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Geomorphic and Land Use Controls on Headwater Channel Morphology in Mark Twain National Forest

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GEOMORPHIC AND LAND USE CONTROLS ON HEADWATER CHANNEL MORPHOLOGY IN MARK TWAIN NATIONAL FOREST

A Master's Thesis

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In Partial Fulfillment

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Master of Science, Geospatial Science

By

Grace Roman

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ABSTRACT

Prescribed burning has been used over the past two decades to manage forests and restore shortleaf pine-oak woodlands in Mark Twain National Forest (MTNF). While soil studies have been completed, no assessments of burning practices on small drainage channel systems have yet been done. Headwater streams may account for more than two-thirds of total stream length and are important to the maintenance of hydrologic connectivity in watersheds. This study's focus is on understanding the relationship between frequency of forest burning and channel morphology (size, shape, and substrate) of headwater streams (<1 km^2). A combination of field measurements, geo-processing methods, hydraulic modeling, and statistical analysis will be used to analyze channel form, substrate properties, and tree/down wood composition in headwater stream channels. Thirty eight channel sites were assessed with drainage areas ranging from 0.003 - 0.2 km^2; reach slopes from 2 - 34%; bank-full channel widths from 0.4 - 10 m; average depths from 0.02 - 0.29 m; and areas from 0.01 – 2.2 m^2. Valley width and drainage area were found to be the best overall predictors of channel form (r^2= >0.70). Stepwise regression models improved single parameter morphology equations (r^2= >0.85). Channel slope and elevation are important variables describing sediment size (r^2=0.35-0.63). In-channel LWD and tree basal area equations were also developed (r^2= 0.41-0.54). Importantly, land use factors such as roads, timber harvest, and prescribed burning had little effect on channel morphology. In Big Barren Creek watershed, headwater channel systems were located within colluvial-alluvial transition zones, included both single- and multiple-threaded forms, and were quantified by traditional hydraulic geometry analysis.

KEYWORDS: hydraulic geometry, prescribed fire, headwater streams, forest management, Ozarks, geomorphology

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INTRODUCTION

Stream channels cover only a small portion of any watershed, but serve as important hydrologic, geomorphic, and biologic conduits that connect and convey water within a watershed (Lowe and Likens 2005). Stream networks form and respond to surrounding environmental characteristics such as climate patterns, geology, soil conditions, vegetation cover, and land use history (Leopold and Maddock 1953; Montgomery and Buffington 1997; Alabyan and Chalov 1998; Ward et al. 2003). Accordingly, the condition of a stream system can be used to assess the quality of a watershed. In particular, stream channel form, substrate and sediment, and stability can be used to assess disturbances such as land use change, infrastructure construction, implementation of land management practices, as well as natural disturbances (Jacobson and Primm 1994; Jacobson 1995). Geomorphic disturbances are defined as events that cause channels to change planform and shape faster or in a different way than the natural or referenced regime. Usually by increasing the amount of flow, sediment, and large woody debris that enters the stream (Jacobson 1995; Kondolf et al. 2002). Some indicators of stream response to disturbance include excessive erosion or sedimentation in adjacent riparian areas as well as changes in channel patterns (Leopold and Wolman 1957; Jacobson and Primm 1997). Measuring and interpreting changes in channel form can give researchers insight into how a watershed responds to different types of disturbances.

Headwater streams constitute the small 1st and 2nd order streams where water collection and initial flow concentration first originates within a channel network (Horton 1945; Strahler 1957). Headwater streams are located at the fingertips of the drainage network and serve as the interface between upland areas and the fluvial system (Figure 1) (Gomi et al. 2002; Adams and

