20.06	57.41	138.22	5.74	16.01	0.0027	1.01
123	1	2.54	-95.53258	34.31221	8.81	18.01	40.36	5.58	14.12	0.0035	1.12
124	1	1.85	-94.74838	34.81250	33.88	77.70	211.92	7.17	12.61	0.0279	1.02
125	1	10.24	-95.33985	34.36120	5.40	14.62	39.59	6.19	9.67	0.0035	1.06
126	1	2.45	-94.51068	34.51058	23.93	71.63	148.41	6.78	13.02	0.0137	1.01
128	1	8.35	-94.56177	34.72701	33.43	68.28	124.22	7.97	15.37	0.0039	1.08
129	1	1.25	-94.99817	34.49825	25.81	69.22	146.80	5.82	19.02	0.0292	1.05
130	2	3.27	-94.58759	34.14943	18.83	44.85	91.53	6.10	14.62	0.0129	1.03

ID[a]	Order[b]	DA[c]	LAT[d]	LONG[d]	D16[e]	D50[e]	D84[e]	BFW[f]	WDR[g]	Gradient	Sinuosity
132	2	6.90	-95.08855	34.87990	9.86	44.16	108.57	7.73	16.46	0.0063	1.16
133	2	21.59	-94.49416	35.08135	10.19	36.04	99.94	12.09	21.64	0.0050	1.04
134	2	7.08	-94.82222	34.68340	1.33	25.34	70.69	8.98	8.09	0.0004	1.20
136	2	3.16	-95.21393	34.40500	14.57	55.52	189.67	7.31	13.49	0.0221	1.10
137	2	7.61	-95.52807	34.61312	12.48	60.49	190.56	6.32	20.82	0.0144	1.07
138	2	4.66	-95.30043	34.27646	1.69	29.60	106.81	9.45	8.53	0.0099	1.07
139	2	14.50	-95.00154	34.30450	45.48	186.92	318.72	10.25	20.73	0.0123	1.04
140	2	8.04	-95.46190	34.58043	50.02	275.83	334.43	9.08	18.57	0.0191	1.08
141	2	7.49	-94.86865	34.68118	1.19	1.59	3.65	5.45	6.22	0.0080	1.28
142	3	61.98	-94.51699	34.78822	22.48	66.40	160.15	33.62	21.75	0.0012	1.14
144	3	29.65	-94.61077	34.47917	17.13	128.30	243.79	15.80	13.43	0.0046	1.30
145	3	78.56	-94.55368	34.72135	55.13	134.28	281.71	20.67	22.98	0.0022	1.02
146	3	107.01	-94.93982	34.55555	78.96	213.01	321.01	21.94	20.76	0.0035	1.02
147	3	47.63	-95.29994	34.83241	22.03	59.00	140.60	14.52	15.60	0.0040	1.13
148	3	34.95	-95.98634	34.49477	12.33	38.05	91.60	20.81	21.47	0.0004	1.04
149	3	82.78	-94.91542	34.53384	21.43	111.28	297.85	21.42	13.71	0.0027	1.01
150	3	65.96	-95.04831	34.27342	5.03	82.06	199.05	16.89	18.66	0.0026	1.05
151	3	33.17	-95.35562	34.44877	20.77	99.71	234.06	16.48	19.24	0.0105	1.06
152	4	68.03	-95.99915	34.47975	22.62	64.78	154.20	21.73	26.62	0.0028	1.08

ID[a]	Order[b]	DA[c]	LAT[d]	LONG[d]	D16[e]	D50[e]	D84[e]	BFW[f]	WDR[g]	Gradient	Sinuosity
154	4	132.88	-94.72392	34.51282	50.18	104.96	214.44	19.83	23.58	0.0092	1.30
155	4	116.33	-94.48869	34.75769	23.41	68.74	158.61	25.23	19.93	0.0024	1.02
157	4	388.04	-94.88200	34.68201	14.93	42.48	91.53	36.68	14.36	0.0006	1.05
158	4	75.74	-94.48157	34.99392	16.75	45.54	90.35	24.32	28.86	0.0042	1.22
159	4	228.24	-94.92401	34.37394	24.48	152.30	284.96	36.57	31.48	0.0014	1.05
160	4	68.95	-94.72762	34.51021	34.94	92.09	198.80	15.63	28.86	0.0113	1.17
161	4	235.24	-94.59865	34.38205	51.33	276.52	334.65	34.25	13.83	0.0001	1.00
162	1	1.21	-94.65205	34.63471	18.96	57.44	135.58	5.57	13.74	0.0252	1.17
164	1	2.06	-94.67850	34.47122	1.36	13.53	52.28	5.22	8.63	0.0060	1.08
165	1	3.10	-95.75102	34.57471	1.16	1.50	1.84	9.50	6.82	0.0007	3.04
166	2	8.26	-95.63025	34.57415	12.19	36.96	115.93	8.85	11.51	0.0039	1.55
167	3	11.73	-94.92234	34.82963	17.39	46.10	92.58	10.95	15.41	0.0046	1.09
169	4	238.42	-94.91394	34.34621	75.82	153.79	301.40	33.68	25.88	0.0019	1.05
911	1	2.85	-95.03087	34.34257	10.22	61.51	141.30	5.86	11.12	0.0090	1.06
920	2	12.62	-95.06297	34.88529	13.01	40.87	105.18	9.80	14.27	0.0030	1.26
930	3	15.11	-95.74686	34.43570	100.99	194.91	328.44	9.40	15.49	0.0093	1.09
940	4	136.11	-94.50804	35.00389	22.40	51.97	117.23	23.29	19.33	0.0029	1.22

CHAPTER 4

STREAM REACH AND WATERSHED DISSIMILARITY IN THREE EASTERN OKLAHOMA ECOREGIONS

Abstract

Ecoregions are homogenous areas that comprise similar associations of geology, climate, soils, land use, and potential natural vegetation (Omernik, 1987). Regional (i.e., ecoregion) boundaries provide a systematic approach for ecosystem management. The physical variability that exists in ecoregions makes them spatially complex. Complexity influences how similar or dissimilar stream channel morphology becomes in each ecoregion. The dissimilarity of stream reaches and watersheds needs to be understood for potential management implications. Dissimilarity of stream reaches and watershed morphology were quantified within and between ecoregions in eastern Oklahoma: Boston Mountains, Ozark Highlands, and Ouachita Mountains. Stream reach dissimilarity was quantified using median particle-size, bankfull width, width-depth ratio, gradient, and sinuosity. Watershed morphology dissimilarity was quantified using drainage density, circularity ratio, relief, relief ratio, and ruggedness number. The most dissimilar stream reaches are in the Ouachita Mountains. The greatest amount of dissimilarity in Ouachita Mountains stream reaches was 18.59. In the Ozark Highlands maximum dissimilarity was 13.11 and 9.58 in the Boston Mountains. Watershed morphology is most dissimilar in the Ouachita Mountains. The greatest amount of dissimilarity in Ouachita Mountains watersheds was 17.62. Maximum watershed morphology dissimilarity in the Boston Mountains was 12.70 and 9.12 in the Ozark Highlands. Stream reaches and watersheds in the Ouachita Mountains are more dissimilar than those in the Boston Mountains or Ozark Highlands because the Ouachita Mountain ecoregion comprises a broader geographic area with more landscape variability than the Boston Mountains or Ozark Highlands. The values of maximum dissimilarity, established for each ecoregion, should be used to assign how different stream reaches and watershed morphology are within a similar region, which can be used in stream management protocols by the Oklahoma Department of Wildlife Conservation.

Key words: Ecoregions, Dissimilarity, Streams, Watersheds, Clusters, Oklahoma

1. Introduction

Ecoregions are homogenous areas that constitute similar geology, climate, soils, land use, and potential natural vegetation (Omernik, 1987). Omernik et al. (2000) state that ecoregions provide for the ... “research, assessment, monitoring, and management of ecosystems.” Classifying biotic and abiotic environments at the ecoregion level provides for large-scale interpretation by environmental scientists between multiple disciplines. Aquatic scientists have studied whether ecoregions provide a good spatial framework to classify macroinvertebrate and fish assemblages (Larsen et al., 1986, Rohm et al., 1987, Whittier et al., 1988, Lyons, 1989, Newall and Magnuson, 1999, McCormick et al., 2000, Rabeni and Doisy, 2000). The classifications of macroinvertebrates and fish assemblages by ecoregion often incorporate the physical habitat of stream channels. Specifically designed fluvial geomorphological studies in ecoregions, however, are lacking in the literature.

The characteristics of stream reaches and watershed morphology confined to ecoregion boundaries are not well documented. Attempting to classify river systems on a large scale can be difficult. Stream channels vary spatially from upstream-to-downstream and within individual reaches (Vannote et al., 1980, Jacobson, 1995, Knighton, 1998, Montgomery, 1999, McDowell, 2001). Much of this variability develops from the complex interaction of channel dynamics and external factors (i.e., geology, land use) in the fluvial hierarchy. Phillips (2003) recognized that geomorphic systems are often nonlinear and complex. Understanding the complexities associated with variability in fluvial systems is important at many spatial scales. Quantitative assessment of stream reach and watershed variability in ecoregions provides a necessary evaluation of whether large-scale classifications are beneficial for environmental management decisions.

Montgomery and Buffington (1998) state that geomorphic regional classifications exhibit broad-level information about channel dynamics. When the characteristics of watersheds (Chapter 2) and stream channels (Chapter 3) were compared between ecoregions, inferences were drawn about how watershed morphology impacts channel processes at the reach scale. Quantification of stream reach and watershed dissimilarity within and between ecoregions provides additional information about regional perspectives in stream classifications that is better than geomorphic classifications. This occurs because geomorphic classifications are largely based on physiography with less influence from climate and land use.

Quantifying stream reach and watershed dissimilarity is important for the following reasons: (1) values of dissimilarity can be used to cluster stream reaches and watersheds within ecoregions; (2) quantifying how much variability exists within and between ecoregions can help in the implementation of strategies for stream restoration; (3) determining where in the fluvial system the greatest amount of variability exists can aid in understanding channel form; and (4) values for dissimilarity, established for ecoregions, helps incorporate regional complexity in watersheds and the characteristics of stream reaches.

Stream reach and watershed clusters provide a necessary classification tool for understanding channel processes at the ecoregion scale. Reaches surveyed on the same stream, however, do not imply similar channel morphology and clustering by spatial proximity. This is because of the inherent complexity and variability that exists within the longitudinal profile of stream reaches, which include bank composition, tributary influences, woody debris recruitment (Montgomery, 1999, Walters 2003).

This study evaluates: (1) the amount of stream reach and watershed dissimilarity that exists between ecoregions; (2) clusters similar stream reaches and watersheds by ecoregion; and (3) classifies stream reach and watersheds without ecoregion constraints and establish how they cluster without a regional boundary. This study provides information on the amount of stream reach and watershed variability that exists in three eastern Oklahoma ecoregions.

2. Background

Variability in the fluvial system is expressed spatially and temporally (Schumm, 1991). The spatial and temporal implication of variability can be easily observed when comparing stream channels of similar sizes at the same scale. The realization that streams have variable tendencies was established long ago. Heraclitus, a Greek philosopher circa 500 BC, expressed the idea that no man crosses the same river twice. Heraclitus established the underlying premise that variability exists in the fluvial system. Today, aquatic scientists and geomorphologists quantify biotic and abiotic variability (i.e., dissimilarity) existing in the fluvial system (Hawkins and Vinson, 2000, Van Sickle and Hughes, 2000, Li et al., 2001, McDowell, 2001, Trainor and Church, 2003). The purpose of these quantifications is to better understand how external factors affect variability in a spatial context.

It is widely accepted in the natural and physical sciences that complexity increases with size (Schumm, 1991). Often a direct relationship exists between complexity and variability in the fluvial system. Schumm explains that a small watershed confined to a similar climate, lithology, and land use will be less complex than a larger watershed that spans different climatic, lithologic and land use boundaries. Omernik's (1987) ecoregions were not delineated by size, but rather on the homogeneity of physical variables (i.e., geology, climate, soils, land use, and potential natural vegetation) that influence ecological similarity (Stoddard, 2005). Ecoregions consist of similar physical variables, which lend themselves to a structured environmental organization that can be applied to fluvial geomorphic studies.

Previous studies report that watershed morphology varies between distinctly different regions (Morisawa, 1962, Lewis, 1969). Chapter 2 reports that statistically significant differences exist between morphometric variables and eastern Oklahoma ecoregions. This is because regions with different geology, climate, soils, land use, and potential natural vegetation control watershed evolution. The amount of variability in the watersheds that exist in similar regions is not often quantified. Rather watersheds are used as a large-scale framework designed as the hierarchal beginning in fluvial studies (Frissell et al., 1986). Morphometric variables are also used to show hydrologic relationships (Jarboe and Hann, 1974, Harlin, 1984, Costa 1987, McNamara et al., 1998, Shaban, 2005).

Chapter 3 of this dissertation reports that the characteristics of stream channels vary spatially in similar regions. These findings support the literature on stream process and function. From upstream-to-downstream channels adjust form under the influence of discharge (Leopold and Maddock, 1953). Typically, as discharge increases, the width-depth ratios of streams increase, gradient decreases, sinuosity increases, and particle-size decreases (Rosgen, 1996). Systematic changes along the longitudinal profile, however, do not always occur (Wood-Smith and Buffington, 1996, Rice et al., 2001). Sinuosity can fluctuate downstream of dams when maximum discharges can disrupt sediment delivery (Marston et al., 2005). Particle-size may increase downstream because the influence of tributaries and debris flows (Rice 1994, Rice and Church, 1996). The rate and amount of change that stream channels undergo is linked to the complex nature of the fluvial system. These complexities are often influenced by human modification to the watershed through which streams flow (McDowell, 2001). Based on the complex nature of the fluvial system, the quantification of stream reach dissimilarity by ecoregion is necessary to understand how channel patterns vary in similar regions.

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 were selected for study because stream morphology, stream habitat, and stream classification of these regions are of interest to the Department of Wildlife Conservation (ODWC). The ODWC recognizes that the management of these streams is influential to the overall wellbeing of the fisheries economy in this portion of the state (Fisher et al., 2002).

The Ozark Highlands exist in parts of Kansas, Missouri, Arkansas, and Oklahoma (Fig. 4.1). In Oklahoma this ecoregion encompasses 2,795 km^2. Woods et al. (2005) describes 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. Common soil series include Clarksville and Noark (Carter, 1997). Much of the native forest and prairie was removed during the logging boom at the turn of the century.

The Boston Mountains lie to the south of the Ozark Highlands in Oklahoma (Fig. 4.1). In Oklahoma, this ecoregion encompasses 1,891km^2. This region is not as dissected as the Ozark Highlands. 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 of mostly oak-hickory forest (Woods et al., 2005). Soils on uplands consist of Ultisols, Inceptisols, and Entisols. Common soil series include Hector and Linker (Carter 1997).

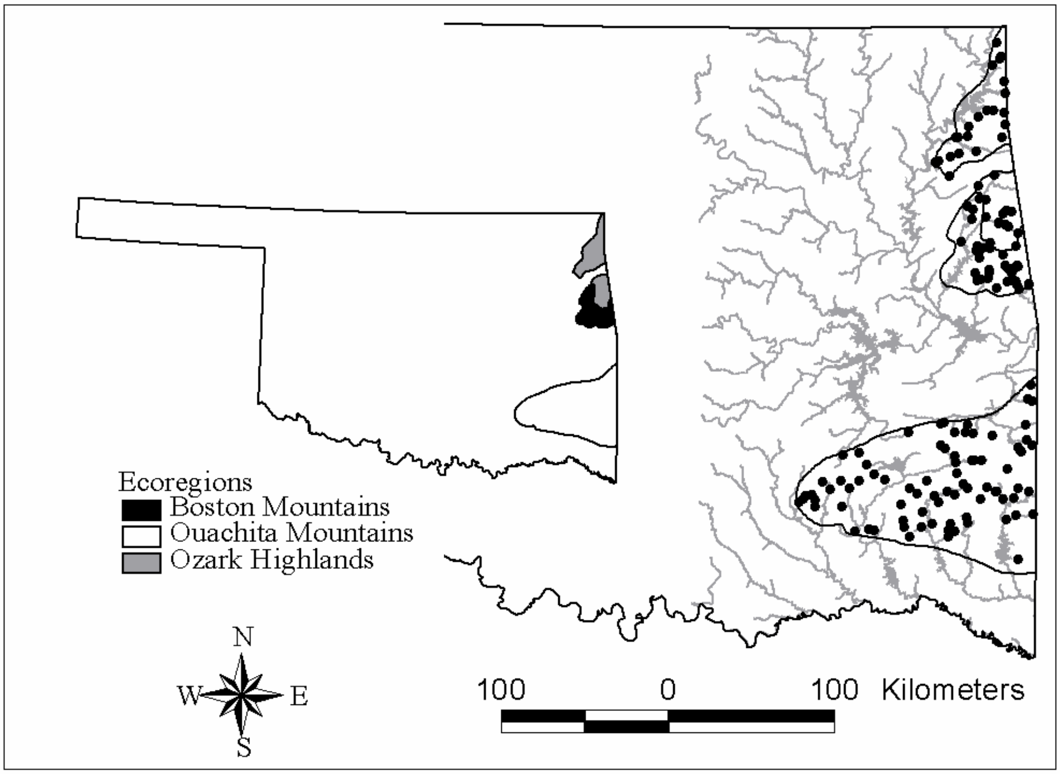

Fig. 4.1. Black dots represent first through fourth order stream reaches that were surveyed to determine channel morphology of eastern Oklahoma streams. Watershed parameters delineated from black dot to drainage divide.

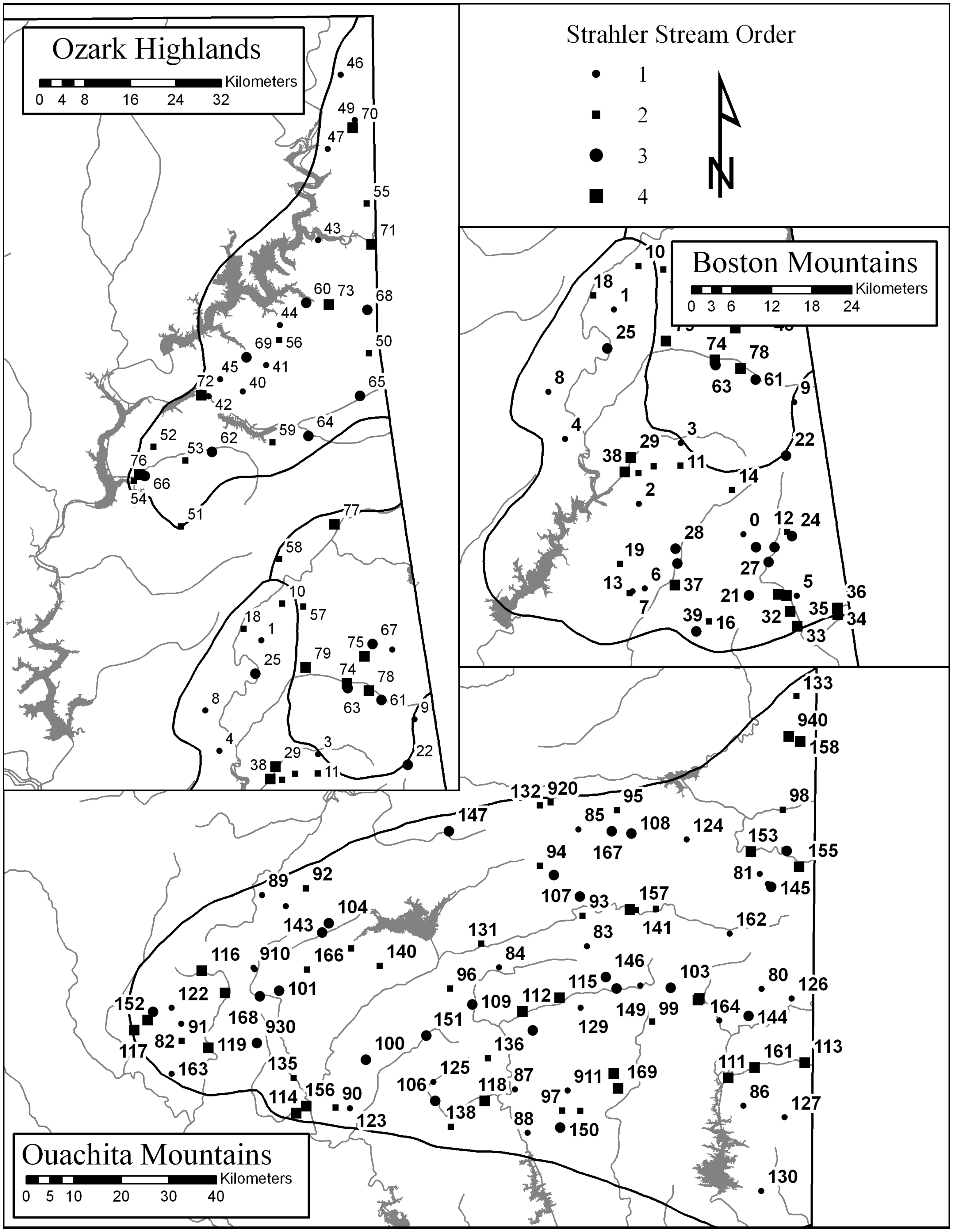

Fig. 4.2. Spatial distribution of randomly selected sites by ecoregion.

The Ouachita Mountains, south of the Boston Mountains, are separated by the Arkansas Valley ecoregion (Fig. 4.1). In Oklahoma, this ecoregion encompasses 10,100 km^2. The region tends to be mosaic of low mountains and high hills of folded Paleozoic rocks. Lithology varies throughout the ecoregion, with rock type of sandstone, shale, and novaculite. Mean annual precipitation (110-145 cm) is greatest on south-facing ridges and decreases to the east. Land use consists of forestry, logging, ranching, woodland grazing, and recreation. The potential natural vegetation is oak-hickory-pine forest (Woods et al., 2005). Soils are Ultisols, Alfisols, and Inceptisols. Common soil series include Clebit, Pirum, Neff, Tuskahoma, Wetsaw, and Wister (Carter 1997).