Spotila 2005; Benda et al. 2005). Headwater streams are important to maintaining hydrologic connectivity and ecosystem integrity at regional scales and account for more than two thirds of total stream length (Leopold et al. 1964; Freeman et al. 2007). For the purpose of this study, headwater streams drain no more than 1 km^2 and are initiated and maintained by local processes that cause water movement to become sufficiently concentrated to cut a definable channel (Montgomery and Foufoula-Georgiou 1993; Knighton 1984). Headwater stream boundaries can also be determined by assessing where hillslope colluvium transitions to alluvial landforms (Montgomery and Foufoula-Georgiou 2010). Headwater stream attributes are more linked to local factors and hillslope characteristics than their downstream counterparts, and therein may be better indicators of watershed disturbance (Whiting and Bradley 1993; Gomi et al. 2002). Disturbances such as land-use and management changes can drastically affect hillslope characteristics and processes than can ultimately affect the hydrology and geomorphology of headwater streams (Jacobson and Primm 1997; Gomi et al. 2002). Currently, one of the largest threats to headwater stream stability is an increase in alteration due to anthropogenic disturbances (Elmore and Kaushal 2008).

The Ozark Highlands ("Ozarks") is a physiographic region in the southern Midwest of the United States that spans across southern Missouri and northern Arkansas and extends into eastern portions of Oklahoma and Kansas (Adamski et al. 1995). The Ozarks consist of a rugged landscape dominated by rolling hills dissected by stream networks that are connected to an underlying karst drainage system (Panfil and Jacobson 2001). Historically, the Ozark Highlands has been subjected to wide spread anthropogenic disturbances. This began with European settlement and land clearing that established row crops and pasture lands for agriculture between 1820 and 1880 (Panfil and Jacobson 2001). Then from 1880 – 1920 a large timber harvesting boom left forests depleted of pine species and altered the natural forest structure (Panfil and Jacobson 2001). Due to these historical disturbances by land clearing, agricultural practices, and logging alluvial channels in the Ozarks have been disturbed by increased gravel inputs, accelerated channel migration and avulsion, and excessive deposition of gravel bars (Jacobson 1995; Jacobson and Gran 1999; Panfil and Jacobson 2001; Martin and Pavlowsky 2011). While numerous studies have been completed on alluvial channel disturbances in the Ozark Highlands, there have been few studies that assess headwater streams (Nickolotsky and Pavlowsky 2007; Shepherd et al. 2011; Mitchell et al. 2012; Thies 2017).

Ozarks forests were in need of protection and restoration in the 1930s due to the widespread timber harvesting that occurred previously during the turn of the century (Panfil and Jacobson 2001). In the Missouri Ozarks, pre-settlement shortleaf pine was estimated to cover 1.1 million ha compared to the estimated 0.17 million ha today, approximately 15% of historic conditions (Cunningham and Hauser 1989; Guyette et al. 2007). Changes in forest structure in the Ozarks due to historic watershed disturbances included a shift from shortleaf pine to oak dominance, increased canopy density, and changes in litter composition and species distribution (Figure 2) (Guyette and Dey 1997). Mark Twain National Forest (MTNF) is Missouri's only national forest and was proclaimed in 1939 as a movement to conserve three million acres of the nation's timberstands. Known early on as Clark National Forest, since 1976 it was established as Mark Twain National Forest (MTNF – History & Culture). The Current land use of MTNF is 80% forested, 18% cold and warm-season grasses, and the remaining 2% glade complexes, row crops, barrens, wetlands, and urban areas (Brosofske et al. 2007). Of the 80% of forested area within MTNF, only 13% or approximately 312,000 acres, is shortleaf pine and shortleaf pine-oak forest and woodlands (Brosofske et al. 2007). To combat this, a combination of appropriate management practices including cyclic harvesting, silviculture, and prescribed fire treatment has been recently instituted to help restore the forest to its original shortleaf pine-oak woodlands habitat (MTNF – Forest's Collaborative Forest Landscape Restoration Project 2012-2022).