4. Methodology

4.1. Site selection

Dissimilarity of stream reaches and watershed morphology was quantified in three eastern Oklahoma ecoregions. One hundred and forty-nine stream reaches and one hundred thirty-four watersheds were used to establish dissimilarity values between and among ecoregions (Fig. 4.2). A random point generator model in ArcView 3.2$^©$ was applied to a stream network constructed using 30-meter DEMs (Fig. 4.1). The stream network was stratified into stream orders (1-4) for each ecoregion (Strahler, 1952). Points (i.e., reaches and watershed outlets) were generated using a stratified random procedure based on the area of the ecoregion, which suggested how many points per ecoregion were necessary for a stream sampling protocol that was equally weighted by ecoregion. Coordinates for stream reaches were downloaded to a Trimble GeoXT GPS receiver$^©$, which was used to navigate to the survey site. Reach length surveyed was attained by multiplying bankfull width by 20. For example, if estimated bankfull width was 20 meters then a reach length of 400 meters was surveyed. Watersheds draining the randomly selected stream reaches were used in the morphometric analyses. Fifteen watersheds overlapped the boundaries of the ecoregions and were not 90 percent confined to a single ecoregion. These watersheds could not be used to establish watershed dissimilarity by ecoregion and were not used in the study. These sites were not reselected for analyses.

4.2. Variables of dissimilarity

The morphologic variables that best describe stream channels are dependent on the scale and type of study being undertaken. Tranior and Church (2003) state no clear criteria exist that characterize stream channels. Channel morphology, however, is often described in terms of D50, width-depth ratio, entrenchment, channel gradient, and sinuosity (Rosgen, 1996). The aforementioned variables, with the exception of entrenchment, were used in the quantification of stream reaches. Entrenchment ratio was excluded because its calculated value exceeded 2.2 (i.e., slightly entrenched) in most instances and could not be calculated past 2.2 with accuracy.

Channel gradient was calculated by surveying the water elevation from upstream-to-downstream with a stadia rod and transit and dividing the drop in elevation by the reach length (Rosgen, 1996). Sinuosity was calculated by dividing channel length by valley length (Rosgen, 1996). Channel length was surveyed with a Trimble GeoXT GPS receiver© while in the field (Dauwalter et al., 2006). The ratio of width-depth, median particle-size (e.g., D50), and bankfull width of the reach was calculated by averaging values from cross-sectional transects that were conducted from upstream-to-downstream in the reach (Wolman, 1954, Rosgen 1996). Three-to-four cross-sections were conducted per reach. Where possible these cross-sections were equally spaced along the reach in alternating pools and riffles.

Watershed dissimilarity is based on drainage density, circularity ratio, relief, relief ratio, and ruggedness number. Drainage density was calculated by dividing the sum of stream lengths in the watershed by the watershed area (Horton, 1945). Circularity ratio constitutes the area of the watershed divided by the area of a circle with the same perimeter as the basin (Miller, 1953). This variable was used to express the overall shape of the watersheds. Circular watersheds have values closer to one, while non-circular watersheds tend towards zero. Relief constitutes the highest elevation in the watershed minus the lowest elevation in the watershed. Relief ratio is calculated by dividing the total basin relief (outlet to summit of watershed) by the basin length (Schumm, 1956). Basin length used to calculate the relief ratio was a straight line from the watershed outlet to the summit, unless the straight line crossed the watershed boundary. Where this occurred, the line was bent along the channel and continued until the watershed and the valley were parallel. The ruggedness number is basin relief multiplied by the drainage density.

4.3. Clustering procedure

Clustan Graphics 8.0© was used to calculate the values of dissimilarity and cluster stream reaches and watersheds. Reach proximities were calculated using squared Euclidean distance. Reach variables were standardized to z-scores, which is the recommended transformation when measurements are continuous and equally weighted in the proximity analyses (Wishart, 2006). Case weights (i.e., reach variables) were assigned a value of one and were equally weighted throughout the analyses. This was because each of the reach variables was deemed equally important in defining the morphology of the reach. Squared Euclidean distance is calculated following equation 1 (Wishart, 2006):

$$d^2_{ih} = \Sigma_j(xij - xhj)^2 / v \tag{1}$$

Where:

j = Each reach variable
xij = Value in reach i
xhj = Value in reach h
v = All reach variables

Wishart (2006) suggests clustering by the increase sum of squares when the purpose of the study establishes clusters that are homogeneous to all the variables. Reaches are clustered according to their similarities. Selecting the number of clusters in each data set was done by significance tests using the best cut function. An upper tail t-test was used to show the largest number of clusters that was significant at $\alpha = 0.05$. T-values that exceed the five percent level are significant deviations from the fusion values on the data set (Wishart, 2006). Multi-dimensional scaling was done to obtain a scatter graph that illustrates the amount of difference between the comparisons.

5. Results and Discussion

5.1. Quantitative data for reaches and watersheds

This section portrays dissimilarity and clustering results for stream reaches and watershed morphology. Reaches and watersheds are clustered by site selection number.

Refer to appendix of chapter 2 for watershed data and the appendix of chapter 3 for stream reach data. At the end of this chapter is an appendix with reach names, stream names, and survey dates.

5.2. Clusters and dissimilarity of stream reaches: Boston Mountains

Thirty-five stream reaches in the Boston Mountains were clustered according to overall dissimilarity. A total of 595 reach combinations (i.e., proximities) were calculated in the initial cluster. A five cluster partition was recognized after proximities were clustered using the increase in sum of squares and conducting a best cut significance test on the data (Fig. 4.3). The most typical reach variables of each cluster (exemplar) are given in Table 4.1. Clusters one and two are comprised of first and second-order streams. Clusters three, four, and five constitute mostly (one second-order reach in cluster three) third and fourth-order streams. Progression of clusters show cluster one and two linking before clusters three and four. This means first and second-order streams are more similar in their characteristics than third and fourth-order streams.

Proximities coefficients (i.e., dissimilarity values) of the ten most dissimilar stream reaches are linked to reach 1 or reach 35 (Table 4.2). Reach 1 is a small first-order stream that drains a 1.20 km^2 watershed, while reach 35 is a large fourth-order stream that drains a 587 km^2 watershed. Reach 1 constitutes a high gradient (0.027) and low width-depth ratio (7.84). Reach 35 constitutes a low gradient (0.001), high sinuosity (1.51), and wide bankfull width (50.42). Multi-dimensional scaling portrays these two reaches as outliers of the representative cluster (Fig. 4.4). The 10 most similar streams are linked to multiple reaches and no definable pattern is observed (Table 4.2).

Table 4.1
Exemplar values for clusters of Boston Mountain stream reaches. Exemplars are the most typical reach in each cluster.

Cluster[a]	DA (km^2)[b]	Gradient	Sinuosity	WDR[c]	D50	BFW[d]
1 (2)	1.31	0.019	1.15	10.34	30.95	5.69
2 (13)	4.21	0.012	1.13	16.09	23.09	11.90
3 (29)	170.15	0.002	1.11	25.34	32.89	33.64
4 (36)	587.31	0.001	1.31	21.73	44.20	46.07
5 (37)	223.29	0.003	1.09	24.63	60.66	22.14

[a] Number of cluster with exemplar for each cluster in (). Single cluster reach assumes exemplar status; [b] Watershed area above reach; [c] Width-depth ratio; [d] Bankfull width.

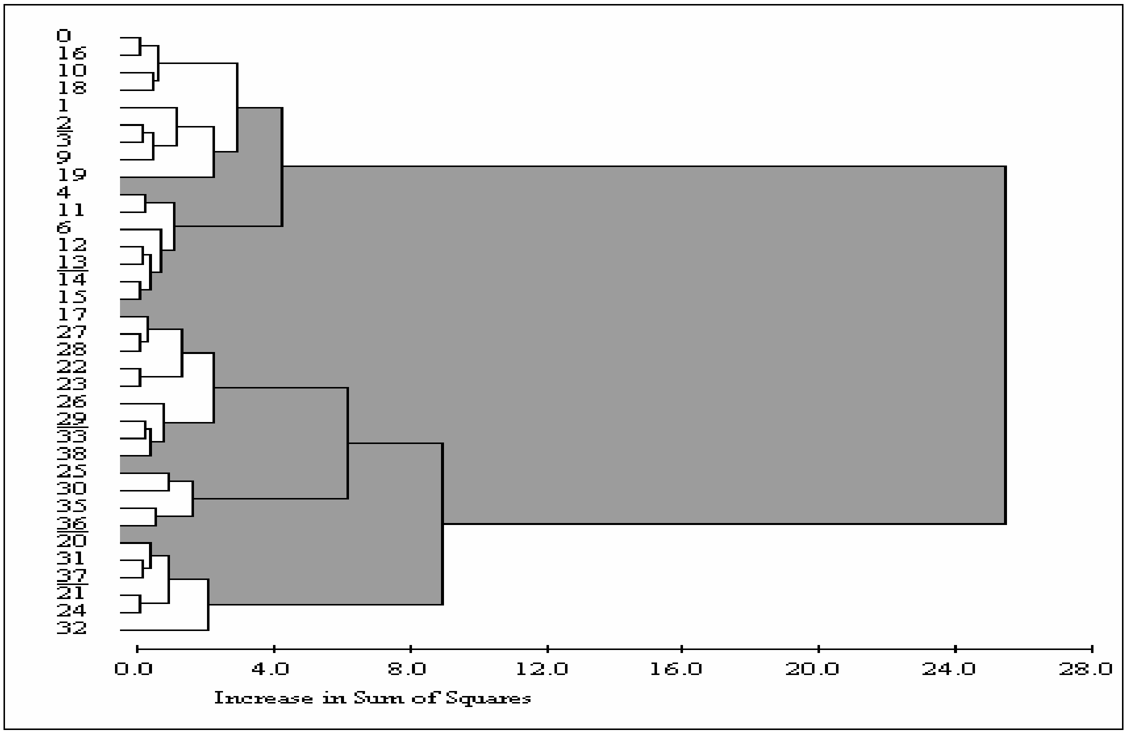

Fig. 4.3. Cluster grouping of Boston Mountain stream reaches. Five clusters (cluster one at top and cluster five at bottom) were attained after a best cut significant test was performed on the data. Exemplars (most typical stream reach of cluster) are underlined.

Table 4.2
Ten most dissimilar and similar stream reaches in the Boston Mountains.

Dissimilarity[a]	Comparison[b]	Comparison[b]	Similarity[a]
9.58	19 (2), 35 (4)	14 (2), 15 (2)	0.03
9.01	1 (1), 35 (4)	32 (4), 33 (4)	0.04
8.87	9 (1), 35 (4)	15 (2), 24 (3)	0.04
8.37	1 (1), 26 (3)	28 (3), 37 (4)	0.06
8.10	3 (1), 35 (4)	27 (3), 28 (3)	0.07
7.62	1 (1), 38 (4)	12 (2), 20 (3)	0.08
7.52	14 (2), 35 (4)	12 (2), 24 (3)	0.08
7.31	2 (1), 35 (4)	22 (3), 23 (3)	0.08
7.20	1 (1), 30 (4)	29 (4), 32 (4)	0.09
6.89	15 (2), 35 (4)	21 (3), 24 (3)	0.09

[a] The larger dissimilarity values link to the most unlike reaches; [b] Number in () is the stream-order of the reach comparison. Comparison on the right goes with similarity. Comparison on the left goes with dissimilarity.

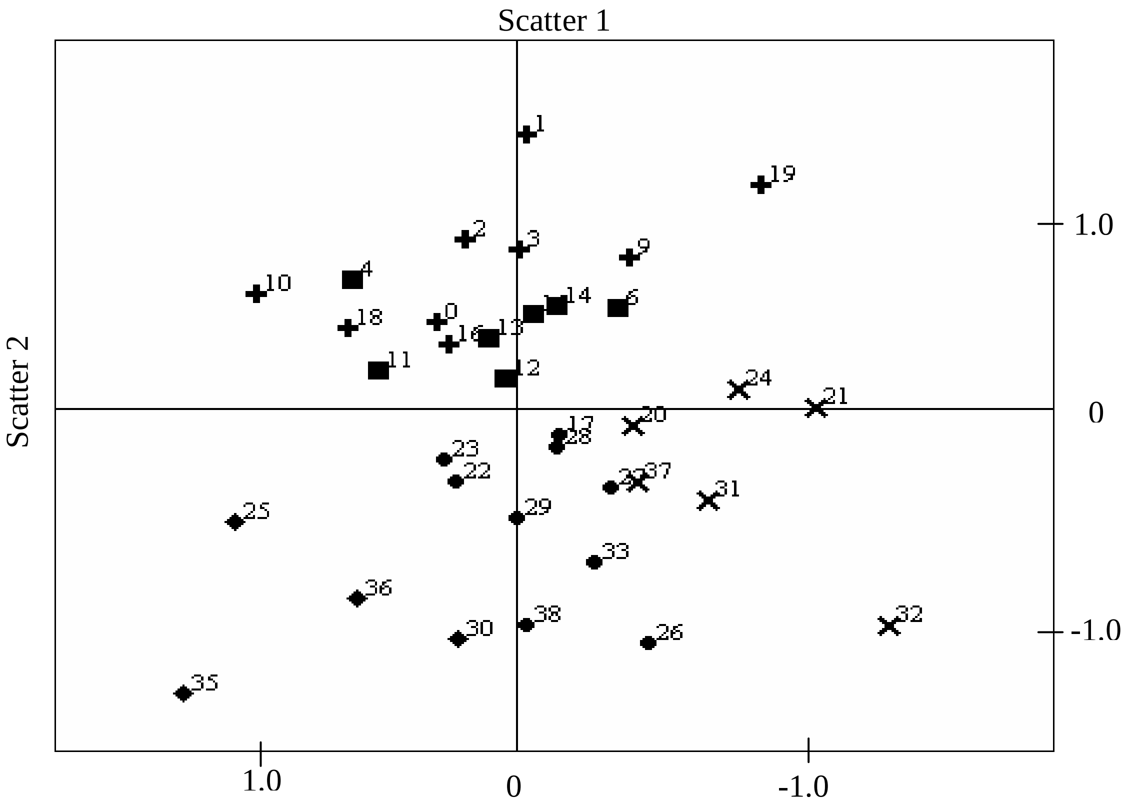

Fig. 4.4. Multi-dimensional scaling of best cut clusters. Similar symbols represent the same cluster. The highest dissimilarity is noted by the distance two numbers (i.e., 35 and 19) are from each other. The more compact the cluster indicates a cluster more similar to all the reaches. Minimum stress is 2.2041 percent.

5.3. Clusters and dissimilarity of stream reaches: Ozark Highlands

Thirty-four stream reaches in the Ozark Highlands were clustered according to overall dissimilarity. A total of 561 reach combinations were compared in the initial cluster. Six clusters were recognized after conducting a best cut significance test on the data (Fig. 4.5). Exemplar values for the clusters are given in Table 4.3. Three of the reaches (44, 46, and 78) exist as single clusters. The progression of clusters is shown in Fig. 4.5. The last cluster occurs when all first, second, and most (except two) third-order reaches combine with two third-order and 10 fourth-order reaches (Fig. 4.5). This cluster differs from the final cluster in the Boston Mountains.

Maximum dissimilarity of stream reaches in the Ozark Highlands exceeds that of the Boston Mountains (Table 4.4). The highest values of dissimilarity are associated with reaches 78, 46, 42, and 44. Three of the four reaches were not initially clustered with a second reach (Fig. 4.5). Reach 78 is a low gradient fourth-order stream (0.001) with an extremely high width-depth ratio (96.87). Reaches 46, 42, and 44 are first-order streams. Reaches 46 and 44 have gradients of 0.021 and 0.0362, respectively. Reach 46 has a much larger particle-size (D50 = 110.86) than reach 44 (D50 = 13.14). Reach 46 has a much higher overall width-depth ratio (32.14 vs. 13.81) and bankfull width (8.68 m vs. 2.11 m) than reach 44. Reach 42 is a low gradient first-order stream (0.007) with a relatively high sinuosity of 1.80. D50 particle-size (20.28), width depth ratio (18.87), and bankfull width (4.58) are between the values for reaches 46 and 44. Multi-dimensional scaling portrays these four reaches as outliers of ecoregion clusters (Fig. 4.6). No one particular variable dictates maximum dissimilarity within the comparison of stream reaches.

Table 4.3
Exemplar values for clusters of Ozark Highland stream reaches. Exemplars are the most typical reach in each cluster. Note that clusters 2, 3, and 6 originated as single clusters.

Cluster[a]	DA (km^2)[b]	Gradient	Sinuosity	WDR[c]	D50	BFW[d]
1 (58)	10.72	0.008	1.00	15.61	30.57	8.39
2 (44)	1.54	0.036	1.06	13.81	13.14	2.11
3 (46)	6.81	0.021	1.02	32.14	110.86	8.68
4 (61)	39.20	0.004	1.51	14.08	27.19	8.79
5 (75)	33.87	0.004	1.09	31.40	29.74	31.74
6 (78)	457.78	0.001	1.10	96.87	30.67	68.30

[a, b, c, d] See Table 4.1

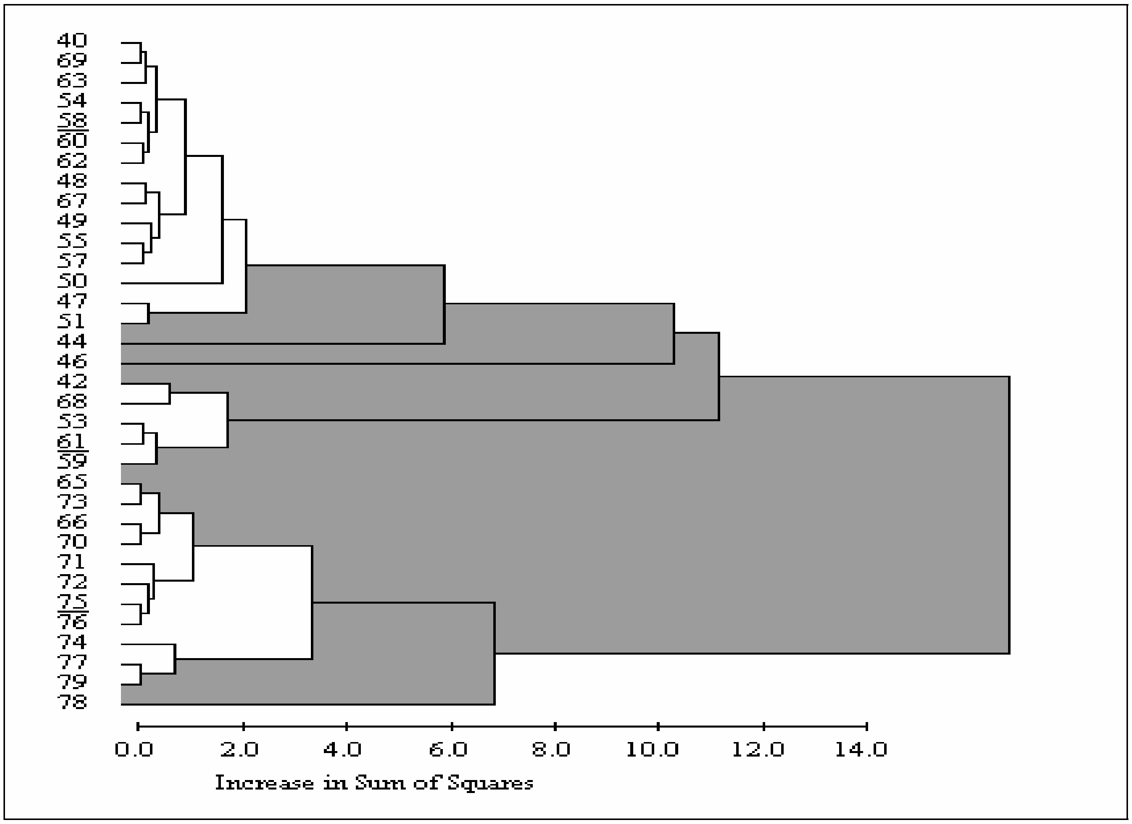

Fig. 4.5. Cluster grouping of Ozark Highland stream reaches. Six initial clusters (cluster one at top and progress accordingly to the bottom) were attained after a best cut significant test was performed on the data. Exemplars are underlined.

Table 4.4
Ten most dissimilar and similar reaches of the Ozark Highlands. Note that dissimilarity is much higher in the Ozark Highlands than the Boston Mountains.