The main focus of this study is to attempt to understand the geomorphic factors controlling channel form and describe headwater channel geomorphology in MTNF. The Eleven Point Ranger District of MTNF including the Big Barren Creek watershed (190.6 km^2) has a unique topography and geology that allows for several fish species of conservation concern, a high density of rare freshwater mussel species, and a variety of other endemic species to thrive (Figure 3) (Finley 2013; MTNF - News & Events). The forest service also frequently institutes prescribed fire treatments in portions of Big Barren Creek watershed that are managed by MTNF in order to restore the forest's shortleaf pine-oak woodlands (MTNF – Land & Resources Management). However, concerns over the effects of frequent prescribed burning on watershed health exists. Previous studies have assessed the effects of prescribed fire on upland vegetation and soil condition and the influence of anthropogenic disturbance on main stem channel morphology in the Big Barren Creek watershed (Bradley 2017; Hente 2017; Roman et al. 2019). However, little is known about headwater channel morphology in this watershed and if and how anthropogenic disturbances, such as prescribed fire, influence headwater channel morphology and sediment characteristics. The purpose of this study is to assess the channel geometry, substrate, and large woody debris (LWD) loads of headwater streams in Big Barren Creek. Furthermore, this study will attempt to determine if these headwater stream properties vary between channels that have and have not been treated with prescribed burns.

Ozark Highlands Watershed Disturbance History

In the Ozark Highlands of Missouri, human control of fire in the landscape was first utilized by Native Americans in order to maintain open woodlands, savannas, and glades (Batek et al. 1999). When exactly Native Americans first started intentionally setting fires is controversial. Although, studies indicate that in the Current River basin increased incidence of fire after 1720 coincides with Native American procurement of the horse (Guyette and Cutter 1997). Early European settlers arrived in the Ozark area in the early 1800s and permanent settlements were well established by the mid to late 1800s. (Jacobson and Primm 1997). A study conducted by Guyette and McGinnes (1982) assessed pre- and post- settlement conditions and determined that after settlement forest fire frequency dropped from a 3.2 year fire return interval to a 22 year fire return interval. However, uses of controlled fire by Euro-American settlers to convert the forested hilltops and valley bottoms into pastures and croplands changed the vegetation mosaic and reduced fuels that might be available during wildfires (Cutter and Guyette 1994; Stambaugh and Guyette 2006).

The encroachment of European settlers into the Missouri Ozarks initiated drastic changes to the landscape including forest clearing that likely initiated direct disturbance of stream channels (Jacobson and Primm 1997). Between 1880 and 1920 commercial timber harvesting and therefore extensive logging and clearing came to the Ozarks. These large-scale logging operations had negative effects on runoff and sediment supply of uplands and valley-side slopes which were coupled with decreases in erosional resistance through road building and extreme regional floods from 1895 to 1915 (Jacobson and Primm 1997).

This stream disturbance factor was then magnified from 1920 to 1960 due to changes in both valley-bottom and upland riparian vegetation as a result of annual burning and over grazing of free roaming livestock (Law et al. 2004). Widespread erosion and a loss of soil moisture holding capacity ensued from the loss of riparian vegetation (Law et al. 2004). Historical records indicate that smaller streams experienced increased rates of gravel release and longer-duration discharge periods (Jacobson and Primm 1997). It was also documented that erosion was notable especially on lands in row-crop cultivation, and that floods were "flashier" (Jacobson and Primm 1997).

During the same time period, the United States Forest Service (USFS) first officially endorsed fire-suppression programs under the Clarke-McNary Act of 1924 (Stephens and Ruth 2005). This was done as a forest management solution to the increasing threat of wildfires due to westward expansion (Cooper 1960). However, throughout the mid-20th century there were numerous debates and studies related to fire ecology that showed the benefits of frequent, low to moderate intensity fire regimes (Stephens and Ruth 2005). It was also found that fire suppression policies were adversely affecting wildlife habitats (Leopold et al., 1963). Then in 1968, Sequoia-Kings Canyon National Park installed the first prescribed natural fire program that lead to the USFS and National Park Service revising their fire exclusion policies (Stephens and Ruth 2005).

Prescribed fire treatments were reintroduced as a restoration and conservation tool by land management agencies in the Ozarks during the late 1990s and early 2000s (Dey and Hartman 2005; Stambaugh and Guyette 2006). In MTNF, prescribe fire treatments began in the early 2000s in order to reduce the threat of wildfire and to improve the health of native plants and wildlife habitat as outlined by the 2005 Land & Resource Management Plan (MTNF - Land & Resources Management). In 2012, the Eleven Point Ranger District of MTNF was selected to be one of the Collaborative Forest Landscape Restoration Program's (CFLRP) projects (MTNF – Forest's Collaborative Forest Landscape Restoration Project 2012-2022). The CFLRP is intended to help restore priority forest landscapes across the country to their pre-settlement condition (MTNF – Forest's Collaborative Forest Landscape Restoration Project 2012-2022). Throughout the Missouri Ozarks, past anthropogenic disturbance in the form of agricultural practices and historic logging has left this area susceptible to invasive species and has degraded shortleaf pine-oak woodland habitats. In MTNF specifically, the CFLRP's focus is on instituting a combination of appropriate silviculture and prescribed burn treatments to help restore the forest to its original condition. (MTNF – Forest's Collaborative Forest Landscape Restoration Project 2012-2022).

As of 2015, approximately 250,000 acres (17%) of MTNF had been identified as priority burn acres that the forest intends to manage into the future (MTNF - Land & Resources Management). These priority burn acres were divided into burn units that have been scheduled to be burned approximately every 2-5 years at the beginning of treatment, and approximately every 3-10 years in the maintenance phase of treatment (MTNF - Land & Resources Management). As of 2015, many of these burn units had been under a burn rotation for 15-20 years (MTNF - Land & Resources Management). In MTNF the forest service works closely with the National Weather Service to conduct prescribed burns under favorable atmospheric conditions that disperse the smoke quickly and minimize smoke impacts to local communities (MTNF - News & Events). Most commonly, prescribed burns in MTNF are scheduled to occur in the spring months, although burning in early winter can occur as well (MTNF - News & Events).

Prescribed fire can reduce low vegetative cover and litter depth causing episodes of excess sediment and runoff entering stream systems (Robichaud 2000; Vega et al. 2005). Prescribed burns can expose bare earth which can lead to soil erosion and an increase in sediment supply and runoff to low order streams (Elliott et al. 1999; Hartman and Heumann 2003; Lane et al. 2006; Singh et al. 2017). Prescribed fires can also decrease rates of infiltration due to an increase in bulk density caused by a collapse in soil structure and clogging of pores by ash and charcoal residues (DeBano et al. 1998). The effect of prescribed fire on forest properties is often based on fire severity which can vary burn to burn, and even vary locally during the same burn event (Parr and Brockett 1999; Johansen et al. 2001). A study conducted by Vega et al. (2005) compared soil erosion and runoff rates between plots affected by different fire intensities during a prescribed burn. This study found that between intensely burned plots and lightly burned plots that runoff was 1.5 times greater, and overall, that burning resulted in runoff rates that were between 2.5 and 1.7 times greater than control plots. It was also determined that intensely burned plots caused significantly more soil erosion that was 5.8 times higher than unburned areas. In the Missouri Ozarks, little research has been conducted on the effects of prescribed burns on forest properties that could therein affect stream channels and water quality.

Headwater Stream Geomorphology

Evaluating the geomorphology of headwater streams is important to understanding watershed disturbance. This is because headwater streams are highly variable, prone to forcing by external influences, and transmit land use disturbances from upland areas down through drainage networks (Reid 1993). Streams channels can be evaluated using a variety of different methods, but are often assessed using a classification framework. Most channel classification frameworks classify rivers into reach types based on their physical characteristics that lend insight into the formative processes that shape that reach (Buffington and Montgomery 2013). Broad stream channel classification can be based on general stream trends such as active/stable, deposition/erosion, anthropogenic/natural, transport-/supply-limited, and state of equilibrium and or evolution (Montgomery and Buffington 1998). For example, Schumm (1977) developed a framework for examining channel processes by broadly defining stream segments within a watershed as erosion, transport, and deposition reaches. More commonly, classification frameworks concentrate on channel form and setting as well as sediment characteristics (Kasprak et al. 2016). Montgomery and Buffington (1997) developed a widely used classification system that categorizes channels into dune ripple, pool riffle, plane bed, step-pool, cascade, bedrock, and colluvial reach types (Figure 4). Based on this classification scheme, headwater streams, especially in Big Barren Creek watershed, tend to lie in the transition between colluvial and alluvial/bedrock categorized channels.