Dissimilarity[a]	Comparison[b]	Comparison[b]	Similarity[a]
13.12	78 (4), 44 (1)	79 (4), 77 (4)	0.01
11.68	78 (4), 46 (1)	76 (4), 75 (4)	0.02
9.76	47 (1), 46 (1)	69 (3), 40 (1)	0.03
9.71	78 (4), 42 (1)	58 (3), 40 (1)	0.04
9.35	78 (4), 53 (2)	58 (3), 54 (3)	0.04
9.33	46 (1), 42 (1)	73 (4), 65 (3)	0.05
9.14	68 (3), 46 (1)	70 (4), 66 (3)	0.05
9.13	78 (4), 51 (2)	58 (3), 56 (3)	0.06
8.93	78 (4), 49 (1)	62 (3), 54 (2)	0.06
8.92	78 (4), 47 (1)	66 (3), 62 (3)	0.07

[a,b] See Table 4.2

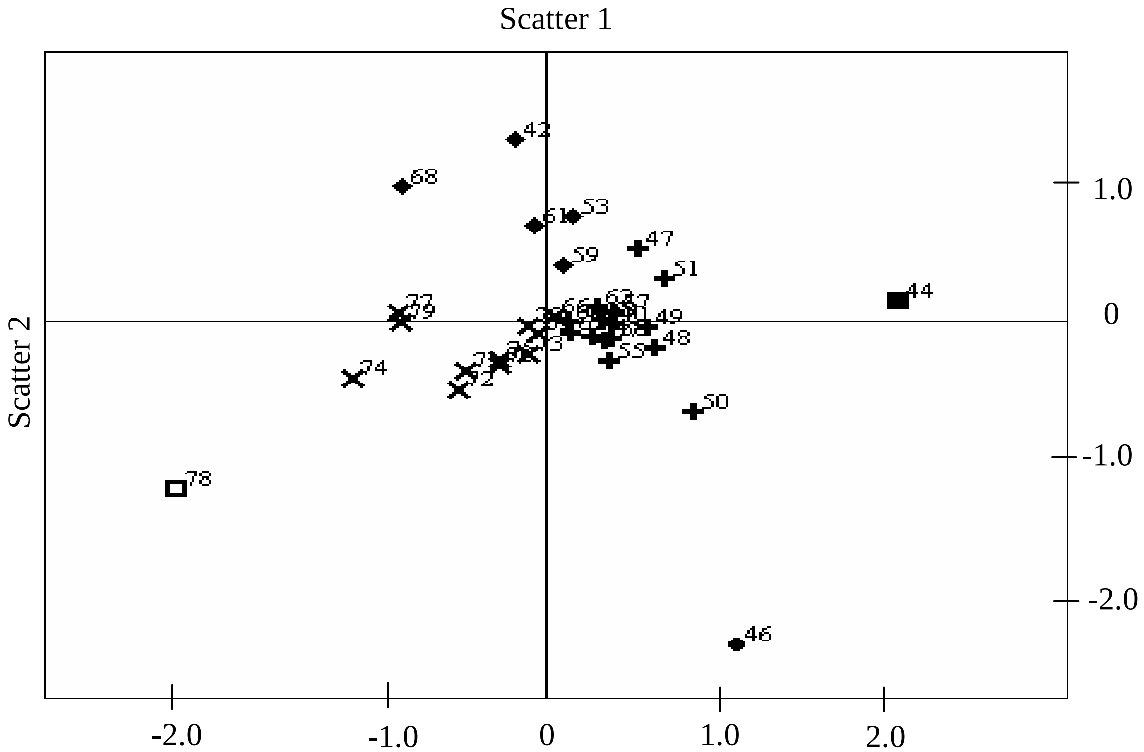

Fig. 4.6. Multi-dimensional scaling (MDS) of best cut clusters. Similar symbols represent the same cluster. The highest dissimilarity is noted by the distance two numbers (i.e., 78 and 44) are from each other. The more compact the cluster indicates a cluster more similar to all the reaches. Reach 78, 46, and 44 failed to initially cluster with any other reach. Minimum stress is 1.4435 percent.

5.4. Clusters and dissimilarity of stream reaches: Ouachita Mountains

Eighty stream reaches in the Ouachita Mountains were clustered according to overall dissimilarity. A total of 3,160 reach combinations were evaluated for the initial cluster. Eleven clusters were identified after the best cut procedure was performed (Fig. 4.7). Exemplars for each cluster are given in Table 4.5. The 11 clusters tend to link by similar stream-orders. As expected, the final cluster occurs when larger third and fourth-order streams combine with smaller first, second, third, and fourth-order streams. A higher number of clusters occurred in the Ouachita Mountains than the Boston Mountains or Ozark Highlands. This is attributed to the increased spatial area in which comparisons were made and more regional complexity that defines the Ouachita Mountain ecoregion from the Boston Mountains and Ozark Highlands (Fig. 4.1).

Table 4.5
Exemplar values for clusters of Ouachita Mountains stream reaches. Exemplars are the most typical reach in each cluster.

Cluster[a]	DA (km^2)[b]	Gradient	Sinuosity	WDR[c]	D50	BFW[d]
1 (80)	2.40	0.027	1.03	15.66	61.45	5.97
2 (94)	13.23	0.020	1.03	20.13	250.44	11.91
3 (82)	5.52	0.019	1.01	16.87	83.66	10.24
4 (103)	12.18	0.003	1.10	15.46	76.88	9.49
5 (105)	49.04	0.004	1.23	8.12	20.76	14.18
6 (166)	8.26	0.004	1.55	11.51	36.96	8.85
7 (165)	3.10	0.001	3.04	6.82	1.50	9.50
8 (154)	132.88	0.009	1.30	23.58	104.96	19.83
9 (159)	228.24	0.001	1.05	31.48	152.30	36.57
10 (155)	116.33	0.002	1.02	19.93	68.74	25.23
11 (111)	293.58	0.002	1.14	16.22	210.48	29.36

[a,b,c,d] See Table 4.1

Maximum dissimilarity (top 10 comparisons) of stream reaches in the Ouachita Mountains exceeds that of the Boston Mountains or Ozark Highlands. The highest stream reach dissimilarity in the Ouachita Mountains (18.59) is nearly double the maximum dissimilarity in the Boston Mountains (9.58) and about one-and-a-half times greater than in the Ozark Highlands (13.12). Maximum dissimilarity in the Ouachita Mountains centers on reach 165, which did not cluster with another reach after the best cut procedure was performed. Reach 165 is a low gradient (0.001) first-order stream that constitutes a drainage area of 3.10 km^2. The reach is extremely sinuous (3.04) and is 100 percent sand (D50 = 1.50). The extremes in sinuosity and particle-size make this reach much different from other reaches in the Ouachita Mountains. This is evident from the maximum dissimilarity comparisons in Table 4. 6. Multi-dimensional scaling portrays reach 165 as an outlier of the ecoregion (Figure 4.8). Five of the 10 comparisons of maximum dissimilarity are of similar size streams (i.e., first and second-order), which is not observed in the Boston Mountains or the Ozark Highlands.

Table 4.6.
Ten most dissimilar and similar reaches of the Ouachita Mountains. Dissimilarity of stream reaches is greatest in the Ouachita Mountains ecoregion.

Dissimilarity[a]	Comparison[b]	Comparison[b]	Similarity[a]
18.59	165 (1), 159 (4)	166 (2), 93 (2)	0.01
18.00	165 (1), 161 (4)	128 (1), 103 (3)	0.01
17.87	165 (1), 109 (3)	164 (1), 125 (1)	0.03
17.57	165 (1), 94 (2)	126 (1), 85 (1)	0.03
17.21	165 (1), 140 (2)	128 (1), 133 (2)	0.04
16.95	165 (1), 83 (1)	89 (1), 85 (1)	0.04
16.74	165 (1), 169 (4)	147 (3), 167 (3)	0.04
16.14	165 (1), 146 (3)	107 (3), 90 (2)	0.05
15.66	165 (1), 129 (1)	167 (3), 128 (1)	0.05
15.42	165 (1), 139 (2)	137 (2), 87 (1)	0.05

[a, b] See Table 4.2

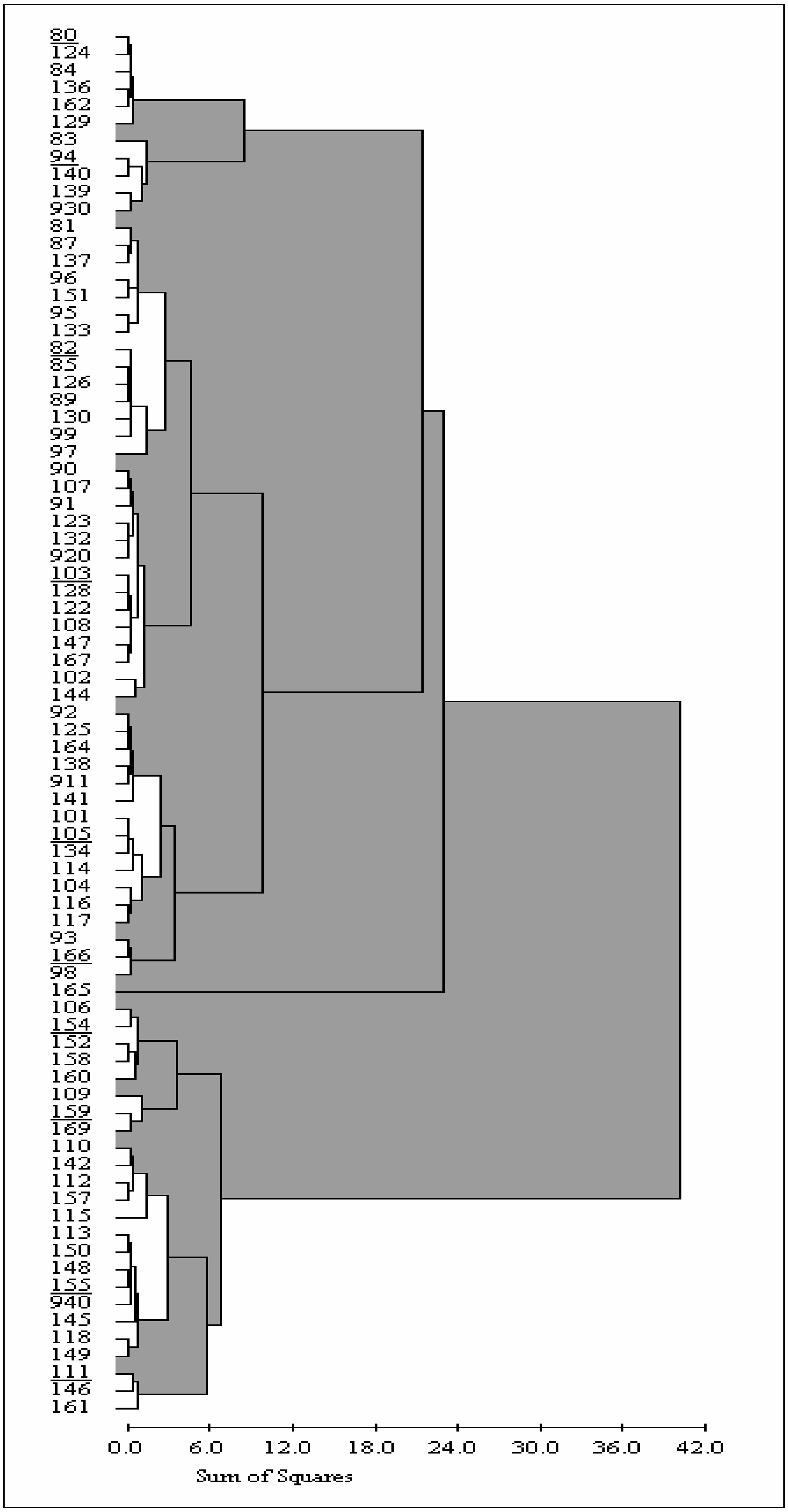

Fig. 4.7. Cluster grouping of Ouachita Mountain stream reaches. Eleven initial clusters (cluster 1 at top and progress accordingly to the bottom) were attained after a best cut significant test was performed on the data.

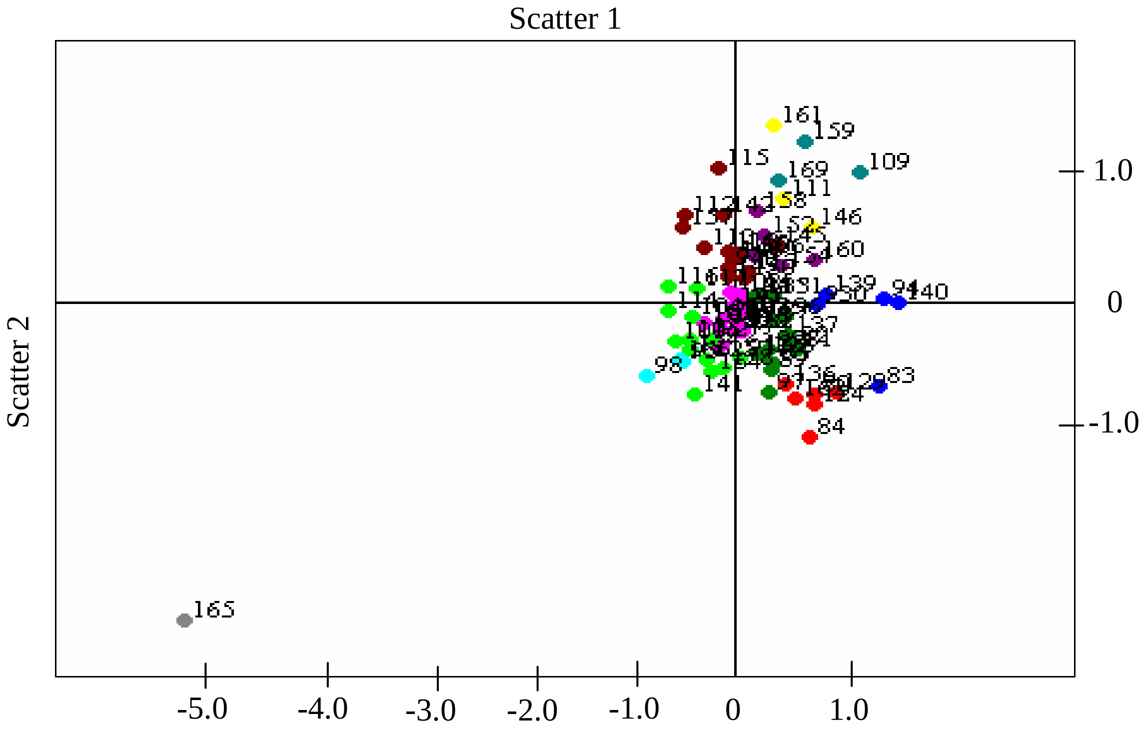

Fig. 4.8. Multi-dimensional scaling (MDS) of best cut clusters. The highest dissimilarity is noted by the distance two numbers (i.e., 165 and 159) are from each other. Reach 165 failed to initially cluster with any other reach. Reach 165 is much different from other Ouachita Mountain reaches. Minimum stress is 1.1905 percent.

5.5. *Clusters and dissimilarity of stream reaches: All ecoregions*

One hundred and forty-nine stream reaches were clustered and compared for dissimilarity upon removing ecoregion constraints. A total of 11,026 reach pair combinations were compared in the initial cluster. Thirteen clusters were recognized after a best cut significance test was performed on the data. No definite pattern exists within the clusters.

Stream reaches of different ecoregions cluster together in many instances (Fig. 4.9). Some clusters provide evidence, however, of ecoregions influencing the characteristics of stream reaches. Cluster 3 consists of eight stream reaches (1 Boston Mountain, 1 Ozark Highland, and 6 Ouachita Mountains) draining watershed areas less than 3.16 km/km^2. The reaches in the Boston Mountains and Ozark Highlands (1 and 44, respectively) are outliers within the respective ecoregions and occurs because of a relatively high gradient. These reaches cluster with the higher gradient streams of the Ouachita Mountains. Cluster 7 is comprised of 15 stream reaches (3 Boston Mountains and 12 Ouachita Mountains) of variable sizes (first- through fourth-order) that are clustered primarily by mid-to-high D50 particle-size. Stream reaches in the Boston Mountains have particle-sizes more similar to the Ouachita Mountains than the Ozark Highlands (Chapter 3). Cluster 10 consists of six Ouachita Mountain stream reaches with the highest D50 particle-sizes. Clusters with large D50 values do not include stream reaches from the Ozark Highlands. This is because Ozark Highland streams have much smaller D50 values than the Boston Mountains or the Ouachita Mountains (Chapter 3).

Cluster 12 consists of one third and ten fourth-order Boston Mountains and Ozark Highlands stream reaches. This cluster consists of stream reaches with wide bankfull widths, high width-depth ratios, and D50 values between 25-54 mm. Ouachita Mountain stream reaches fail to link with this cluster because of low width-depth ratios and large particle-sizes. The large particle-sizes of the Ouachita Mountains do not allow for the streams to downcut or laterally migrate, which decreases the width-depth ratio of streams in this region.

Four stream reaches failed to cluster with another when compared within their respective ecoregion. These reaches include 44, 46, 78, and 165. After being compared without ecoregion constraints, reaches 44 and 46 clustered with other stream reaches (Fig. 4.9). Reaches 78 and 165 have channel characteristics that are distinctly different from streams in this study and remained discrete reaches from the others surveyed.

Reach 78 is different from the others because of an extreme bankfull width (68.30 m) and a high width-depth ratio (96.87); while reach 165 has a sinuosity of 3.04 and consists of all sand substrate. Multidimensional scaling portrays these outliers graphically (Fig. 4.10).

The 10 greatest dissimilarities are linked to stream reaches 165 and 78, with the greatest dissimilarity (34.26) existing between these two reaches (Table 4.7). Four of the 10 greatest dissimilarities exist between stream reaches of the Ouachita Mountains. This shows that an extensive amount of dissimilarity exists between stream reaches in this region. Four dissimilarity comparisons exist between the Ozark Highlands and the Ouachita Mountains. A high amount of dissimilarity exists in stream channel morphology between the Ozark Highlands and Ouachita Mountains. Only one of the top 10 maximum dissimilarity comparisons involves the Boston Mountains and the Ozark Highlands. None of the top 10 dissimilarity comparisons includes the Boston Mountains and the Ouachita Mountains.

Table 4.7
Ten most dissimilar and similar reaches. Comparisons were without ecoregion constraints.

Dissimilarity[a]	Comparison[b]	Comparison[b]	Similarity[a]
34.26	165 (1), 78 (4)	79 (4), 77 (4)	0.01
23.28	165 (1), 161 (4)	166 (2), 93 (2)	0.01
22.56	165 (1), 94 (2)	152 (4), 37 (4)	0.01
22.42	165 (1), 140 (2)	95 (2), 62 (3)	0.01
22.14	78 (4), 44 (1)	75 (4), 76 (4)	0.01
22.07	165 (1), 83 (1)	128 (1), 103 (3)	0.01
21.90	83 (1), 78 (4)	16 (2), 0 (1)	0.01
21.49	78 (4), 1 (1)	125 (1), 47 (1)	0.02
20.90	78 (4), 84 (1)	55 (2), 57 (2)	0.02
20.69	140 (2), 78 (4)	164 (1), 47 (1)	0.02

[a, b] See Table 4.2

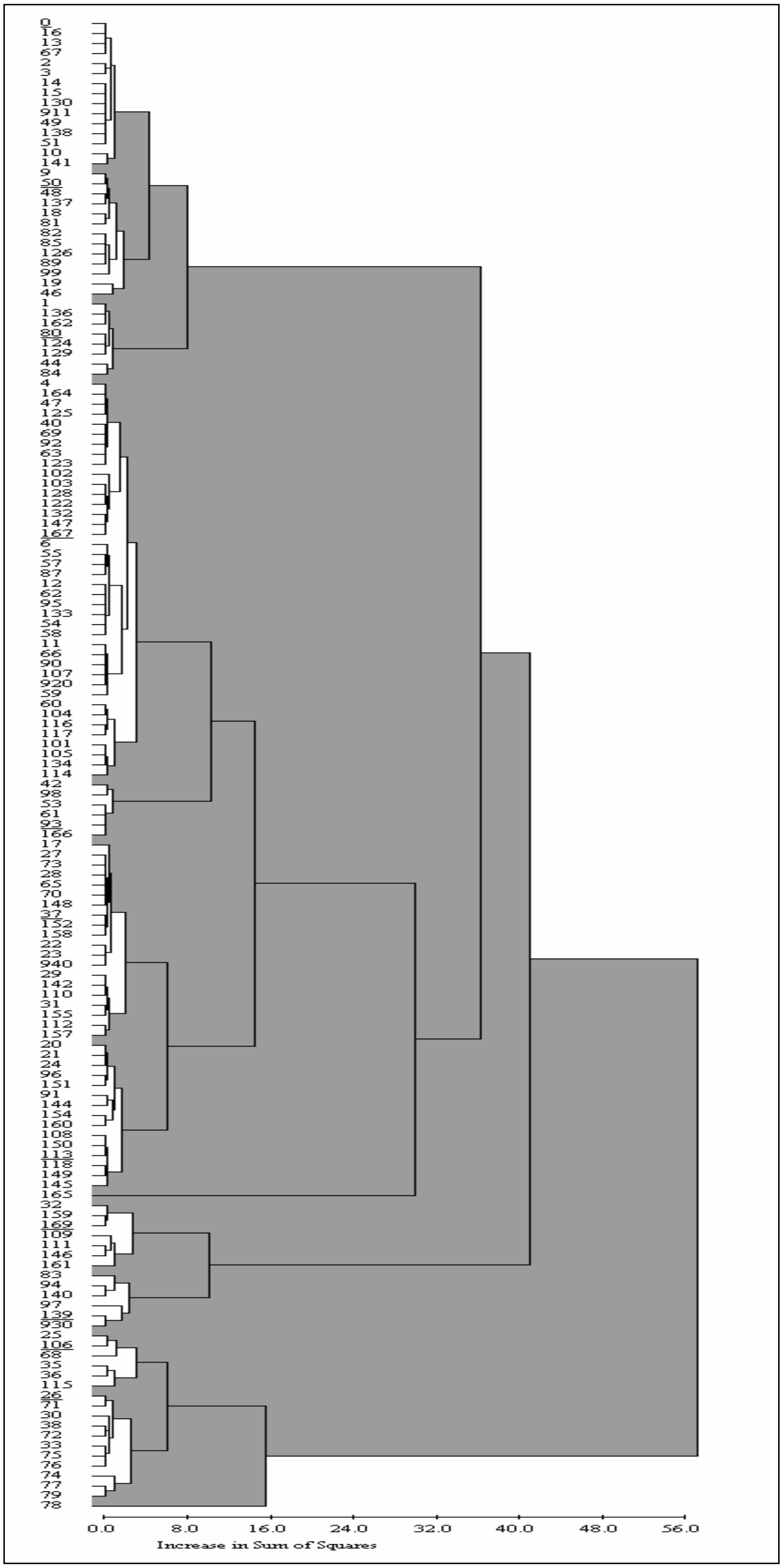

Fig. 4.9. Cluster grouping of all stream reaches. Thirteen initial clusters (cluster 1 at top and progress accordingly to the bottom) were attained after a best cut significant test was performed on the data.