Headwater stream geomorphology can be influenced by a number of factors that affect channel form. The underlying geology of an area can significantly influence how rainfall is routed to streams and the type and quantity of sediment that can be introduced to the stream system (Panfil and Jacobson 2001). The geology of an area is also critical in establishing surface divides between watersheds, valley confinement of stream channels, and subsurface flow systems (Ward 2003). Slope, a factor influenced by geology, is also important when considering a reach's sediment transport capacity and flow rates (Benda et al. 2005). For example, in the Pacific Northwest and the Rocky Mountains headwater streams are dominated by debris-flow processes and those with steeper slopes are more inclined to be supply-limited, while lower-gradient headwaters tend to be transport-limited (Figure 5) (Montgomery and Buffington 1998).

Soil type of a surrounding catchment is also a factor that influences headwater geomorphology. A variety of soil properties can directly influence rates of infiltration and erosion within a catchment (Menashe 1998). For example, shallow and dense soil types tend to have decreased rates of infiltration that can increase rainfall runoff entering adjacent streams (Gomi et al. 2002). It is also known that soils with high silt content tend to be more erodible

(Ward et al. 2003). Catchments composed of highly erodible soil types can lead to an excess of sediment entering nearby streams (Wohl 2014). The soil type of a surrounding catchment can also indicate what sediment may potentially be supplied to the stream. Soils types that contain large rock fragments may supply coarser sediment to headwater streams than soil types composed of finer grains (Wohl 2014). The geomorphology of stream channels, particularly headwater stream channels, is strongly dependent on inputs of sediment and discharge from surrounding catchments (Leopold and Maddock 1953).

The local hydrology of an area and its associated discharge regime can also influence headwater stream geomorphology. Due to the location of headwater streams within a watershed, hillslope hydrology influences headwater channel morphology more so than larger channels (Gomi et al. 2002). For example, headwater channels situated within steep and confined valleys have shorter flow paths and smaller storage capacities (Adams and Spotila 2005). Headwater channels are also unique in that they can more easily accumulate shallow groundwater. Throughflow from the soil matrix at the foot of hillslopes and riparian areas contributes to increased channel flow that gradually increases with increasing wetness of the basin (Gomi et al. 2002). In some steep catchments, subsurface flow can actually exceed overland runoff contributions (Sidle et al. 2000). This subsurface flow, especially during storm events, can also be supplemented by increased saturation overland flow from surrounding hillslopes due to shallow water tables emerging at the soil surface (Bonell 1998). Karstic features such as springs and hollows aid in the concentration of saturated overland flow that initiates channel incision (Jaeger et al. 2007). The rapid transmission of water from hillslopes to headwater streams due to hillslope proximity and contributions from groundwater connections can cause headwater hydrographs to be “flashier” (Figure 6) (Ritter et al. 1995; Bonell 1998; Adams and Spotila

2005). Overall, water inputs of similar magnitudes can have more drastic effects on headwater channels than larger stream channels, and therein be a larger factor in shaping channel morphology.

The hydrology of forest catchments can be greatly affected by the neighboring land use. Land use shifts from forest to agriculture can increase rates of runoff and induce erosion (Lee 1980). Channelization, through the use of agricultural ditches, as well as land clearing for row crops and pasture lands can increase the magnitude and frequency of runoff events (Allan 2004). Soil compaction from grazing-animal traffic can decrease soil infiltration rates and leave soils susceptible to increased runoff and subsequent erosion (Brion et al. 2011). Timber harvesting disturbances including the establishment of logging roads, extraction tracks, landings, and land clearing can also alter local hydrology. Research has also shown that timber harvesting can strongly influence the timing and amount of water, sediment, and nutrients exported to streams from surrounding hillslopes and upland areas (Roberts et al. 2007). Timber harvesting activities, especially the use of heavy machinery, can also lead to persistent surface soil compaction in harvest areas. Soil compaction can lead to increased soil bulk density and decreased rates of surface infiltration (Ole-Meiludie and Njau 1989; Croke et al. 2001). Forest stand composition and density can also lead to dissimilarities in the hydrologic regimes of headwater catchments. Lee (1980), found that annual runoff for mixed-deciduous forest was greater than annual runoff for an oak-hickory forest. Certain tree species also have a higher capacity for rainfall interception than others. Specifically, shortleaf pines have an anticipated interception rate of 0.14 in. compared to 0.10 in. for leafed out hardwoods and 0.05 in. for bare hardwoods (Ward et al. 2003). Differences in dominant tree species and stand densities can affect rates of interception which can ultimately influence runoff rates in surrounding catchments.

Headwater stream geomorphology can also be shaped by forced obstructions. A frequent obstruction to headwater streams is the recruitment of large woody debris. In the Ozark Plateaus region, the geomorphic function of LWD in stream channels includes facilitating pool formation, altering stream flow, forcing local scour, stabilizing banks, increasing bed roughness and heterogeneity, and retaining sediment and coarse organic matter (Montgomery and Buffington 1997; Mitchell et al. 2012). Standing trees within headwater channels have similar geomorphic functions as LWD, but also assist in LWD recruitment as well as bank armoring and stabilization due to root growth (Opperman and Merenlender 2007; Buffington and Montgomery 2013). LWD, standing trees, large clasts, and bedrock outcrops are all obstructions that can contribute to forced planforms such as forced pool-riffle and step-pool channels (Montgomery and Buffington 1998; Nickolotsky and Pavlowsky 2007). The accumulation and distribution of LWD and larger grain sediment in the Ozarks is influenced mainly by inputs from hillslopes and or other low-order tributaries and occasionally by infrequent landslides and debris flows (Montgomery and Buffington 1997; Gomi et al. 2002; Mitchell et al. 2012). Riparian timber stand age, natural perturbations such as ice storms, windstorms, and insect infestations can also contribute to the recruitment of LWD in Ozark headwater streams (Mitchell et al. 2012). Overall, the spatial arrangement of channel obstructions can have a profound effect on headwater morphology.

Geomorphic Analysis of Channels

It is a prominent geomorphic tenet that analysis of channel form can imply the formative hydrogeomrophic processes that control a channel reach (Kasprak et al. 2016). The focus of geomorphic inquiry is often put on understanding the processes at the bank-full stage due to its control on channel equilibrium state and wide application to the field of river management

(Wolman and Miller 1960; Dunne and Leopold 1978; Rosgen 1996). Wolman and Leopold (1957) defined bank-full discharge as the stage when the channel is completely filled just before flow begins to overtop the banks. Studies have indicated that this type of discharge occurs approximately every 1-2 years in humid regions and transports the majority of suspended sediment in many rivers, making this type of flow important for controlling sediment transport processes and channel form (Simon et al. 2014). The notion behind the bank-full concept is that channel form is maintained by the flood energy and sediment load imposed by the watershed over a timespan long enough for the channel to respond or adjust to the "average" hydrologic and sediment inputs (Wolman and Miller 1960). The bank-full concept is often used because it simplifies the complex interactions among flow, sediment, and channel geometry through time (Rosgen 1996). Consistent analysis of fluvial forms and processes at the bank-full stage can also give insight on a channel's progression towards equilibrium (Wohl 2014).