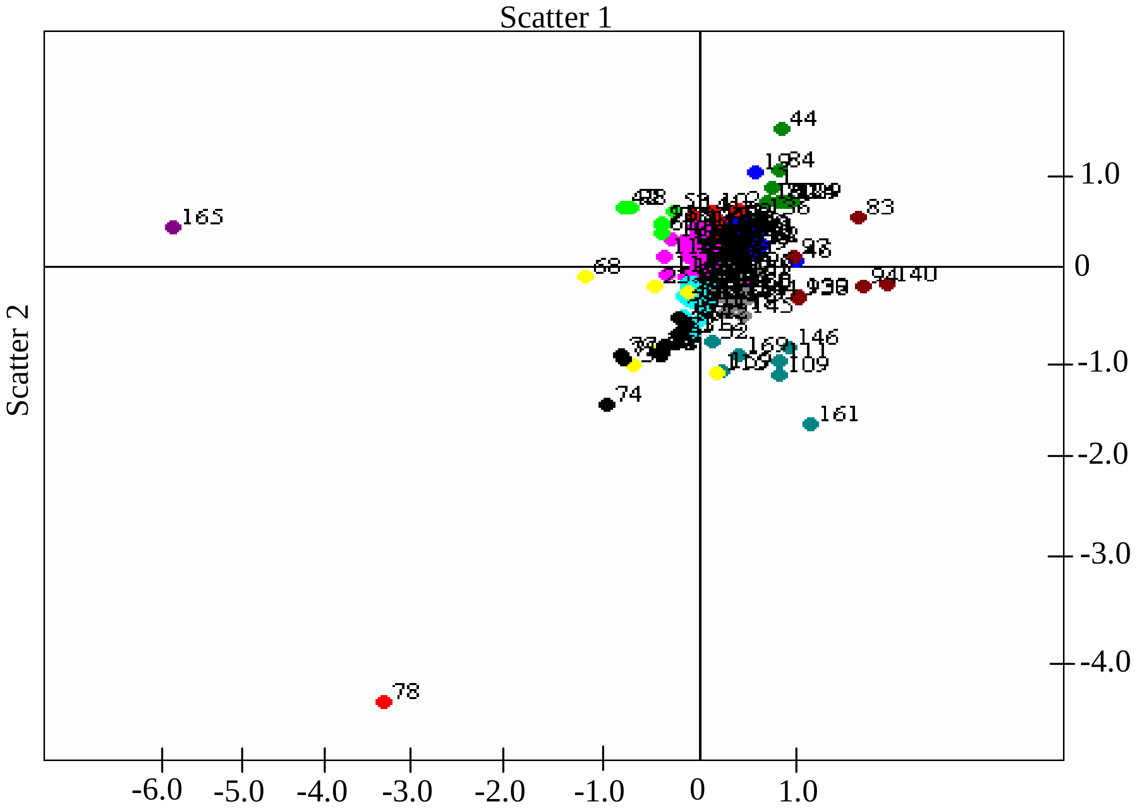

Fig. 4.10. Multi-dimensional scaling (MDS) of best cut clusters. Clusters are difficult to distinguish. Note that reaches 78 and 165, however, are the main outliers and fail to initially cluster with another reach. These two reaches have the greatest dissimilarity (34.2570) of all the reach comparisons. Minimum stress is 0.9067%.

5.6. Dissimilarity of watershed morphology: Boston Mountains

Thirty-one of the 34 watersheds delineated in the Boston Mountains were clustered by dissimilarity. Four watersheds could not be analyzed because they were not 90 percent confined to the Boston Mountains. Four hundred and sixty-five reach combinations were evaluated in the initial cluster. A four cluster partition was recognized after performing a best cut test on the data (Fig. 4.11). Exemplars are reported in Table 4.8. Multi-dimensional scaling presents clusters in a graphical format (Fig. 4.12). Clusters one and two consist of first and second-order watersheds. Cluster three consists of mostly third and fourth-order watersheds. Cluster four contains two large fourth-order watersheds (35 and 36) draining Lee Creek.

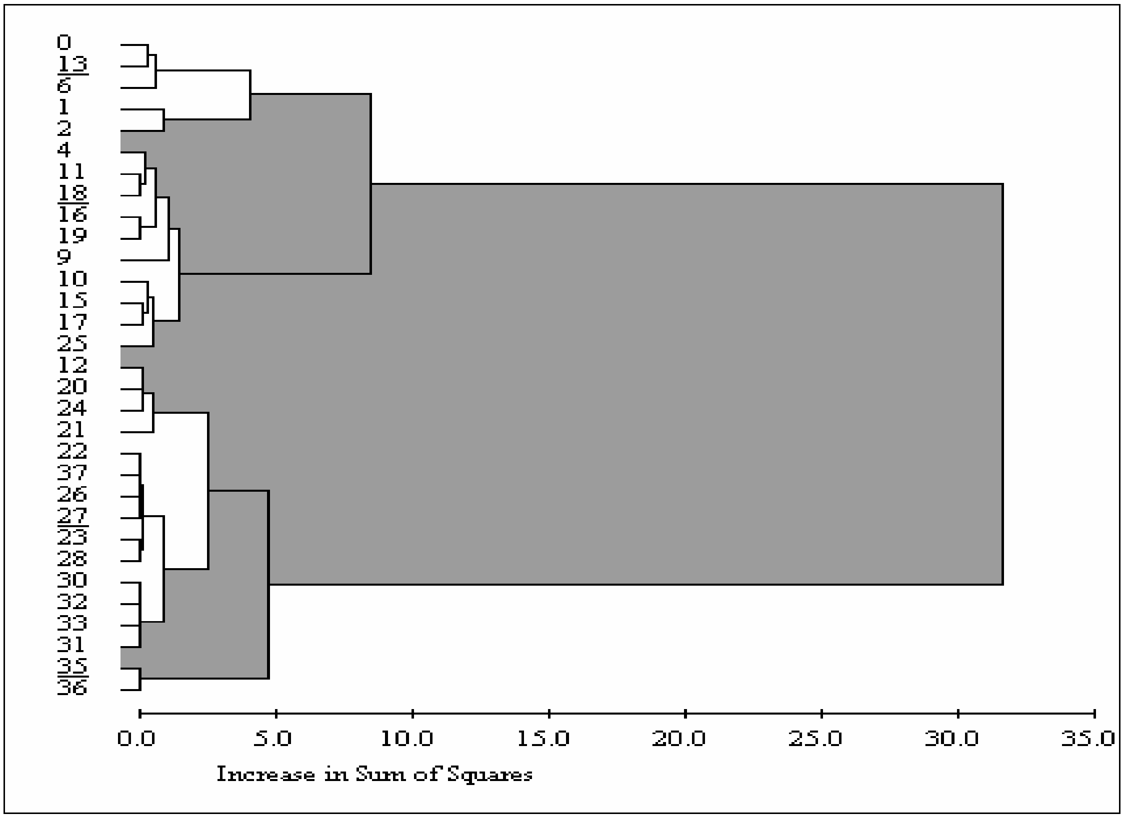

Fig. 4.11. Cluster grouping of Boston Mountain watersheds. Four initial clusters (cluster 1 at top and progress accordingly to bottom) were attained after a best cut significant test was performed on the data.

Table 4.8
Exemplar values for clusters of Boston Mountain watersheds. Exemplars have the most typical watershed morphology in each cluster.

Cluster[a]	DA (km^2)[b]	CR[c]	DD[d]	Relief (m)	RR[e]	Ruggedness[f]
1 (13)	4.21	0.580	0.37	193.68	0.084	0.072
2 (18)	5.25	0.548	0.53	139.81	0.035	0.074
3 (27)	88.24	0.373	0.62	302.52	0.017	0.189
4 (35)	587.46	0.257	0.64	485.38	0.007	0.310

[a] Number of cluster with exemplar for each cluster in (). Single cluster reaches assumes exemplar status; [b] Watershed area for exemplar only; [c] Circularity Ratio; [d] Drainage Density; [e] Relief Ratio; [f] Ruggedness Number

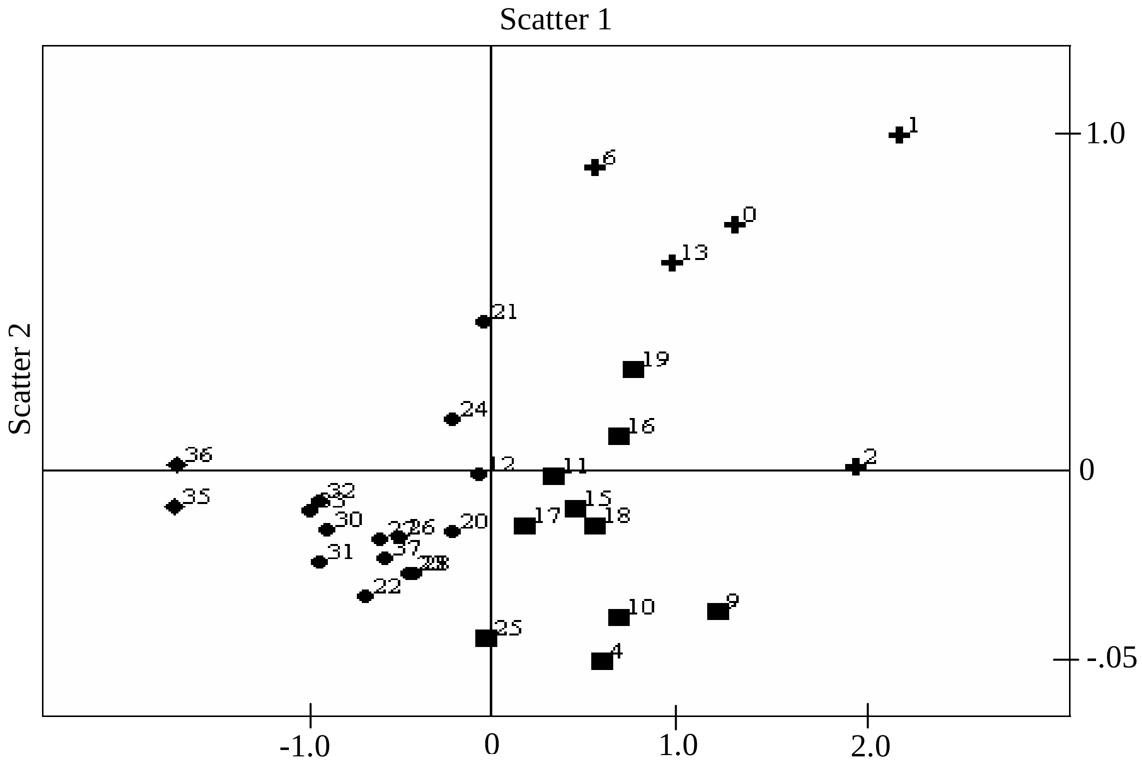

Fig. 4.12. Multi-dimensional scaling (MDS) of best cut clusters. Similar symbols represent the same cluster. The highest dissimilarity is noted by the distance two numbers (i.e., 1 and 35) are from each other. The more compact the cluster indicates a cluster more similar to all the watersheds. Minimum stress is 0.9124%.

The greatest amount of dissimilarity among watersheds involves comparisons between watersheds 1, 35, and 36 (Table 4.9). Reaches 1 and 35 were linked to the 10 most dissimilar reach pair comparisons in the Boston Mountains (Table 4.2). This demonstrates that reaches (1, 35) with the greatest amount of pairwise dissimilarity in the Boston Mountains are located in watersheds that have the greatest amount of morphometric dissimilarity. Watershed 1 drains a 1.20 km^2 area with an extremely low drainage density (0.001 km/km^2), low ruggedness number (0.001), low relief (82.61 m), and high relief ratio (0.106). Watershed 35 drains a 587.46 km^2 area with a low circularity ratio (0.257), high relief (485.38 m), and high ruggedness number (0.310).

Table 4.9
Ten most dissimilar and similar watersheds in the Boston Mountains.

Dissimilarity[a]	Comparison[b]	Comparison[b]	Similarity[a]
12.70	1 (1), 35 (4)	35 (4), 36 (4)	0.00
12.70	1 (1), 36 (4)	23 (3), 28 (3)	0.00
10.55	2 (1), 35 (4)	32 (4), 33 (4)	0.00
10.54	2 (1), 36 (4)	30 (4), 32 (4)	0.00
9.42	1 (1), 33 (4)	30 (3), 33 (4)	0.01
9.19	1 (1), 31 (4)	26 (3), 27 (3)	0.01
9.14	1 (1), 32 (4)	23 (2), 37 (4)	0.03
9.08	1 (1), 30 (4)	28 (3), 37 (4)	0.03
8.82	0 (1), 35 (4)	22 (3), 37 (4)	0.03
8.82	0 (1), 36 (4)	27 (4), 37 (4)	0.03

[a] The larger dissimilarity values link to the most unlike watersheds; [b] Number in () is the basin-order of the watershed comparison. Comparison on the right goes with similarity. Comparison on the left goes with dissimilarity.

The greatest amount of dissimilarity exists between first and fourth-order watersheds (Table 4.9). This occurs because the quantitative value associated with morphometric variables generally increase or decrease with watershed size (Horton, 1945, Strahler 1957). For example, drainage density increases with watershed size, while relief ratio decreases as drainage area increases (Chapter 2). The most similar watershed morphology exists in third and forth-order streams of the Boston Mountains. This occurs because the majority of third- and fourth-order stream reaches in this study drain the watersheds of Little Lee Creek, Sallisaw Creek, and Lee Creek. Morphologically these watersheds are nearly identical (Table 4.9). Multidimensional scaling portrays a relatively tight grouping among these morphologically identical watersheds (Fig. 4.12).

5.7. Dissimilarity of watershed morphology: Ozark Highlands

Twenty-five of the 34 watersheds delineated in the Ozark Highlands were clustered using overall dissimilarity (Fig. 4.13). Nine watersheds could not be analyzed because they were not 90 percent confined to the Ozark Highlands. Three hundred reach pair combinations were evaluated for the initial cluster. Four clusters were partitioned after a best cut test was conducted on the data. Exemplars are shown in Table 4.10. Multi-dimensional scaling presents clusters in a graphical format (Fig. 4.14). Clusters one and two consist of first and second-order watersheds; clusters three and four consist of third and fourth-order watersheds. First and second-order watersheds cluster with third and fourth-order watersheds (Fig 4.13).

Table 4.10
Exemplar values for clusters of Ozark Highland watersheds. Exemplars have the most typical watershed morphology in each cluster.

Cluster[a]	DA (km^2)[b]	CR[c]	DD[d]	Relief (m)	RR[e]	Ruggedness[f]
1 (48)	4.55	0.475	0.67	59.09	0.015	0.039
2 (44)	1.54	0.790	0.09	51.89	0.038	0.005
3 (53)	11.12	0.445	0.80	101.26	0.014	0.081
4 (79)	104.00	0.487	0.73	147.24	0.006	0.107

[a, b, c, d, e, f] See Table 4.8

The greatest pairwise dissimilarity constitutes comparisons involving either watershed 44 or 47 (Table 4.11). Watersheds 44 and 47 are low relief (51 and 54 meters, respectively) first-order watersheds, with small drainage densities (0.09 and 0.07 km/km^2, respectively). These watersheds are very dissimilar to fourth-order watersheds (Table 4.11). First and second-order watersheds cluster with third and fourth-order watersheds. Maximum comparisons of dissimilarity are less in the Ozark Highlands than the Boston Mountains. More dissimilarity of watershed morphology exists in the Boston Mountain than the Ozark Highlands. Watershed morphology in the Boston Mountains is more dissimilar than that of the Ozark Highlands because of a more complex and variable lithology that controls basin evolution and form.

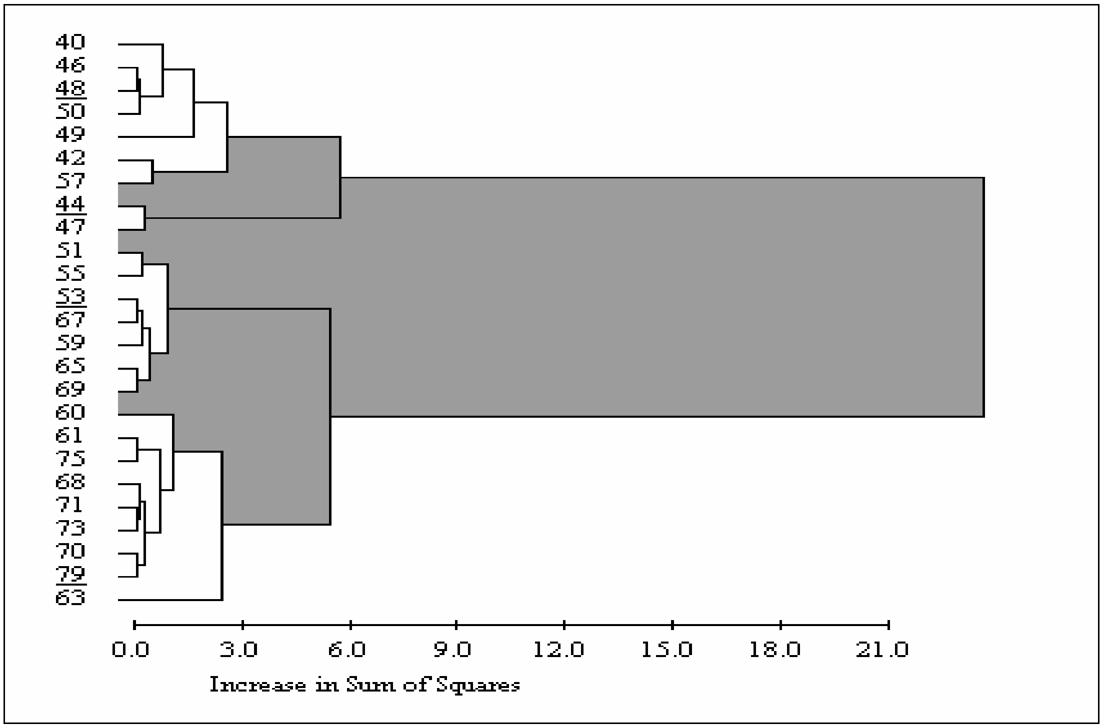

Fig. 4.13. Cluster grouping of Ozark Highland watersheds. Four initial clusters (cluster 1 at top and progress accordingly to bottom) were attained after a best cut significant test was performed on the data.

Table 4.11
Ten most dissimilar and similar watersheds in the Ozark Highlands.

Dissimilarity[a]	Comparison[b]	Comparison[b]	Similarity[a]
9.12	44 (1), 73 (4)	46 (1), 48 (1)	0.09
8.49	44 (1), 71 (4)	46 (1), 50 (2)	0.06
8.05	44 (1), 60 (3)	71 (4), 73 (4)	0.07
7.62	44 (1), 68 (4)	53 (3), 67 (4)	0.08
7.60	44 (1), 79 (4)	70 (4), 79 (4)	0.09
7.49	47 (1), 73 (4)	65 (3), 69 (3)	0.10
6.94	44 (1), 75 (4)	75 (4), 79 (4)	0.11
6.77	44 (1), 70 (4)	73 (4), 79 (4)	0.11
6.76	47 (1), 71 (4)	61 (3), 75 (4)	0.11
6.72	49 (1), 60 (3)	68 (3), 79 (4)	0.11

[a,b] See Table 4.9

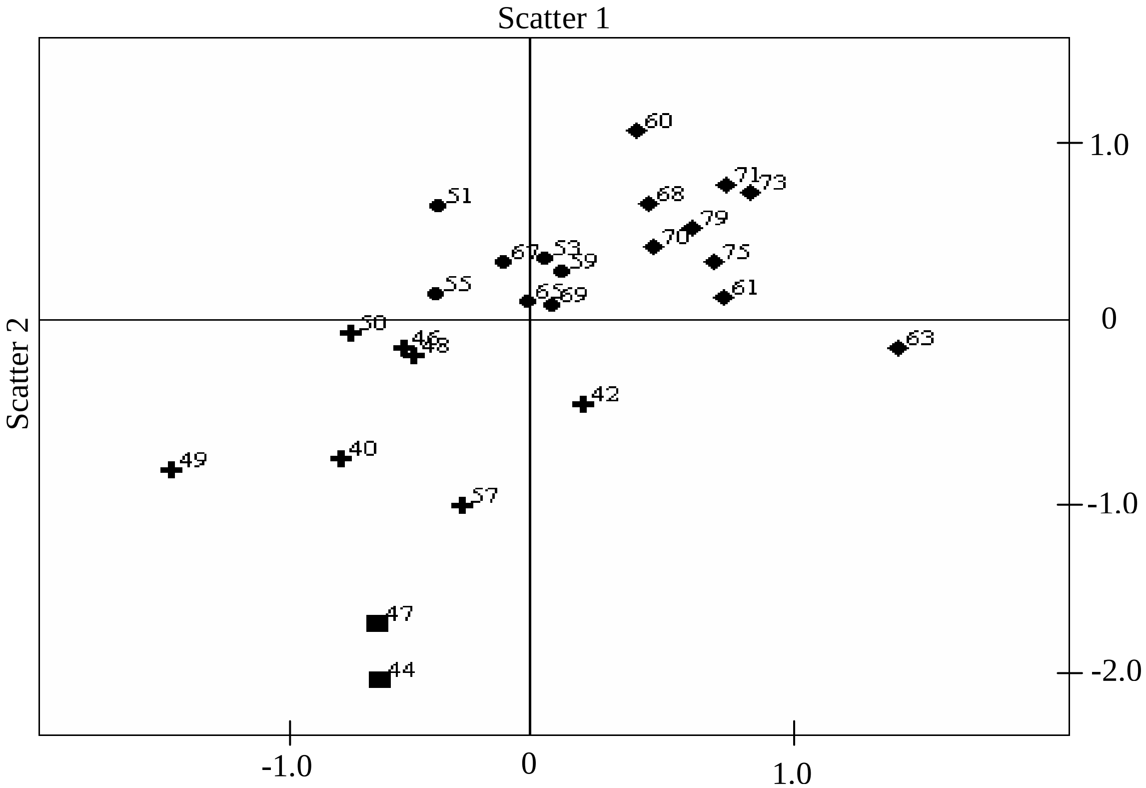

Fig. 4.14. Multi-dimensional scaling (MDS) of best cut clusters. Similar symbols represent the same cluster. The highest dissimilarity is noted by the distance two numbers (i.e., 44 and 73) are from each other. The more compact the cluster indicates a cluster more similar to all the watersheds. Minimum stress is 1.2978%.

5.8. Dissimilarity of watershed morphology: Ouachita Mountains

Seventy-eight of 80 watersheds delineated in the Ouachita Mountains were clustered according to dissimilarity. Two watersheds could not be analyzed because they were not 90 percent confined to the Ouachita Mountains. Three thousand and three reach combinations were evaluated in the initial cluster. An eight cluster partition was recognized after constructing a best cut fit test on the data (Fig. 4.15). Exemplars are given in Table 4.12. Multi-dimensional scaling presents clusters in a graphical format (Fig. 4.16).

Table 4.12
Exemplar values for clusters of Ouachita Mountain watersheds. Exemplars have the most typical watershed morphology in each cluster.

Cluster[a]	DA (km^2)[b]	CR[c]	DD[d]	Relief (m)	RR[e]	Ruggedness[f]
1 (84)	1.23	0.678	0.07	209.76	0.122	0.014
2 (89)	2.57	0.584	0.39	159.87	0.058	0.062
3 (82)	5.52	0.579	0.61	109.04	0.022	0.067
4 (92)	16.38	0.157	0.65	130.15	0.018	0.085
5 (101)	34.26	0.369	0.92	208.24	0.012	0.192
6 (159)	228.24	0.368	0.76	342.69	0.012	0.262
7 (160)	68.95	0.492	0.72	335.73	0.022	0.242
8 (154)	132.88	0.351	0.65	515.44	0.018	0.336

[a, b, c, d, e, f] See Table 4.8

Dissimilarity of watershed morphology in the Ouachita Mountains greatly exceeds that of the Boston Mountains or Ozark Highlands. The greatest amount of dissimilarity constitutes comparisons involving watersheds 162 and 93. The first and second-order watersheds, respectively, have the greatest pairwise dissimilarity of all the watersheds in the Ouachita Mountains (Table 4.13). Maximum dissimilarity of watershed morphology in the Boston Mountains and the Ozark Highlands involves comparisons between first and fourth-order basins, which is expected. Studies show that as watershed size gets larger, so to does the quantitative values between the watersheds (Horton, 1945, Strahler, 1957). It is generally expected that watersheds of contrasting sizes (i.e., first and fourth-order basins) should be more dissimilar in morphometric variables than similar size watersheds; this does not occur the Ouachita Mountains.

Watershed 162 constitutes a first-order basin draining an area of 1.21 km^2, which consists of a low drainage density (0.021 km/km^2) and low ruggedness number (0.004). It has a high circularity ratio (0.782) and high relief ratio (0.132). Watershed 93 constitutes a second-order basin draining an area of 16.38 km^2. It has a high drainage density (0.978 km/km^2) and high ruggedness number (0.473). Watershed 93 has a low circularity ratio (0.157) and low relief ratio (0.028).

High values of dissimilarity values in watershed morphology suggest that a large amount of spatial complexity exists in basins of the Ouachita Mountains. This is evident by the large value of dissimilarity between small basins. Large values of dissimilarity occur in the Ouachita Mountain because the region encompasses more spatial area than the Boston Mountains or Ozark Highlands. Much of the Ouachita Mountains consist of high mountains while other locations consist of low hills (Woods et al., 2005). More topographic variability exists in the Ouachita Mountains than the Boston Mountains or the Ozark Highlands. The regional topography of the regions directly impacts watershed morphometry.

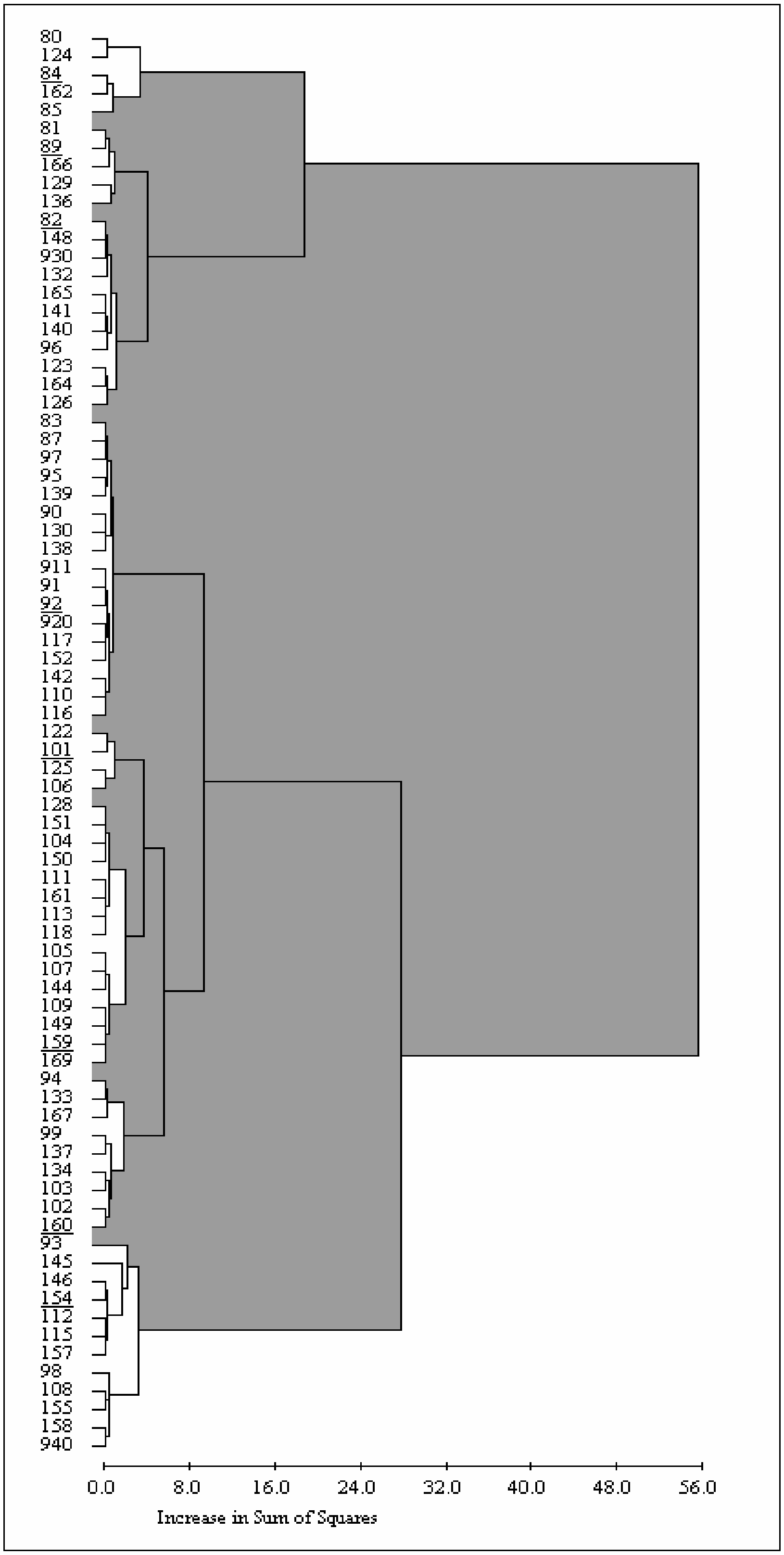

Fig. 4.15. Cluster grouping of Ouachita Mountains watersheds. Four initial clusters (cluster 1 at top and progress accordingly to bottom) were attained after a best cut significant test was performed on the data.

Table 4.13
Ten most dissimilar and similar watersheds in the Ouachita Mountains.

Dissimilarity[a]	Comparison[b]	Comparison[b]	Similarity[a]
17.63	93 (2), 162 (1)	117 (4), 152 (4)	0.00
14.84	93 (2), 84 (1)	123 (1), 162 (1)	0.01
14.04	93 (2), 85 (1)	159 (4), 169 (4)	0.01
13.87	125 (1), 162 (1)	111 (4), 161 (4)	0.01
13.45	157 (4), 162 (1)	112 (4), 115 (4)	0.02
13.08	112 (4), 162 (1)	90 (2), 130 (2)	0.02
12.50	106 (3), 162 (1)	116 (4), 110 (4)	0.02
12.32	115 (4), 162 (1)	148 (3), 930 (3)	0.02
11.59	109 (3), 162 (1)	113 (4), 161 (4)	0.03
11.48	101 (3), 162 (1)	109 (3), 169 (4)	0.03

[a, b] See Table 4.9

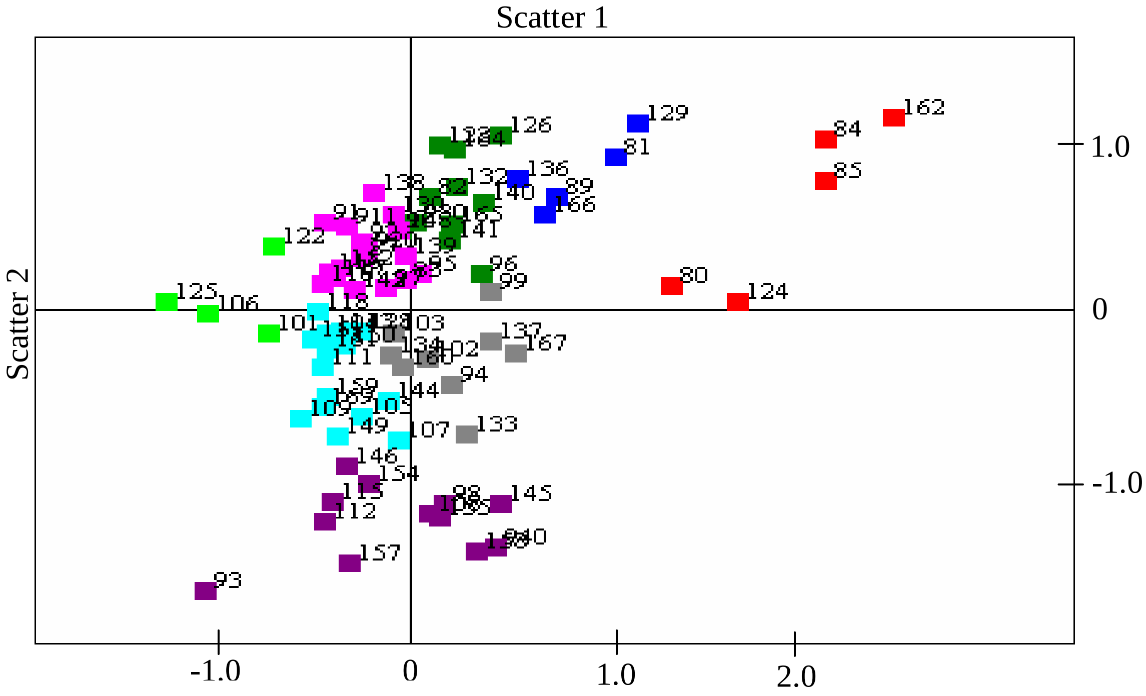

Fig. 4.16. Multi-dimensional scaling (MDS) of best cut clusters. Similar symbols represent the same cluster. The highest dissimilarity is noted by the distance two numbers (i.e., 93 and 162) are from each other. The more compact the cluster indicates a cluster more similar to all the watersheds. Minimum stress is 0.8099 %.

5.9. *Clusters and dissimilarity of watershed morphology: All ecoregions*

Watershed morphology was compared for 134 basins without ecoregion constraints. A total of 8,911 watershed combinations were compared in the initial cluster. Ten clusters were recognized after a best cut significance test was performed on the data. Two of the 10 clusters (three and 10) are comprised solely of Ouachita Mountain watersheds (Fig. 4.17). Cluster three is comprised of small watersheds (< 2 km/km^2) that have low relief and small drainage densities. Cluster 10 is comprised of watersheds draining areas between 20 to 136 km/km^2. These watersheds have high relief, intermediate drainage density, and high ruggedness numbers.

Four of the 10 clusters show watersheds of the Boston Mountains clustering with Ouachita Mountain watersheds. This occurs because watershed relief is similar in the two regions (Chapter 2). Watersheds of the Ozark Highlands cluster in only four of the 10 groupings. Sixty percent of those watersheds are in cluster six. Cluster six is comprised of 13 Ouachita Mountain and one Boston Mountain watersheds. The characteristics of cluster six are relatively low relief and low relief ratios.

Table 4.14
Ten most dissimilar and similar watersheds without ecoregion constraints.

Dissimilarity[a]	Comparison[b]	Comparison[b]	Similarity[a]
18.3478	93 (2), 162 (1)	35 (4), 36 (4)	0.0000
15.5521	93 (2), 84 (1)	23 (3), 28 (3)	0.0006
15.5172	93 (2), 1 (1)	32 (4), 33 (4)	0.0031
14.6105	93 (2), 85 (1)	75 (4), 152 (4)	0.0037
14.5902	157 (4), 162 (1)	30 (4), 32 (4)	0.0042
14.0445	112 (4), 162 (1)	117 (4), 152 (4)	0.0046
14.0271	93 (2), 2 (1)	30 (4), 33 (4)	0.0057
13.6822	93 (2), 44 (1)	42 (1), 130 (2)	0.0067
13.2046	115 (4), 162 (1)	75 (4), 117 (4)	0.0088
12.9507	93 (2), 47 (1)	46 (1), 50 (2)	0.0091

[a,b] See Table 4.9

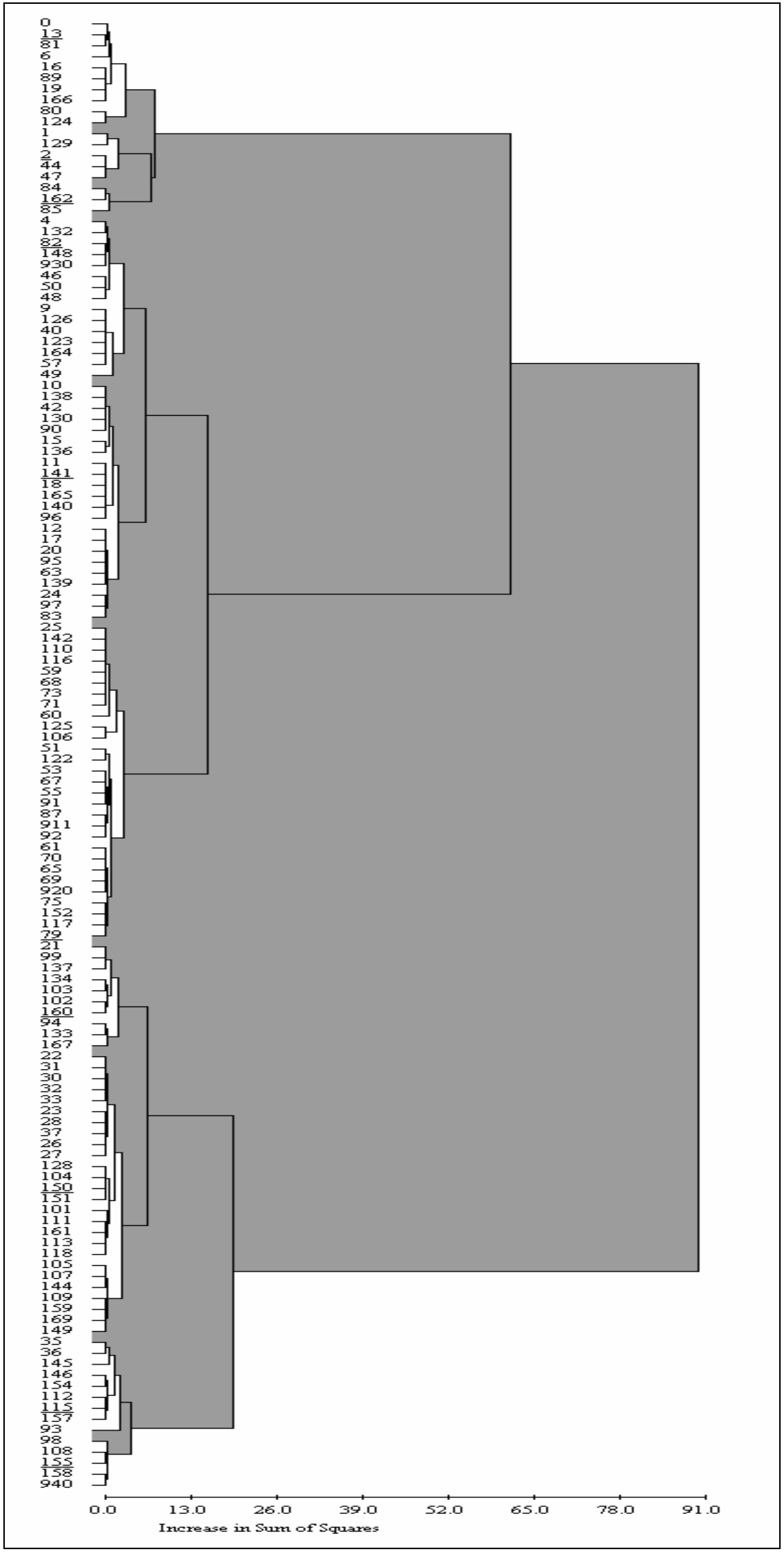

Fig. 4.17. Cluster grouping of watersheds. Ten initial clusters (cluster 1 at top and progress accordingly to bottom) were attained after a best cut significant test was performed on the data.

Maximum dissimilarity includes comparisons between watersheds 93 and 162 (Table 4.14). Seven of the 10 highest dissimilarity values involve comparisons between first and second-order watersheds. Three comparisons include watersheds of the Ouachita Mountains, two compare the Ouachita Mountains and the Boston Mountains, while another two compare the Ouachita Mountains and the Ozark Highlands. A large amount of dissimilarity exists between first and second-order watersheds in eastern Oklahoma. Five of the ten most similar watersheds involve basins of the Boston Mountains. This is because the comparisons occur in the same watershed, but farther downstream. Watershed selection was based on a randomly stratified site selection method within the ecoregions. Little can be inferred of the similarity comparisons.

6. Conclusion

The characteristics of streams vary spatially by watershed size, along their longitudinal profile, definable reach or segment, and channel units. Controls on watershed morphology and stream channel pattern are a function of ecoregion variables. It is important to understand how watershed morphology and stream channel pattern differ between and among ecoregions. This information is useful for understanding how dissimilar stream reaches and watersheds are within these homogenous regions. Ecoregions with less dissimilar stream reaches and watersheds provide evidence for less regional complexity. This information helps stream restoration professionals better understand the overall stream classification structure of stream reaches and watersheds on a regional basis.

Stream reach dissimilarity was evaluated using median particle-size, bankfull width, width-depth ratio, gradient, and sinuosity. In the Boston Mountains, thirty-five reaches were compared and clustered using overall dissimilarity. Five initial clusters were constructed after performing a best cut test on the data. Thirty-four reaches in the Ozark Highlands were compared and clustered. Six initial clusters were constructed after performing a best cut test on the data. Eighty reaches in the Ouachita Mountains were compared and clustered by dissimilarity. Eleven initial clusters were constructed after performing a best cut test on the data. The highest stream reach dissimilarity occurred in the Ouachita Mountains (18.59), which was followed by the Ozark Highlands (13.12) and Boston Mountains (9.58), respectively.

Each region had one or more reaches that were distinctly different from the others, which lead to the highest dissimilarity comparisons. The Ouachita Mountains ecoregion has the greatest contrast in stream reach characteristics. This can be attributed to the complex landscape of high mountains and low hills that streams traverse through. The Ouachita Mountains ecoregion is much larger than either the Boston Mountains or Ozark Highlands and has a larger opportunity of regional complexity based on size alone. The least amount of dissimilarity in stream reaches occurs in the Boston Mountains. This region is less physically complex and smaller than either the Ozark Highlands or Ouachita Mountains in Oklahoma (Woods et al., 2005).

Dissimilarity comparisons were conducted after removing ecoregion constraints. One hundred forty-nine reaches were compared. Thirteen clusters were recognized after a best cut test was performed on the data. Most of the clusters show stream reaches clustering from different regions. In some instances the reach extremes from one region will cluster with multiple reaches of a single ecoregion. When ecoregion constraints are removed, stream reaches of different ecoregions will cluster together. This implies that stream reaches sometimes cluster better out of an ecoregion and into adjacent ecoregions. Removing ecoregion constraints, however, drastically increased maximum dissimilarity from 18.59 in the Ouachita Mountains to 34.26. The increase comes from the comparison between reaches 78 (Ozark Highlands) and 165 (Ouachita Mountains). This increase in dissimilarity provides evidence for studying the morphology of stream reaches by ecoregion.

Watershed dissimilarity was evaluated using drainage density, circularity ratio, relief, relief ratio, and ruggedness number. Thirty-one watersheds in the Boston Mountains were clustered using dissimilarity. Four clusters were initially constructed after performing a best cut test on the data. Twenty-five watersheds in the Ozark Highlands were clustered, with four clusters constructed after the best cut test. Seventy-eight watersheds were clustered in the Ouachita Mountains. An eight cluster partition was recognized in this region. In most instances smaller watersheds tend to cluster progressively with larger watersheds. The greatest amount of dissimilarity occurs in the Ouachita Mountains (17.63), which is followed by the Boston Mountains (12.70) and Ozark Highlands (9.12).

Maximum dissimilarity of watersheds in the Ouachita Mountains involves comparisons of similar size watersheds. In the Boston Mountains and Ozark Highlands the most dissimilar watersheds compared first-order watersheds to fourth-order watersheds. This implies that the morphology in small basin (i.e., first and second-order) is distinctly different throughout the Ouachita Mountains ecoregion. Highly dissimilar watersheds in the Ouachita Mountains did not lead to high dissimilarity of reaches. This is probably because stream reaches in the Ouachita Mountains are more influenced by local structural geology (i.e., particle-size, bedrock, outcrops) than morphometric variables. In the Boston Mountains and Ozark Highlands a pattern between maximum dissimilarity of watersheds and stream reach dissimilarity is noted. In these two regions, morphometric variables probably influence the morphology of stream reaches more than in the Ouachita Mountains.

Quantification of reach and watershed dissimilarity by ecoregion provides an opportunity to evaluate whether classifying and managing streams is possible at a large-scale. Stream reaches and watershed morphology clustered within the respective ecoregions provides evidence for characteristics that are atypical. Identifying atypical reaches and watersheds helps in stream restoration activities and watershed management. Establishing reference conditions for stream management should begin with exemplars of clusters. Variability exists in all stream systems. The goal of stream reach and watershed management is to better understand how much variability exists in these dynamic systems. Once the regional variability of stream reaches and watersheds has been quantified, management planning of these resources can begin. Ecoregions provide a useful large-scale framework by which to understand the variable nature of stream reaches and watersheds.