Channel equilibrium at the bank-full condition is typically evaluated in two ways. First, Lane (1955) conceptualized the equilibrium within a stream channel as a balance between force factors that affect flow energy (discharge & channel gradient) and resistance factors that reflect friction or the energy expended at the channel boundary (sediment load & sediment size). Lane's Balance indicates that sediment transport is proportional to stream power and inversely proportional to sediment size (Brierley and Fryirs 2005). Second, Leopold and Maddock (1953) used hydraulic geometry analysis to describe the influence of discharge on channel dimensions both during rising stage at a single cross-section (i.e., at-a-station hydraulic geometry) and downstream variations among a series of cross-sections at bank-full discharge (i.e., longitudinal hydraulic geometry). Channel width, depth, and flow velocity tend to vary systematically with discharge in log-log regression equations, with intercept and slope coefficients varying with water and sediment input regimes (Bieger et al. 2015). Disturbances in the water and sediment regime will first affect bed configuration and sediment size distributions. Then, as the disturbance persists, adjustments will occur to channel geometry including width-depth ratios. Finally, more prolonged disturbances will affect the channel planform such as when braided channels transition to meandering forms (Wohl 2014).

The continuity equation is used in all process-response models of channel form and is defined as Q = w • d • v, where Q is channel discharge (m^3/s), w is the width of the water surface (m), d is the average flow depth (m), and v is the average velocity of flow (m/s) (Knighton 1984). Hydraulic geometry analysis uses regression equations that relate width, depth, and velocity to discharge as power functions: $w = aQ^b$, $d = cQ^f$, and $v = kQ^m$ (Leopold and Maddock 1953). In theory, the product of the intercept coefficients (a x c x k) and sum of the slope coefficients (b + f + m) should both equal unity (1) in a balanced stream channel. Dunne and Leopold (1978) also proposed that if stream discharge data are not available that drainage area could be used as a surrogate. Furthermore, these equations can be used to assess a channel's resistance to changes in discharge and sediment regimes and can be adapted to form regional curves to improve the reliability of local width, depth, velocity, and discharge relationships for stream in different regions (Bieger et al. 2015).

Purpose and Objectives

The purpose of this study is to understand and describe variations in headwater stream channel geomorphology in an Ozarks watershed under forest management. In doing so, this study will attempt to identify geomorphic relationships which help to understand channel form and assess the question of whether prescribed burns affect the hydrology and geomorphic characteristics of small headwater channels.

Studies relating to the geomorphic assessment of headwater streams in the Ozarks has been limited. Shepherd et al. (2011) found that longitudinal characteristics of headwater streams in the Ozarks are controlled by land use and regional geology and that bank-full cross-sectional area and the distribution of bed materials can be used to assess response to land use change. However, these relationships were found on headwater streams that range in drainage area from 12 - 36 km^2 (Shepherd et al. 2011). Geomorphic assessments and classification as well as evaluation of watershed factors for larger streams have also been used to discuss the amount of stream reach dissimilarity within and between the Boston Mountains, Ozark Highlands, and Ouachita Mountains ecoregions (Splinter et al. 2010a; Splinter et al. 2010b; Splinter 2013). Mitchell et al. (2012) assessed the structure and function of large wood in Ozark headwater streams and found the primary functions are to store sediment and stabilize banks. Nickolotsky and Pavlowsky (2007) also determined that for headwater reaches in the Boston Mountains, variations in step height and wavelength are also largely affected by geology. More work that evaluates the variability of Ozark Highland headwater channel morphology and addresses how headwater channel form responds to disturbance events is needed. Recall, that headwater streams include more than two thirds of total stream length in a watershed (Leopold et al. 1964), are sensitive to local hydrogeomrophic conditions, and may therefore be suitable indicators of watershed health (Whiting and Bradley 1993; Sidle et al. 2000, Gomi et al. 2002).

The aims of this research are to analyze and describe low order channel morphology and substrate in Big Barren Creek watershed. Additionally, this study hopes to determine if continued prescribed fire use over multiple years produces variation in headwater geomorphic properties. In order to achieve this goal, four objectives have been identified:

1) Complete a geomorphic assessment of headwater channels draining catchments with different prescribed burn histories and physiography in Big Barren Creek watershed;

2) Evaluate hydraulic geometry relationships for headwater channels;

3) Develop regression equations that use watershed characteristics and channel resistance variables such as LWD and standing trees, to predict channel form and substrate conditions; and

4) Evaluate the influence of channel type, varying catchment relief, and prescribed burn history on headwater channel morphology and substrate.