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Appendix

[a] Represents the randomly selected stream reaches that were surveyed in this study. Numbers are not in sequential order because some reaches were not surveyed due to primary disturbance. Sites were randomly selected and assigned a different number.

[b] Reach name is included to help assign a geographic location to the stream. Reach names were selected using the Oklahoma Gazetteer. In some instances reach name and stream name is identical.

[c] Stream name is often unnamed in headwater reaches. In some instances headwater reaches were unnamed but confluence into a named stream.

[d] Date when survey of stream reach began.

Ecoregion	Site[a]	Reach Name[b]	Stream Name[c]	Date[d]
Boston	0	Cherry Tree	Unnamed	7-16-04
Mountains	1	Tully Hollow	Unnamed	5-23-03
	2	Unnamed	Unnamed	7-14-04
	3	Coon Mountain	Unnamed	6-28-04
	4	Murrel Home	Unnamed	6-18-03
	6	Cookson WMA	Unnamed	6-29-04
	9	Piney	Unnamed	6-27-04
	10	Kirk Springs Hollow	Kirk Spring Creek	6-20-03
	11	Smith Hollow	Smith Hollow Creek	7-18-04
	12	Sally Bull Hollow	Unnamed	6-16-04
	13	East Jackson Mountain	Unnamed	7-19-04
	14	Blanch	Unnamed	6-28-04
	15	Rocky Mountain School	Unnamed	7-17-04
	16	Brushy Mountain	Unnamed	6-15-04
	17	Rocky Mountain	Unnamed	7-18-04
	18	Telamay Hollow	Unnamed	5-28-03
	19	Elk Creek	Elk Creek	6-14-04
	20	Jenkins Creek	Jenkins Creek	6-19-04
	21	Sonny Gile Hollow	Unnamed	6-18-04
	22	Evansville Creek	Evansville Creek	5-25-04
	23	Bunch	Sallisaw Creek	6-14-04
	24	Little Britches Creek	Little Britches Creek	6-17-04
	25	Pumpkin Hollow	Unnamed	5-22-03
	26	Bell	Little Lee Creek	6-10-04
	27	Stuart Mountain	Little Lee Creek	6-09-04
	28	Lead Min	Sallisaw Creek	6-19-03
	29	Powerline	Caney Creek	6-17-03
	30	Glass Hollow	Little Lee Creek	5-26-04
	31	Little Lee Creek	Little Lee Creek	5-25-04
	32	Copic Slab	Little Lee Creel	5-26-04

Ecoregion	Site[a]	Reach Name[b]	Stream Name[c]	Date[d]
	33	Nicut	Little Lee Creek	6-17-04
	35	Arkansas Border	Lee Creek	8-03-05
	36	Arkansas Border	Lee Creek	8-03-05
	37	D4642 Rd	Sallisaw Creek	8-02-05
	38	Tenkiller Confluence	Caney Creek	5-12-03
Ozark Highlands	40	New Eucha	Unnamed	6-20-04
	42	Choleta	Unnamed	6-25-04
	44	Woodward Hollow	Unnamed	6-25-04
	46	Peoria	Trib to Warren Bran	8-01-05
	47	Wyandotte	Trib to Lost Creek	7-09-04
	48	Westville	Unnamed	6-27-03
	49	Yankee Bill Prairie	Trib to Lost Creek	7-08-04
	50	E0373 Rd	Whitewater Creek	8-01-05
	51	Rose	Wickliffe Creek	6-27-04
	53	Kenwood	Unnamed	6-26-04
	54	Saline Confluence	Wickliffe Creek	6-01-04
	55	N4697 Rd	Trib to Elk River	8-01-05
	57	Chewey	Unnamed	5-27-03
	58	Black Fox Hollow	Trib to Illinois River	7-19-04
	59	Teesquatnee	Unnamed	6-07-07
	60	Honey Creek Cove	Whitewater Creek	6-03-04
	61	Baron Fork Confluence	Shell Branch Creek	5-24-04
	62	Big Acorn Hollow	Saline Creek	6-01-04
	63	Scraper Hollow	Unnamed	6-27-03
	65	Beaty Creek	Beaty Creek	6-06-04
	66	Little Saline Creek	Little Saline Creek	5-27-04
	67	Jaybird Creek	Jaybird Creek	6-27-04
	68	Upper Honey Creek	Honey Creek	6-03-04
	69	D0410 Rd	Trib to Grand Lake	7-10-04
	70	Lost Creek	Lost Creek	6-04-04

Ecoregion	Site[a]	Reach Name[b]	Stream Name[c]	Date[d]
	71	Elk River Confluence	Buffalo Creek	6-05-04
	72	Spavinaw Lake Confl	Spavinaw Creek	6-02-04
	73	Lower Honey Creek	Honey Creek	6-26-04
	74	Christie	Baron Fork Creek	6-25-03
	75	Peacheater Creek	Peacheater Creek	5-26-03
	76	Grand Lake	Saline Creek	5-31-04
	77	Flint Creek	Flint Creek	5-12-04
	78	Addielee	Baron Fork Creek	5-23-04
	79	Tyner Creek	Tyner Creek	5-25-03
Ouachita Mountains	80	CR 1725	Trib to Hurricane Cr	7-26-04
	81	Shawnee Ridges	Trib to Black -Poteau	7-25-04
	82	Peacock Hollow	Trib to Potapo Creek	8-07-04
	83	Smith Ridge	Trib to Honobia Cr	7-25-04
	84	K Trail	Trib to Black Fork Cr	8-06-04
	85	Round Top Mountain	Trib to Long Creek	5-22-05
	87	Devils Backbone	Trib to S. Holly Cr	8-05-04
	89	New State Mountain	Trib to Brushy Creek	5-17-05
	90	4190 Rd	Unnamed	8-07-04
	91	Kennedy Hollow	Trib to Potapo Creek	6-27-05
	92	Ti Valley	Unnamed	6-04-03
	93	E1630 Rd	Trib to Kiamichi R	6-18-05
	94	Upper Rock Creek	Rock Creek	6-07-05
	95	271 Bridge	Cedar Creek	5-20-04
	96	Clayton Creek	Unnamed	5-17-05
	97	County Line	Middle Terrapin Cr	6-13-05
	98	Forrester	Sugar Creek	6-17-05
	99	Spring Mountain	East Fork Glover R	7-27-04
	101	Goss	Fobb Creek	6-01-03
	102	Watson Creek	Watson Creek	5-15-04
	103	Upper Big Eagle Trib	Trib to Big Eagle Cr	6-06-05

Ecoregion	Site[a]	Reach Name[b]	Stream Name[c]	Date[d]
	104	Weathers	Buck Creek	6-03-03
	105	CR E1590	Buzzard Creek	6-18-05
	106	Blackjack Mountain	Cloudy Creek	8-04-04
	107	Talihina WWTP	Rock Creek	6-07-05
	108	CR 1510	Holson Creek	5-20-04
	109	Honobia Powerline	Black Fork Little R	5-18-04
	110	North Redden	McGee Creek	6-02-03
	111	Mountain Fork Confluen	Buffalo Creek	7-01-03
	112	East Nashoba	Little River	5-19-04
	113	Plunketville	Buffalo Creek	8-06-04
	114	Hwy 2	Tenmile Creek	6-26-05
	115	Fewell	Little River	5-16-04
	116	Wesley	MeGee Creek	7-14-05
	117	Stringtown	Chickasaw Creek	6-26-05
	118	Cloudy Road	Cloudy Creek	8-05-04
	122	Atoka WMA	Trib to Chickasaw Cr	5-18-05
	123	Sunshine Hollow	Trib to Cedar Creek	5-15-05
	124	Short Hollow	Trib to Conser Creek	5-21-05
	125	Rattan Trail	Cloudy Creek	5-15-05
	126	Zafra	Trib to Mountain Fk	5-20-05
	128	Page	Trib to Big Creek	6-16-05
	129	Nolia Trail	Trib to Watson Creek	5-19-05
	130	Taberville	Luksuklo Creek	6-15-05
	132	Limestone Ridge	Pigeon Creek	6-07-05
	133	CR E1380	Gap Creek	6-22-05
	134	Lenox	Trib to Kiamichi R	6-24-05
	136	Pickens Creek Trail	Pickens Creek	6-03-05
	137	SE Corner Pittsbu Coun	Rock Creek	6-12-05
	138	Cloudy Road	Trib to Cloudy Creek	6-14-05
	139	Clealik Road	East Terrapin Creek	6-05-05

Ecoregion	Site[a]	Reach Name[b]	Stream Name[c]	Date[d]
	140	Flagpole Road	Crumb Creek	6-02-05
	141	Whitesboro	Trib to Kiamichi R	6-23-05
	142	Haw	Haw Creek	7-11-05
	144	Smithville	Hurricane Creek	6-14-05
	145	Blackfork Wilderness	Big Creek	6-17-05
	146	Honobia	Honobia Creek	6-03-05
	147	Yourman WMA	North Gaines Creek	6-24-05
	148	Hwy 43	Breadtown Creek	6-28-05
	149	Honobia Confluence	Little River	6-04-05
	150	County Line	Terrapin Creek	6-14-05
	151	Sulphur Springs	Cedar Creek	6-02-05
	152	Hwy 43	Chickasaw Creek	6-27-05
	154	Hwy 144	Big Eagle Creek	6-04-05
	155	Moyers	Black Fk Poteau R	6-23-05
	157	Whitesboro Bridge	Kiamichi Creek	7-12-05
	158	Monroe	Sugarloaf Creek	6-23-05
	159	Cabins	West Fork Glover R.	7-09-05
	160	Lower Big Eagle Trib	Trib to Big Eagle Cr	6-06-05
	161	Buffalo	Buffalo Creek	6-16-05
	162	Big Cedar	Unsure	7-10-05
	164	Smithville	Trib to Big Eagle Cr	7-10-05
	165	E1680 Rd	Buck Creek	7-13-05
	166	Adel	Unsure	7-13-05
	167	Boardstand Flat	Unsure	7-12-05
	169	Powerline	West Fork Glover R.	7-09-05
	911	Signal Creek	Unsure	7-08-05
	920	Limestone Ridge	Unsure	7-12-05
	930	Jumbo	Clear Creek	7-13-05
	940	Monroe	Sugarloaf Creek	7-11-05

CHAPTER 5

CLASSIFYING STREAM CHANNELS IN EASTERN OKLAHOMA ECOREGIONS

Abstract

Classifications provide a framework by which the fluvial system is organized. Regional classifications of stream reaches help correlate site specific morphology to non-surveyed locations, which is necessary when time-consuming and expensive field surveys are not possible. One hundred and forty-nine stream reaches were classified using the Rosgen system in the Boston Mountains, Ozark Highlands, and Ouachita Mountains. Surveys of stream reaches were conducted during the summers of 2003, 2004, and 2005. A chi-squared test for differences between the classifications by region and stream order was employed. No statistically significant associations exist between reach type and position in the watershed between ecoregions. The Boston Mountains and Ozark Highlands have nine and eight Level II types of streams, respectively. The most prominent type of stream in the Boston Mountains and Ozark Highlands is C4. These stream are slightly entrenched (>2.2) with moderate-to-high width-depth ratios (>12), contain a gravel substrate, and gradient between 0.001-0.02. The Ouachita Mountains have 20 Level II types of stream reaches. The most prominent type of stream in the Ouachita Mountains is C3. This type of stream has the same characteristics as C4 except the gravel substrate is replaced by cobbles. First and second-order streams in the Ouachita Mountains contain many different stream types that occur only once or twice. This was an anticipated considering the highly variable landscape topography within the Ouachita Mountains.

Key words: Stream Classification, Rosgen, Ecoregions, Oklahoma

1. Introduction

The classification of streams is not a recent development in geomorphology (Rosgen, 1994). One of the earliest non-process based classifications was based on stages of stream maturity (Davis, 1899). Research involving stream processes in the mid 20th century led to process-based stream classifications over the last few decades (Leopold and Wolman, 1957, Schumm, 1963, Schumm, 1981, Grant et al., 1990, Rosgen, 1996, Montgomery and Buffington, 1997). Stream classifications are important to geomorphologists because they structure data into groups, which provides for systematic organization. Classification schemes are named to define a unique set of characteristics that open communication between researchers (Kondolf et al., 2003, Schaetzl and Anderson, 2005). Statistical comparisons used in classifications help researchers interpret whether groups are significantly different from each other (Marston, 1982, Grant et al., 1990, Bledsoe and Watson, 2001). Differentiating the reasons why classified phenomena occurs leads to the development of different management strategies for the classified groups. For an expansive and through review of stream classifications see Kondolf et al. (2003).

The Rosgen (1996) stream reach classification is currently the most popular and widely used among government agencies (Kondolf et al., 2003). Objectives of the classification are to: (1) predict river response based on its morphology; (2) develop hydraulic and sediment relationships for stream types at a current condition; (3) extrapolate site-specific data to similar reaches; and (4) provide a classification that will facilitate communication between different disciplines (Rosgen, 1996). Rosgen states that these objectives can be attained by studying stream morphology in a hierarchical context.

The top rung of the fluvial hierarchy incorporates regional characteristics. Omernik (1987) recognizes that regional (i.e., ecoregion) delineations can be made by different associations of geology, climate, soils, land use, and potential natural vegetation. Frissell et al. (1986) documented that the fluvial hierarchy is nested within the regional or ecoregion delineation. Rosgen recognized that types of streams classified at the reach scale (Level I-II) are a product of the interconnectedness of regional characteristics, watersheds, and stream networks. Level I classifications recognize nine types of streams that are based on a generalized geomorphic characterization. Level II classifications recognizes 94 different types of stream reaches that are defined by differences in entrenchment ratio, width/depth ratio, sinuosity, gradient, and median particle-size.

A classification of stream reaches was conducted in three eastern Oklahoma ecoregions to establish whether Rosgen types of streams differed between the regions. The three ecoregions compared were: Boston Mountains, Ozark Highlands, and Ouachita Mountains. The ecoregions of Omernik were selected over all other regional classifications because they are designed to promote the research and assessment of ecosystems (Omernik et al., 2000). In addition, the inclusion of land use is seldom incorporated into regional classification. Stream surveys were conducted in the summers of 2003, 2004, and 2005.

The objectives of this study were to: (1) classify eastern Oklahoma stream reaches using the Rosgen classification; and (2) examine whether stream reach classifications were statistically significant between stream order and ecoregions. The Oklahoma Department of Wildlife Conservation (ODWC) uses the Rosgen classification system in stream management and restoration designs. Understanding the characteristics of stream channels flowing through eastern Oklahoma's most important and economically viable streams will provide the ODWC with a model of stream types indicative of each region.

2. Background and study area

The Ozark Highlands ecoregion exists in parts of Kansas, Missouri, Arkansas, and Oklahoma. In Oklahoma, this ecoregion encompasses 2,795 km^2 (Fig. 5.1). Woods et al. (2005) describes the region as being comprised of watersheds that are highly-to-moderately dissected. Lithology is mostly Mississippian-aged limestone with interbedded chert. Mean annual precipitation is approximately 100-125 cm. Land use includes grazing, logging, poultry and livestock farming, and quarrying. Potential natural vegetation includes mainly oak-hickory forest and grassland. Soils orders on uplands consist of Ultisols, Alfisols, and Mollisols. Common soil series include Clarksville and Noark (Carter, 1997). Much of the native forest and prairie was removed during the logging boom at the turn of the 20th century.

Evidence exists that logging, grazing, and the removal of riparian vegetation in the Ozark Highlands of Missouri has disturbed watershed morphology, which in-turn has disturbed stream processes that influence reach morphology and channel unit formation (Jacobson, 1995). Commercial logging between 1880 and 1920 and non-conservation agricultural practices and grazing influenced stream disturbance between 1920 and 1960 (Jacobson, 1995, Jacobson and Primm, 1997). Jacobson and Primm (1997) proposed that land use disturbances caused streams to migrate headward and create a more elaborate stream network. This has lead to an increased amount of gravel delivered to low-order streams (Jacobson, 1995, Jacobson and Primm, 1997, Jacobson and Gran, 1999). Implications of sediment routing from headwater streams to lower order streams includes aggradation of the channel, increased amounts of channel bars, lateral migration of stream banks, and pools infilling with sediment (Jacobson, 1995, Jacobson and Primm, 1997). All of which have lead to changes in stream-ecosystem function.

The Boston Mountains are south of the Ozark Highlands (Fig. 5.1). The Boston Mountains have been mapped as part of the Ozark Highlands (Fenneman, 1938). Based on their less dissected appearance and lithologic differences the Boston Mountains are physically different from the Ozark Highlands. Lithology includes Pennsylvanian-age sandstone, with minor amounts of Pennsylvanian and Mississippian-age limestone and shale. Mean annual precipitation is approximately 110-130 cm. Land use consists of forest and woodland, with flatter areas used for ranching and farming. The potential natural vegetation includes mostly oak-hickory forest (Woods et al., 2005). Soils orders on uplands consist of Ultisols, Inceptisols, and Entisols. Common soil series include Hector and Linker (Carter 1997).

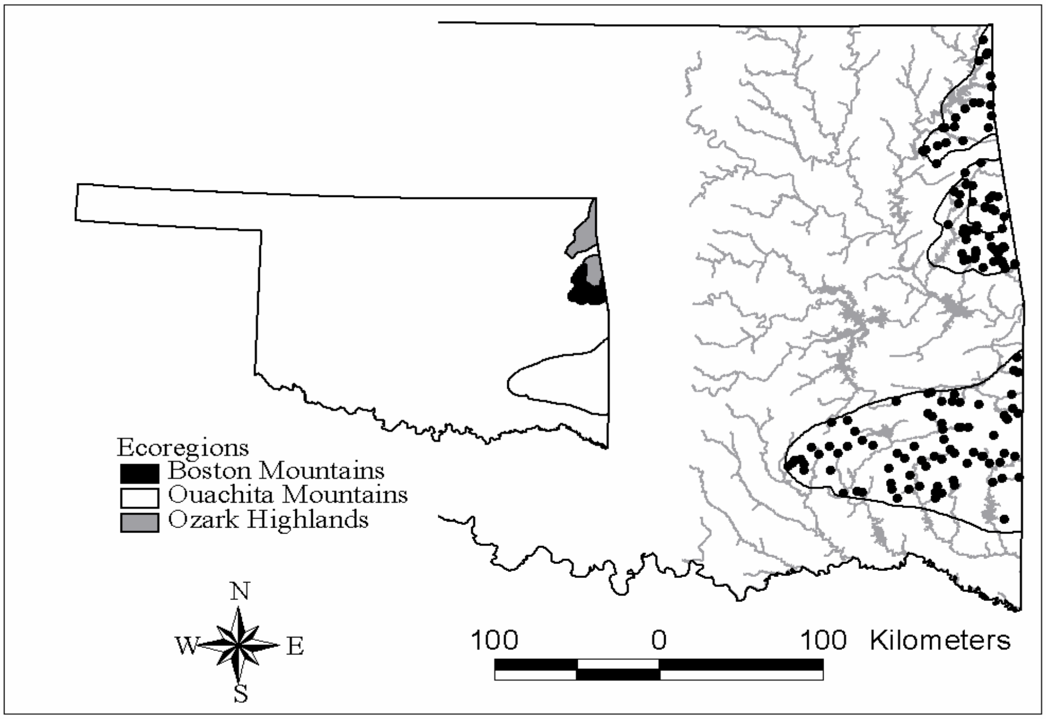

Fig. 5.1. Black dots represent study sites of first through fourth order streams that were investigated to determine the characteristics of eastern Oklahoma streams.

Less is known about the characteristics of stream channels in the Boston Mountains than the Ozark Highlands. An open-file report by Femmer (1997) describes streams in the Boston Mountains with high gradients, variable particle-size and flow regimes, and little in-stream cover. Streamflow is a function of rainfall. Few springs exist and during summer dry months streams become intermittent due to a lack of rainfall. Basin relief and channel gradient is greater in the Boston Mountains than the Ozark Highlands (Femmer, 1997). Nickolotsky and Pavlowsky (In Review) studied the character of step-pools in a second-order headwater stream in Arkansas and report that the reach is influenced by colluvial blocks and large particle-sizes.

The Ouachita Mountains are south of the Boston Mountains and are separated by the Arkansas Valley ecoregion (Fig. 5.1). In Oklahoma, this ecoregion encompasses

$10{,}107\ km^2$. The region tends to be a mosaic of low mountains and high hills of folded Paleozoic rocks. Lithology varies throughout the ecoregion, including sandstone, shale, and novaculite. Maximum mean annual precipitation occurs on south-facing ridges, decreases to the east, and is 110-145 cm. Land use includes forestry, logging, ranching, woodland grazing, and recreation. The potential natural vegetation includes oak-hickory-pine forest (Woods et al., 2005). Soils orders consist of Ultisols, Alfisols, and Inceptisols. Common soil series include Clebit, Pirum, Neff, Tuskahoma, Wetsaw, and Wister (Carter 1997).

Streamflow in the Ouachita Mountains is driven by rainfall. Because springs are uncommon in this region, during summer, first-order streams become dry and lower-order streams become intermittent (Williams et al., 2002, Splinter, unpublished data). Reaches of pool-riffle-run sequences become isolated pools. In high gradient reaches, steps and cascades can replace the pool-riffle-run sequence (Marion and Weirich, 2003). Boulder size particles are common in Ouachita Mountain streams (Smithson and Johnston, 1999, Taylor, 2000, Marion and Weirich, 2003, Schaefer et al., 2003). Particle-size often varies, however, from silt-to-boulder in small streams (Marion and Weirich, 2003).

3. Methodology

3.1. Site selection

One hundred and forty-nine stream reaches were randomly selected for classification in eastern Oklahoma (Fig. 5.1). Thirty-five were surveyed in the Boston Mountains, 34 in the Ozark Highlands, and 80 in the Ouachita Mountains. A random point generator model in ArcView 3.2$^{©}$ was applied to a stream network constructed using 30-meter DEMs. The stream network was stratified into stream orders (1-4) for each ecoregion (Strahler, 1952). Points (i.e., reaches) were generated using a stratified random procedure based on ecoregion area, which suggested how many points per ecoregion were necessary for a stream sampling protocol that was equally weighted by ecoregion. Stream reach coordinates were downloaded to a Trimble GeoXT$^{©}$ GPS receiver, which was used to navigate to the survey site. Where access was denied or the reach was primarily disturbed (i.e., gravel mined, channelized, etc.) the reach point was reselected.

3.2. Classification of stream reaches

The software program RIVERMorph 3.0$^{©}$ was used to store and analyze data. Rosgen classifications are generally based on reference reach conditions for a particular stream. Reference reaches are defined as those that are stable in nature (Rosgen, 1996). By defining and classifying reference reaches extrapolation of reference reach conditions can be applied to unstable reaches for restoration (Rosgen, 1996). The focus of this study was not in defining reference reaches, but rather how randomly selected reaches differed between ecoregions. Each reach was assigned a classification based on particle-size, width-depth ratio, entrenchment, gradient, and sinuosity (Fig. 5.2).

Three-to-four cross-sections were surveyed in each reach. Normally two were in riffles and two in pools. This was not always the case because some reaches were completely dry, while others were intermittent. Some reaches contained one long pool. For the purpose of stream reach classification, only one cross-section portrayed the cross-sectional geometry of the reach. The cross-section selected for the reach classification was determined by the following criteria: (1) the cross-section of the channel was conducted through a riffle, when no riffle existed cross-sections in pools or dry sections were used; and (2) the D50, width-depth ratio, and entrenchment ratio at the selected cross-section had similar values to unselected cross-sections, and therefore did not change the classification between the selected and unselected cross-sections. The remaining criteria for stream reach classification were based on gradient and sinuosity.

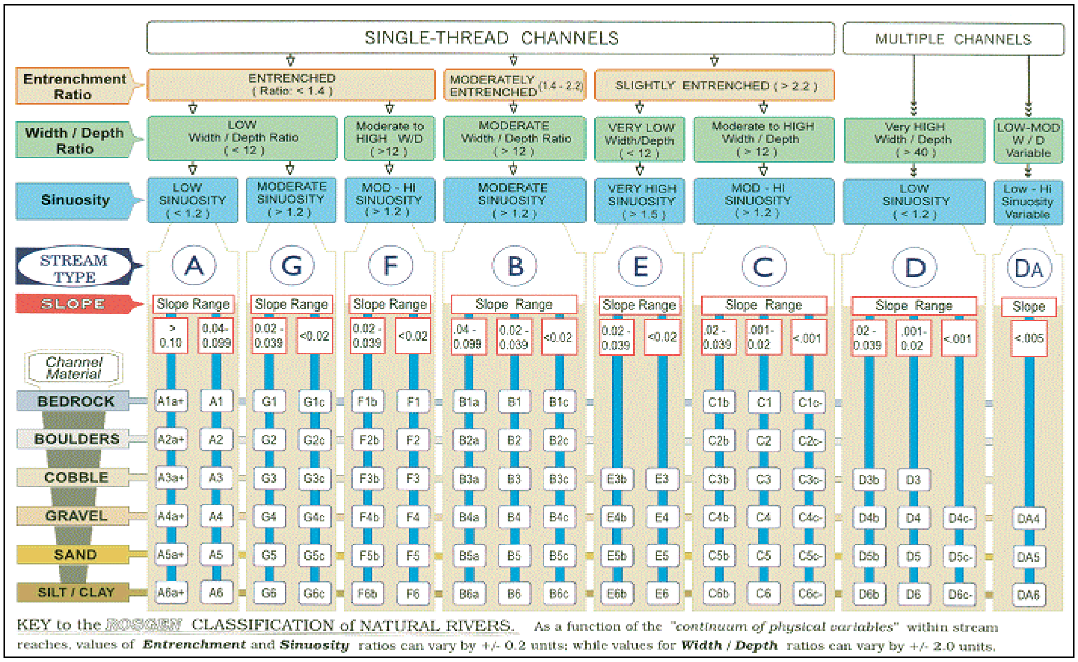

Fig. 5.2. Stream types used to classify reaches in this study (Rosgen 1996). Image of the Rosgen stream classification scheme taken from the internet on February 12, 2006. Website is http://www.r6.fws.gov/pfw/images/Class2.gif.

The majority of the reaches surveyed met the above criteria. However, channel unit frequency and type dictated where cross-sections were surveyed in the reach. Where the D50, width-depth ratios, and entrenchment ratios constituted values that changed the classification of the reach, I selected the value most similar to the other three transects.

For example, if three cross-sections had width-depth ratios > 12 and one < 12, I selected one of the reaches with a with-depth ratio > 12. Cross-sections flowing through riffles were given priority. The majority of the reaches had entrenchment values greater than 2.2. Entrenchment ratio played a small role in helping to classify stream channels that could have changed the classification of the reach.

Particles were collected following the Wolman method (1954). Particle measuring device was a standard ruler (Fig. 5.3). Particles less than 2 mm were classified as fines, while boulders were clasts bigger than 256 mm. Bedrock size was not measured, but counted as a percentage of the reach. At each cross-section 100 particle-size observations were made. The distribution of particles was entered into RIVERMorph 3.0©, which was used to create a frequency distribution of particle-sizes. The particle-size classification is based on the Wentworth scale. Particles less than 2.0 mm could not be measured in the field and were classified as fines.

During data entry fines were classified into the 2.0 mm - 1.0 mm size fraction. Boulder size was not measured in the field. During data entry boulders were classified into the 256 mm - 362 mm size fraction. Particle-size was capped on the low end at 1 mm and 362 mm on the high end. Bedrock was not classified in the particle-size distribution. Stream classification was overridden from the D50 value to one of a bedrock reach if half of the reach was bedrock. Support for this override comes from a review on bedrock channels by Tinkler and Wohl (1998) who define bedrock channels as those reaches that have greater than 50 percent exposed bedrock. If any of the cross-sections had 50 percent bedrock, the reach was classified as having some bedrock control.

Fig. 5.3. Mark Murphy, Raymond Ary, and Kyle Winters measuring the A, B, and C axes of particles on Spavinaw Creek in the Ozark Highlands. Survey date was June 6, 2004.

The width-depth ratio was calculated by dividing the bankfull width by the mean channel depth (Rosgen, 1996). A problem occurred when plotting cross-section data in RIVERMorph 3.0©. When a survey point across the channel was on a rock that was higher than the bankfull indicator on the left-side of the channel, bankfull width was taken to that high value. This shortened the bankfull width of the channel and led to inaccurate results for the width-depth ratio. When this occurred the cross-section data was invalid and a different cross-section was used to establish a representative reach for classification purposes. The shortening of the cross-section did not impact the upstream to downstream trends data in Chapter 3. Those problems were adjusted to make bankfull width the correct length to accurately calculate the width-depth ratio for the reach.

The entrenchment ratio is defined as the as the ratio of the width of the flood-prone area to the surface width of the bankfull channel (Rosgen, 1996). Flood-prone area width is twice the maximum depth of the channel from the bankfull stage (Rosgen, 1996). Stream reaches that have entrenchment ratios greater than 2.2 times are slightly entrenched. Entrenchment ratios were not calculated for these types of streams. This is because values greater than 2.2 do not change the classification for the stream reach. Cross-sections where the reach was moderately entrenched (1.4 - 2.2) and entrenched (1.0 - 1.4) were calculated for entrenchment following the procedures previously mentioned.

The gradient of the reach was attained by surveying the change in water surface elevation with a stadia rod and transit from upstream-to-downstream of reach (Rosgen, 1996). GPS maps of channel length were used to divide surface elevation change by length of the reach. When the channel was dry, tape measures were used to measure length of the reach. Sinuosity is calculated by dividing stream length by valley length (Rosgen, 1996). GPS map were used for both stream length and valley length. Sinuosity carries the least amount of weight in the stream classification scheme (Rosgen 1996). Upon entering data into RIVERMorph 3.0©, it became apparent that sinuosity often failed to fit into the flow chart of stream reach classifications.

3.3. Statistical analysis: stream classification

A chi-squared test was used to check for independence between ecoregion and stream classification by stream order. The program Statistix 8© was used to conduct the chi-squared test (Analytical Software, 2003). This test utilizes frequency data of the types of stream classifications, which is employed to test for independence between ecoregions. The test was performed using two different levels of stream characterization.

The Level I geomorphic characterization includes the broad level description (i.e., B, C, and E) of the major stream types. Characteristics used to classify stream types at this level include the entrenchment ratio, width-depth ratio, sinuosity, and gradient. The Level II morphological description (i.e., B1, C1b, E3b, etc.) is a more defined level of classification that includes Level I variables, and median particle-size.

The advantage of using Level I characterization over Level II characterization is that the sample size increases per classification, however, the geomorphic controls on channel pattern decrease. Level I classifications allow for a generalized depiction of stream channel geometry. A disadvantage of using the Level II stream classification is that sample size decreases, but geomorphic variables used in the classification increase. This helps depict stream channel morphology on a more localized level and with greater detail.

4. Results and Discussion

4.1. Rosgen stream reach classification: Level I

No statistically significant differences exist between Level I classifications of stream reaches and stream order between ecoregions (Table 5.1). Spatial relationships of the type of reach, however, do exist between stream order and ecoregion (Fig. 5.4). B stream types are the least frequently identified and are only found in first and second-order streams (Fig. 5.4). B types of streams have entrenchment ratios between 1.4 and 2.2. No B types of streams were classified in the Boston Mountains. The proportion of first and second-order B types of streams is 0.03. The lack of entrenched streams in eastern Oklahoma is supported by definable floodplains adjacent to the channel. Steep hillslopes adjacent to the channel are common on one side of the channel, but not on both sides. This allows for lateral migration on the unconfined side and a minimum of one definable floodplain. The rare occurrence of B types of streams is depicted in Fig. 5.5.

E stream types have entrenchment ratios > 2.2 and width/depth ratios < 12. E streams differ from B streams in that they are not as entrenched and have a lower width-depth ratio (Fig. 5.6). The proportion of E streams classified was 0.20. The number and proportion of E stream types decrease as stream order increases (Fig. 5.4). Sixty-seven percent of the first and second-order streams in the Boston Mountains and Ozark Highlands are classified as E stream types. Fifty-five percent of the first and second-order streams in the Ouachita Mountains are E streams. E streams do not exist in third and fourth order-streams in the Boston Mountains. One third-order E stream type exists in the Ozark Highlands. A higher proportion of E stream types exist in third and fourth-order streams in the Ouachita Mountains (0.35) than the Boston Mountains (0.00) or the Ozark Highlands (0.11).

C types of streams have entrenchment ratios > 2.2 and width/depth ratios > 12. This type of stream is more commonly classified in eastern Oklahoma than B or E. The proportion of C streams is 0.77. The proportion of C types of streams increase with stream order. All second, third, and fourth-order streams in the Boston Mountains were classified as C types of streams (Fig. 5.4). The increase in C types of streams with stream order and the decrease in E streams with stream order suggest that C types of streams replace E types of streams in the downstream direction. This relationship exists because streams tend to get wider and deeper downstream, which increases the width/depth ratio of the channel and the classification of the reach (Fig. 5.7).

Table 5.1
Results of the chi-squared test. Observed values are the first numbers in the order column, expected values ( ) are to the right of the observed.

Reach Type[a]	Chi-Square[b] /P-value w df	Region[c]	1st Order[d]	2nd Order[d]	3rd Order[d]	4th Order[d]
B	1.88	BM	0 (0)	0 (0)	0 (0)	0 (0)
	0.1709 (1)	OH	1 (0.40)	1 (1.60)	0 (0)	0 (0)
		OM	0 (0.60)	3 (2.40)	0 (0)	0 (0)
E	4.86	BM	4 (2.24)	1 (1.38)	0 (1.03)	0 (0.34)
	0.5615 (6)	OH	3 (2.69)	2 (1.66)	1 (1.24)	0 (0.41)
		OM	6 (8.07)	5 (4.97)	5 (3.72)	2 (1.24)
C	3.20	BM	3 (4.74)	9 (7.37)	9 (8.42)	9 (9.47)
	0.7835 (6)	OH	3 (4.11)	5 (6.39)	8 (7.30)	10 (8.21)
		OM	12 (9.16)	14 (14.25)	15 (16.28)	17 (18.32)

[a] Reach types as defined by Rosgen (1996), [b] Chi-square = E = $(n_i - E_i)^2 / E_i$ (top value), P-value (second value), df = degrees of freedom, [c] BM = Boston Mountains, OH = Ozark Highlands, OM = Ouachita Mountains, [d] Strahler stream order (1952)

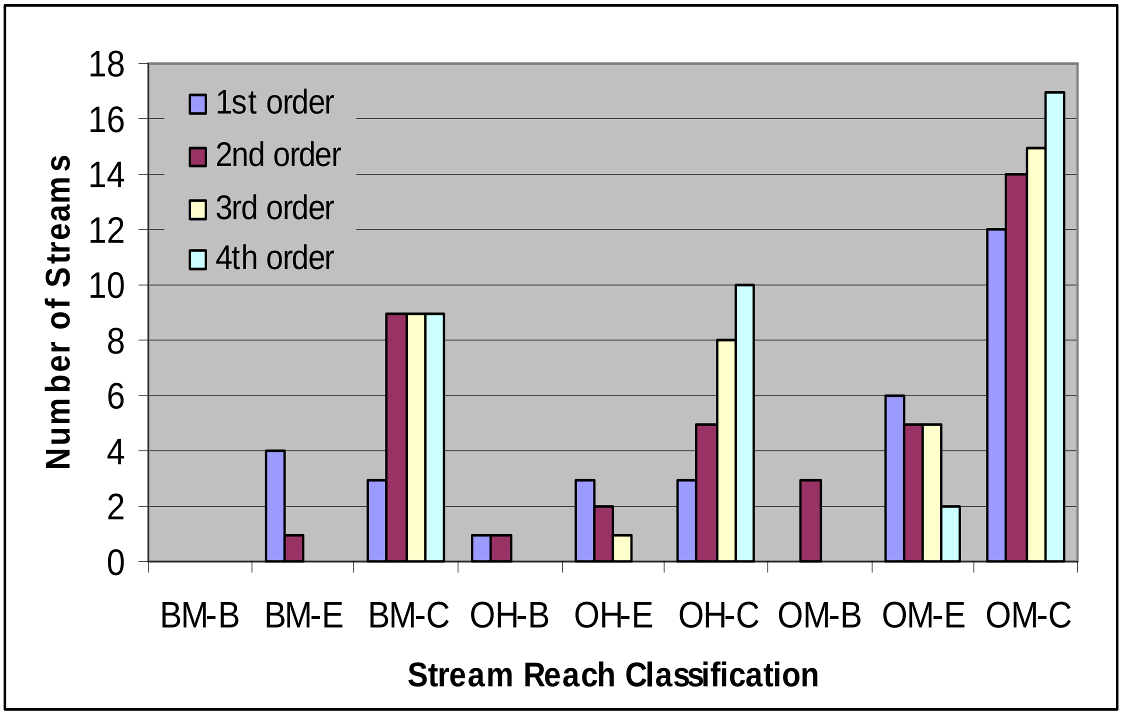

Fig. 5.4. Stream reach classification by ecoregion and stream order. BM=Boston Mountains (n = 35); OH = Ozark Highlands (n = 34); OM = Ouachita Mountains (n=80).

Fig. 5.5. Unnamed first-order stream in the Ozark highlands (Reach 40) classified as reach type B.

Fig. 5.6. Unnamed first-order tributary stream (Reach 49) to Lost Creek in the Ozark Highlands classified as reach type E.

Fig. 5.7. Little Lee Creek (Reach 27) is a third-order stream in the Boston Mountains that is classified as reach type C.

4.2. Rosgen stream reach classification: Level II

The Level I classification does not consider particle-size when classifying reach types. A second chi-square test was performed that included particle-size. Slope was not included because the sample size would have been too small. Reaches with stream types B2, E2, E3, C2, and G4 were not able to be statistically evaluated because of a small sample size. No statistically significant differences exist between ecoregion, reach type, or stream order when comparing Level II classifications (Table 5.2). This is in part due to the limited number of stream reach classifications per ecoregion. Regional generalizations about Level II stream channel classifications were made that include particle-size and slope.

Table 5.2
Results of chi-squared test. Observed values are the first numbers in the order column, expected values ( ) are to the right of the observed.

Reach Type[a]	Chi-Square[b] /P-value w df	Region[c]	1st Order[d]	2nd Order[d]	3rd Order[d]	4th Order[d]
B4	0.75	BM	0 (0)	0 (0)	0 (0)	0 (0)
	0.3865 (1)	OH	1 (0.67)	1 (1.33)	0 (0)	0 (0)
		OM	0 (0.33)	1 (0.67)	0 (0)	0 (0)
E4	4.43	BM	3 (1.68)	1 (1.47)	0 (0.42)	0 (0.42)
	0.6192 (6)	OH	1 (1.68)	2 (1.47)	1 (0.42)	0 (0.42)
		OM	4 (4.63)	4 (4.05)	1 (1.16)	2 (1.16)
E5	0.4145	BM	1 (0.57)	0 (0.14)	0 (0.29)	0 (0)
	0.4145 (4)	OH	2 (1.14)	0 (0.29)	0 (0.57)	0 (0)
		OM	1 (2.29)	1 (0.57)	2 (1.14)	0 (0)
C1	1.33	BM	1 (0.75)	1 (1.50)	0 (0)	1 (0.75)
	0.5134 (2)	OH	0 (0)	0 (0)	0 (0)	0 (0)
		OM	0 (0.25)	1 (0.50)	0 (0)	0 (0.25)
C3	5.75	BM	0 (1.17)	1 (1.00)	2 (1.67)	3 (2.17)
	0.4521 (6)	OH	1 (0.19)	0 (0.17)	0 (0.28)	0 (0.36)
		OM	6 (5.64)	5 (4.83)	8 (8.06)	10 (10.47)
C4	5.32	BM	2 (2.96)	7 (5.62)	7 (6.21)	5 (6.21)
	0.5031 (6)	OH	2 (3.52)	5 (6.69)	8 (7.39)	10 (7.39)
		OM	6 (3.52)	7 (6.69)	6 (7.39)	6 (7.39)

[a, b, c, d] See Table 5.1

Nine stream classifications exist in the Boston Mountains, eight in the Ozark Highlands, and 20 in the Ouachita Mountains (Table 5.3). Streams in the Boston Mountains and Ozark Highlands have five similar stream reach classifications. The most prominent classification of stream reaches is C4. C4 streams account for 42 percent of the types of streams in the Boston Mountains and 68 percent in the Ozark Highlands. C4 types of streams are slightly entrenched with width-depth ratios > 12. Reach slopes range between 0.001-0.02 and have mostly gravel substrate.

The two main differences in classification structure of the Boston Mountains and Ozark Highlands are related to particle-size and percent bedrock. Streams in the Boston Mountains have larger particle-sizes and more bedrock than streams in the Ozark

Highlands. Six stream reaches in the Boston Mountains were classified as C3 streams. Only one C3 stream was surveyed in the Ozark Highlands. C3 streams constitute cobble-size channel materials. Seven stream reaches in the Boston Mountains are either completely bedrock controlled or are comprised by bedrock somewhere along the reach. Only one stream reach is bedrock controlled in the Ozark Highlands.

Fifty-nine percent of the 20 classifications of stream reaches assigned to the Ouachita Mountains are E4, C3, and C4 (Table 5.3). Eleven stream classifications in the Ouachita Mountains are some type of C class. Seventy-three percent of the streams classified in the Ouachita Mountains involve C stream types. These range from C streams consisting of bedrock (C1), boulders (C2), cobbles (C3), and gravel (C4). C stream types tend to have variable reach gradients. Gradients <0.001 tend to be in third and fourth-order reaches, while gradients ranging between 0.02-0.039 are in first and second-order streams. The most prominent Level II stream type is C3. These reaches have large particle-sizes than the reaches in the Ozark Highlands or Boston Mountains. Eleven percent (9 out of 80) of the classified stream reaches in the Ouachita Mountains occurs only once (Table 5.3). Of the nine, seven occur in first and second order basins. This implies that stream morphology in upper watersheds tends to be quite variable in the Ouachita Mountains. One stream reach was classified as entrenched (G4c), while three were slightly entrenched.

Table 5.3

Level II classifications of stream reaches by ecoregion and stream order. The Boston Mountains (top left) and Ozark Highlands (top right) have nine and eight classifications of stream reaches, respectively. The Ouachita Mountains have 20 classifications of stream reaches. Refer to Table 5.2 for descriptions of stream reaches.

BM[a]	E4b	E4	E5	C1b	C1	C3	C4[1]	C4	C4c-
1st	1	2	1	0	1	0	0	2	0
2nd	0	1	0	1	0	1	2	5	0
3rd	0	0	0	0	0	2	2	5	0
4th	0	0	0	0	1	3	0	3	2

OH[a]	B4c	E4	E5b	E5	C3b	C4[1]	C4	C4c-
1st	1	1	1	1	1	0	2	0
2nd	1	2	0	0	0	0	5	0
3rd	0	1	0	0	0	0	8	0
4th	0	0	0	0	0	1	8	1

OM[a]	G4c	B2	B2c	B4c	E3[1]	E3	E4b	E4	E5	C1	C2	C2c-	C3[1]	C3b	C3	C3c-	C4[1]	C4b	C4	C4c-
1st	1	0	0	0	0	0	1	3	1	0	1	0	0	2	4	0	0	2	4	0
2nd	0	1	1	1	0	0	0	5	1	1	0	0	0	1	4	0	1	1	5	0
3rd	0	0	0	0	1	1	0	1	2	0	1	0	1	0	6	1	0	0	5	1
4th	0	0	0	0	0	0	0	2	0	0	0	1	3	0	5	2	1	0	3	2

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[a] BM = Boston Mountains, OH = Ozark Highlands, OM = Ouachita Mountains

[1] One of the reaches surveyed had greater than 50 percent bedrock along transect surveyed

5. Conclusion

A chi-squared test reported no statistically significant associations existing between classification of stream reaches and stream order between ecoregions. Based on Level I classifications of stream reaches certain trends were recognized. Few B stream types exist in these three regions. B stream types do not exist in the Boston Mountains, which implies that streams in this region have well defined floodplains and are not entrenched. Those that exist in the Ozark Highlands and Ouachita Mountains exist in first and second-order streams. E stream types decrease as stream order increases in all ecoregions. C stream types increase as stream order increases. E streams transition into C streams from upstream to downstream in these three ecoregions. More detail about stream reaches is inferred from Level II classifications. In the Ozark Highlands and Boston Mountains the most prominent stream type is C4. These streams have width/depth ratios > 12 and gravel size substrate. More C1 and C3 stream types exist in the Boston Mountains than the Ozark Highlands.

More types of stream reaches exist in the Ouachita Mountains than the Boston Mountains or Ozark Highlands combined. Twenty Level II classifications of stream reaches were identified in the Ouachita Mountains. Over half of the stream reaches in the Ouachita Mountains are E4, C3, and C4. The high number of classifications of stream reaches is indicative of the spatial variability in the region. The Ouachita Mountains encompasses a more diverse geographic area than the Boston Mountains or the Ozark Highlands. This leads to more variable characteristics of stream reaches in the Ouachita Mountains. Most of the stream reach classifications that occur only once are in first and second-order streams, which suggest that the watershed factors controlling these stream reaches are also quite variable.

Classification of stream reaches in eastern Oklahoma ecoregions provides a description of morphological changes between regions. Similar patterns in stream channel morphology exist between stream order and ecoregions. This information should be used by the ODWC to help establish a stream classification structure for eastern Oklahoma. The ODWC, however, should not use the classifications of these reaches to perform stream restoration designs on a regional scale. Too much complexity and variability exists in the fluvial system for streams to be restored by region. Applications of stream restoration must proceed on a case-by-case basis and should only be attempted when a firm understanding of the fluvial hierarchy of that particular case has been established.

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Appendix

[a] BM = Boston Mountains, OH = Ozark Highlands, OM = Ouachita Mountains. The number next to the region abbreviation is stream order

[b] ID = randomly selected points that serve a reaches (see page 100)

[c] ER = Entrenchment Ratio

[d] W/D = Width/depth ratio

[1] These reaches have bedrock greater than 50 percent at one of the cross-sections. These reaches are bedrock controlled.

Region[a]	ID[b]	ER[c]	W/D[d]	Sinuosity	Slope	D50	Type
BM-1	0	> 2.2	14.39	1.20	0.0118	37.20	C4
BM-1	1	> 2.2	6.59	1.17	0.0267	39.80	E4b
BM-1	2	> 2.2	8.54	1.15	0.0194	48.17	E4
BM-1	3	> 2.2	8.24	1.05	0.0162	26.36	E4
BM-1	4	> 2.2	6.91	1.14	0.0055	1.89	E5
BM-1	6	> 2.2	24.36	1.02	0.0112	1.92	C1
BM-1	9	> 2.2	14.70	1.01	0.0192	40.67	C4
BM-2	10	> 2.2	11.50	1.36	0.0140	17.89	E4
BM-2	11	> 2.2	12.98	1.21	0.0063	5.49	C4[1]
BM-2	12	> 2.2	14.82	1.09	0.0073	32.00	C4
BM-2	13	> 2.2	14.22	1.13	0.0116	22.60	C4
BM-2	14	> 2.2	15.38	1.02	0.0115	37.20	C4
BM-2	15	> 2.2	16.30	1.03	0.0097	36.33	C4[1]
BM-2	16	> 2.2	14.33	1.20	0.0111	66.60	C3
BM-2	17	> 2.2	19.05	1.10	0.0099	46.90	C4
BM-2	18	> 2.2	25.57	1.28	0.0178	58.37	C4
BM-2	19	> 2.2	42.88	1.05	0.0274	19.3	C1b
BM-3	20	> 2.2	21.61	1.14	0.0079	133.78	C3
BM-3	21	> 2.2	18.62	1.00	0.0073	87.11	C3
BM-3	22	> 2.2	25.44	1.19	0.0016	43.23	C4
BM-3	23	> 2.2	13.30	1.20	0.0009	38.24	C4
BM-3	24	> 2.2	14.73	1.06	0.0090	53.14	C4[1]
BM-3	25	> 2.2	35.72	1.41	0.0024	30.66	C4
BM-3	26	> 2.2	44.41	1.04	0.0033	43.63	C4
BM-3	27	> 2.2	27.60	1.02	0.0035	34.17	C4
BM-3	28	> 2.2	27.4	1.05	0.0047	30.43	C4[1]
BM-4	29	> 2.2	25.15	1.11	0.0016	42.64	C4
BM-4	30	> 2.2	20.52	1.29	0.0033	60.21	C4
BM-4	31	> 2.2	20.19	1.01	0.0031	132.00	C3
BM-4	32	> 2.2	41.52	1.08	0.0025	93.45	C3

Region[a]	ID[b]	ER[c]	W/D[d]	Sinuosity	Slope	D50	Type
BM-4	33	> 2.2	29.35	1.09	0.0028	80.71	C3
BM-4	35	> 2.2	24.93	1.51	0.0008	40.97	C4c-
BM-4	36	> 2.2	25.46	1.31	0.0008	45.00	C4c-
BM-4	37	> 2.2	27.43	1.09	0.0034	136.67	C1
BM-4	38	> 2.2	36.76	1.16	0.0024	37.57	C4
OH-1	40	1.69	13.40	1.05	0.0070	39.22	B4c
OH-1	42	> 2.2	15.78	1.80	0.0060	22.6	C4
OH-1	44	> 2.2	8.56	1.06	0.0362	1.85	E5b
OH-1	46	> 2.2	32.20	1.02	0.0211	154.00	C3b
OH-1	47	> 2.2	8.55	1.07	0.0043	1.53	E5
OH-1	48	> 2.2	16.56	1.07	0.0156	42.40	C4
OH-1	49	> 2.2	10.78	1.04	0.0116	25.89	E4
OH-2	50	> 2.2	15.84	1.04	0.0194	39.43	C4
OH-2	51	> 2.2	11.61	1.05	0.0110	6.21	E4
OH-2	53	> 2.2	6.15	1.47	0.0048	27.10	E4
OH-2	54	> 2.2	17.85	1.01	0.0082	35.06	C4
OH-2	55	> 2.2	13.56	1.03	0.0088	39.50	C4
OH-2	57	2.07	15.58	1.08	0.0094	37.11	B4c
OH-2	58	> 2.2	12.48	1.00	0.0078	30.12	C4
OH-2	59	> 2.2	18.15	1.36	0.0092	16.41	C4
OH-3	60	> 2.2	13.13	1.08	0.0041	27.30	C4
OH-3	61	> 2.2	13.28	1.51	0.0037	34.83	C4
OH-3	62	> 2.2	29.80	1.08	0.0057	28.34	C4
OH-3	63	> 2.2	11.64	1.14	0.0043	35.79	E4
OH-3	65	> 2.2	25.63	1.07	0.0034	50.32	C4
OH-3	66	> 2.2	22.94	1.18	0.0039	38.93	C4
OH-3	67	> 2.2	26.52	1.14	0.0120	25.82	C4
OH-3	68	> 2.2	36.26	1.80	0.0029	36.06	C4
OH-3	69	> 2.2	15.18	1.03	0.0033	24.77	C4
OH-4	70	> 2.2	31.76	1.16	0.0022	17.20	C4

Region[a]	ID[b]	ER[c]	W/D[d]	Sinuosity	Slope	D50	Type
OH-4	71	> 2.2	44.62	1.05	0.0023	26.63	C4
OH-4	72	> 2.2	21.04	1.04	0.0005	22.09	C4c-
OH-4	73	> 2.2	26.67	1.00	0.0018	21.82	C4
OH-4	74	> 2.2	69.77	1.25	0.0013	43.14	C4
OH-4	75	> 2.2	31.33	1.09	0.0043	34.00	C4
OH-4	76	> 2.2	31.2	1.04	0.0037	28.42	C4[1]
OH-4	77	> 2.2	39.42	1.40	0.0025	27.30	C4
OH-4	78	> 2.2	40.49	1.10	0.0011	34.89	C4
OH-4	79	> 2.2	72.34	1.37	0.0020	29.99	C4
OM-1	80	> 2.2	13.27	1.03	0.0268	56.69	C4b
OM-1	81	> 2.2	15.96	1.20	0.0180	46.81	C4
OM-1	82	> 2.2	20.40	1.01	0.0185	85.13	C3
OM-1	83	> 2.2	18.83	1.04	0.0301	275.11	C2
OM-1	84	> 2.2	12.17	1.13	0.0315	56.40	C4b
OM-1	85	> 2.2	11.28	1.04	0.0158	64.00	E4
OM-1	87	> 2.2	21.68	1.09	0.0111	68.65	C3
OM-1	89	> 2.2	13.84	1.07	0.0178	100.13	C3
OM-2	90	> 2.2	25.94	1.25	0.0032	15.55	C4
OM-2	91	> 2.2	29.96	1.25	0.0021	120.76	C3
OM-2	92	> 2.2	10.52	1.03	0.0038	39.43	E4
OM-2	93	> 2.2	11.94	1.56	0.0052	46.83	E4
OM-2	94	1.50	27.98	1.03	0.0204	250.44	B2
OM-2	95	> 2.2	17.91	1.05	0.0071	17.20	C4
OM-2	96	> 2.2	20.62	1.02	0.0132	78.53	C3
OM-2	97	> 2.2	14.55	1.51	0.0163	143.60	C1
OM-2	98	1.40	14.68	1.72	0.0023	19.64	B4c
OM-2	99	> 2.2	16.36	1.23	0.0135	56.40	C4
OM-3	101	> 2.2	6.48	1.30	0.0011	1.77	E5
OM-3	102	> 2.2	6.62	1.01	0.0016	95.69	E3
OM-3	103	> 2.2	23.41	1.10	0.0030	95.55	C3

Region[a]	ID[b]	ER[c]	W/D[d]	Sinuosity	Slope	D50	Type
OM-3	104	> 2.2	10.13	1.07	0.0047	1.96	E5
OM-3	105	> 2.2	9.40	1.23	0.0035	28.24	E4
OM-3	106	> 2.2	23.12	1.40	0.0047	64.00	C4
OM-3	107	> 2.2	21.11	1.27	0.0050	36.33	C4
OM-3	108	> 2.2	16.29	1.00	0.0008	87.83	C3c-
OM-3	109	> 2.2	48.64	1.16	0.0053	168.84	C3
OM-4	110	> 2.2	27.73	1.07	0.0030	33.63	C4[1]
OM-4	111	> 2.2	18.35	1.14	0.0018	159.20	C3
OM-4	112	> 2.2	16.49	1.14	0.0005	100.23	C3c-
OM-4	113	> 2.2	14.96	1.15	0.0038	104.93	C3[1]
OM-4	114	> 2.2	9.32	1.37	0.0004	50.94	E4
OM-4	115	> 2.2	29.18	1.44	0.0003	43.63	C4c-
OM-4	116	> 2.2	11.71	1.08	0.0001	8.00	E4
OM-4	117	> 2.2	14.61	1.13	0.0027	26.63	C4
OM-4	118	> 2.2	26.16	1.03	0.0008	157.71	C3c-
OM-1	122	> 2.2	15.63	1.01	0.0027	60.04	C4
OM-1	123	> 2.2	12.64	1.12	0.0035	6.27	C4
OM-1	124	> 2.2	14.35	1.02	0.0279	84.8	C3b
OM-1	125	1.35	9.86	1.06	0.0035	7.23	G4c
OM-1	126	> 2.2	18.35	1.01	0.0137	80.42	C3
OM-1	128	> 2.2	18.74	1.08	0.0039	60.38	C4
OM-1	129	> 2.2	22.02	1.05	0.0292	69.20	C3b
OM-2	130	> 2.2	15.79	1.03	0.0129	66.36	C3
OM-2	132	> 2.2	12.34	1.16	0.0063	41.29	C4
OM-2	133	> 2.2	14.05	1.04	0.0050	4.85	C4[1]
OM-2	134	> 2.2	10.54	1.20	0.0004	49.75	E4
OM-2	136	> 2.2	13.91	1.10	0.0221	97.13	C3b
OM-2	137	> 2.2	30.05	1.07	0.0144	69.20	C3
OM-2	138	> 2.2	8.20	1.07	0.0099	31.22	E4
OM-2	139	> 2.2	19.09	1.04	0.0123	258.59	C2

Region[a]	ID[b]	ER[c]	W/D[d]	Sinuosity	Slope	D50	Type
OM-2	140	1.82	25.67	1.08	0.0191	290.13	B2c
OM-2	141	> 2.2	3.45	1.28	0.0080	1.52	E5
OM-3	142	> 2.2	16.41	1.14	0.0012	57.67	C4
OM-3	144	> 2.2	13.68	1.30	0.0046	101.88	C3[1]
OM-3	145	> 2.2	22.33	1.02	0.0022	122.00	C3
OM-3	146	> 2.2	25.36	1.02	0.0035	262.00	C2
OM-3	147	> 2.2	20.54	1.13	0.0040	57.21	C4
OM-3	148	> 2.2	15.18	1.04	0.0004	26.31	C4c-
OM-3	149	> 2.2	11.76	1.01	0.0027	150.00	E3[1]
OM-3	150	> 2.2	17.03	1.05	0.0026	97.82	C3
OM-3	151	> 2.2	17.07	1.06	0.0105	92.24	C3
OM-4	152	> 2.2	23.37	1.08	0.0028	83.07	C3
OM-4	154	> 2.2	36.84	1.30	0.0092	109.00	C3
OM-4	155	> 2.2	35.46	1.02	0.0024	100.86	C3[1]
OM-4	157	> 2.2	16.47	1.05	0.0006	57.29	C4c-
OM-4	158	> 2.2	28.48	1.22	0.0042	44.13	C4
OM-4	159	> 2.2	19.11	1.05	0.0014	103.41	C3[1]
OM-4	160	> 2.2	29.93	1.17	0.0113	103.41	C3
OM-4	161	> 2.2	15.2	1.00	0.0001	276.52	C2c-
OM-1	162	> 2.2	6.11	1.17	0.0252	62.94	E4b
OM-1	164	> 2.2	11.18	1.08	0.0060	24.17	E4
OM-1	165	> 2.2	6.49	3.04	0.0007	1.50	E5
OM-2	166	> 2.2	10.90	1.55	0.0039	54.50	E4
OM-3	167	> 2.2	17.15	1.09	0.0046	47.59	C4
OM-4	169	> 2.2	37.98	1.05	0.0019	180.00	C3
OM-1	911	> 2.2	10.25	1.06	0.0090	51.65	E4
OM-2	920	> 2.2	17.24	1.26	0.0030	36.88	C4
OM-3	930	> 2.2	18.82	1.09	0.0093	165.14	C3
OM-4	940	> 2.2	14.92	1.22	0.0029	43.23	C4

CHAPTER 6

CONCLUSION

This study was developed to investigate whether the characteristics and spatial patterns of the fluvial system could be differentiated by the Level III ecoregions of Omernik (1987). Completion of this study showed that watershed morphology (Chapter 2) and the characteristics of stream channels (Chapter 3) often differed by ecoregion. In addition, the dissimilarity of watershed morphology and channel morphology was quantified and compared between ecoregions (Chapter 4). Stream reach classifications were conducted to evaluate whether channel pattern differed between ecoregion and stream order (Chapter 5).

The results of this suggest that ecoregions provide a large-scale framework necessary for the hierarchical classification of the fluvial system. The physical and environmental variables (geology, soils, climate, potential natural vegetation, and land use) used to construct ecoregions influence watershed morphology, which in-turn influence the construction of the stream network and the characteristics of stream channels in the upstream-to-downstream direction. By establishing that ecoregions provide a useful large-scale regional delineation in the hierarchical classifications of streams, a regional framework by which the fluvial hierarchy begins can be established and utilized in spatially organized studies.

6.1. Synopsis of results

Morphometric variables of watersheds were statistically significant between ecoregions. Variables measured were drainage density, circularity ratio, relief, relief ratio, and ruggedness number. A Kruskil-Wallis non-parametric test was used to test for statistical differences at $\alpha = 0.05$. Watersheds in the Ozark Highlands consist of a relatively high drainage density despite having low relief, which produces a highly dissected landscape. Watersheds in the Boston Mountains are characterized as having a relatively high relief, low drainage, and a high circularity ratio in first and second-order watersheds. Watersheds in the Ouachita Mountains consist of a high relief and relief ratio, high drainage density and ruggedness number.

An analysis of y-intercept coefficients revealed that statistical differences (at $\alpha = 0.05$) for D16 values exist between the Boston Mountains and Ouachita Mountains. D84 y-intercept coefficients show statistical differences between the Ozark Highlands and the Ouachita Mountains. Particle-size is smallest in the Ozark Highlands and largest in the Ouachita Mountains. In all regions, particle-size increases from upstream-to-downstream. This probably occurs because of the influence of tributaries and bank erosion in the Ozark Highlands and Boston Mountains. In the Ouachita Mountains this trend is attributed to the influence of bedrock outcrops and prominent valley walls in the downstream direction.

An analysis of slope and y-intercept coefficients revealed that statistical differences (at $\alpha = 0.05$) exist in bankfull channel width been Ozark Highland streams and Ouachita Mountain streams, while slope coefficients show differences between Ozark Highland streams and Boston Mountain streams. Streams in the Ozark Highlands increase in width at a more rapid rate than streams in the Boston Mountains or Ouachita Mountains. This increase is attributed to the aggradation of the streambed in forth-order streams in the Ozark Highlands, which has caused lateral bank erosion to increase bankfull channel width.

Boston Mountain and Ozark Highland streams have width-depth ratios with slope coefficients statistically different (at $\alpha = 0.05$) from Ouachita Mountain streams. Width-depth ratios of the Boston Mountains and Ozark Highlands are not statistically significant. The width-depth ratio of Ozark Highland streams increase more rapidly than the streams in the Boston Mountains or Ouachita Mountains. Streams in the Ouachita Mountains show a subtle increase in width-depth ratio. The large particle-size and the confinement of streams by bedrock outcrops in the Ouachita Mountains hinder lateral migration and downcutting. No statistical differences exist between gradient or sinuosity and ecoregion.

Dissimilarity of watersheds and channel morphology was quantified by ecoregion using a sum of squares method. Dissimilarity measures how different watersheds and channel morphologies are between ecoregions. Stream reaches with the greatest amount of pairwise dissimilarity occur in the Ouachita Mountains. Watershed dissimilarity is also highest in the Ouachita Mountains. Streams in the Ouachita Mountains flow through watersheds that possess a topographic and structural variability that the Boston Mountains or Ozark Highlands do not encounter. This has produced greater variability in watershed and stream morphology than in the other two regions.

Rosgen stream classifications were identified at surveyed reaches (Rosgen, 1996). A chi-squared test was used to test for differences between the classifications by region and stream order. No statistically significant associations exist between the type of reach and position in the watershed between ecoregions. The Boston Mountains and Ozark Highlands have nine and eight Level II stream types, respectively. The most prominent stream type in the Boston Mountains and Ozark Highlands is C4. The Ouachita Mountains have 20 Level II types of stream reaches. The most prominent stream type in the Ouachita Mountains is C3. First and second-order streams in the Ouachita Mountains contain many different types of streams that occur only once or twice. This occurs because of the highly variable landscape topography within the Ouachita Mountains.

6.2. Suggestions for further study

Landowners living along third and fourth-order streams in the Ozark Highlands expressed concern that streams are much more dynamic than decades prior. High magnitude discharges are transporting more gravel, which has caused deep pools to become shallow. An increase in bank erosion is leading to more large woody debris in the stream. These sentiments were echoed by landowners up and down reaches of Baron Fork Creek. A study should be designed that investigates the concerns of the local landowners in the Baron Fork Creek watershed.

Since this study was completed, more detailed ecoregion maps (Level IV) have been created for Oklahoma. Dissimilarity of watershed morphology and stream reaches should be reevaluated using the Level IV ecoregion maps. The highly variable Ouachita Mountains have been redefined into five regions (Level IV) instead of one (Level III). A study should be designed to determine whether dissimilarity and clusters are better portrayed using the Level IV ecoregions.

References

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VITA

Dale Keith Splinter

Candidate for the Degree of

Doctor of Philosophy

Dissertation: SPATIAL PATTERNS IN THE FLUVIAL SYSTEM: COMPARISONS AMONG THREE EASTERN OKLAHOMA ECOREGIONS

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Title of Study: SPATIAL PATTERNS IN THE FLUVIAL SYSTEM: COMPARISONS AMONG THREE EASTERN OKLAHOMA ECOREGIONS

Pages in Study: 183 Candidate for the Degree of Doctor of Philosophy

Major Field: Environmental Science

Scope and Method of Study: Ecoregions are homogeneous regions delineated by similar associations of geology, climate, soils, land use, and potential natural vegetation. Ecoregions provide a spatial framework to establish whether geographic phenomena differ between ecoregions. A study was initiated to establish whether watershed morphology and the characteristics of stream channels could be differentiated by ecoregions in eastern Oklahoma: the Ozark Highlands, Boston Mountains, and Ouachita Mountains were selected for study. One hundred and forty-nine watersheds and stream reaches were randomly selected for investigation.

Findings and Conclusions: Four lines of inquiry were used to evaluate whether differences exist among ecoregions. These include morphometric analyses of watersheds, upstream-to-downstream trends in channel morphology, dissimilarity and cluster analysis of variables for watersheds and reaches, and classification of stream reaches. Statistical results are reported at $\alpha = 0.05$. Morphometric analyses of drainage density, circularity ratio, relief, relief ratio, and ruggedness number reveal statistical differences between some watershed orders and ecoregions. Regression coefficients were used to test for significant differences in the upstream-to-downstream trends in channel morphology. Significant differences exist in particle-size, bankfull width, and width-depth ratio. Cluster analysis and dissimilarity were conducted using a sum of squares method. The most dissimilar watersheds and stream reaches exist in the Ouachita Mountains. A chi-squared test reported no differences between Rosgen stream classifications by region and stream order. Spatial patterns of the types of reaches, however, could be inferred in the upstream-to-downstream direction. The results of this study show that ecoregions in eastern Oklahoma provide a spatial framework that explains morphological differences in watersheds and reaches, clusters and dissimilarity, and the characteristics of channel reaches.

Advisor's Approval: William L. Fisher