The information gathered by meeting these objectives will benefit both scientific research and local land management goals. Prescribed fires are becoming an increasingly popular land management tool in the Ozark Highlands and across the country. However, there is a gap in knowledge concerning the effects of prescribed fire on the morphology and substrate of headwater streams. In MTNF, a better understanding of the physical effects of prescribed fires on small streams that drain the majority of forested areas is needed. Additionally, this study will provide valuable insight about the influence of prescribed fires on runoff, sediment, and LWD inputs that control headwater morphology. By understanding how prescribed fires effect headwater channel morphology, this study gives land managers a better understanding of the effects of prescribed burning on forest systems and can aid land managers in making appropriate decisions to further prevent erosion and protect headwater stream stability and hydrologic connectivity.

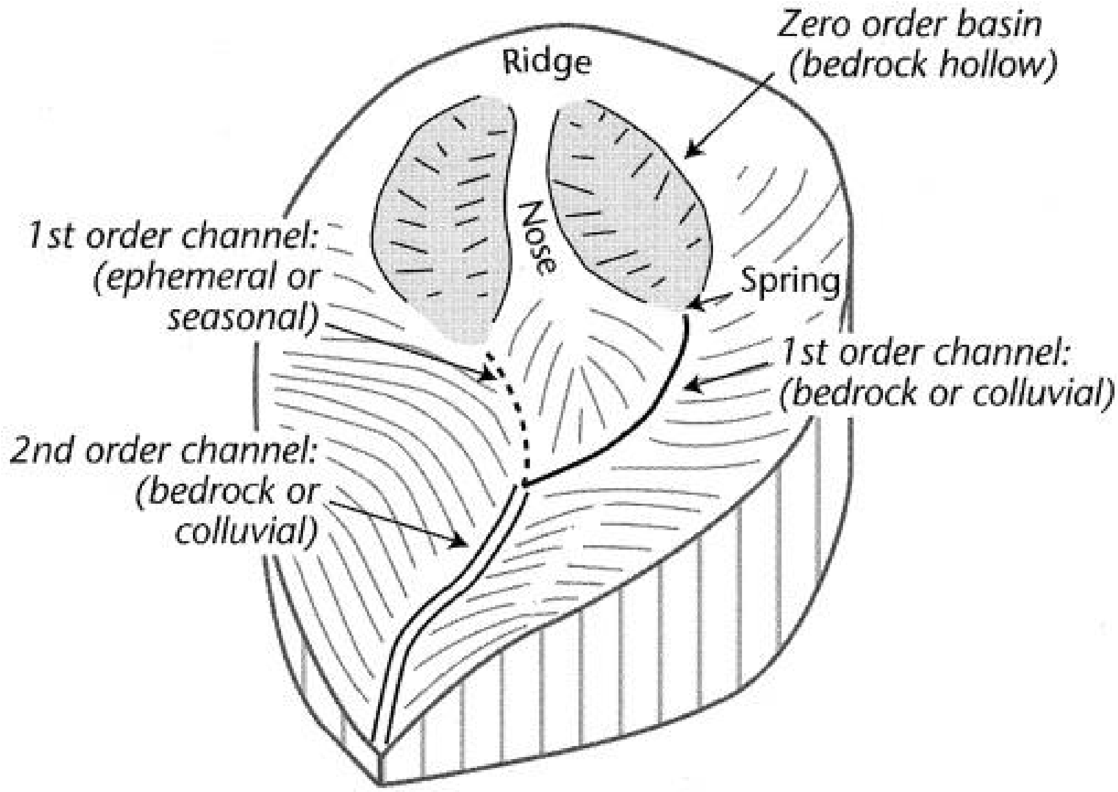


Figure 1. Anatomy of headwater drainage systems (after Hack and Goodlett 1960; Montgomery and Buffington 1997; Benda et al. 2005).

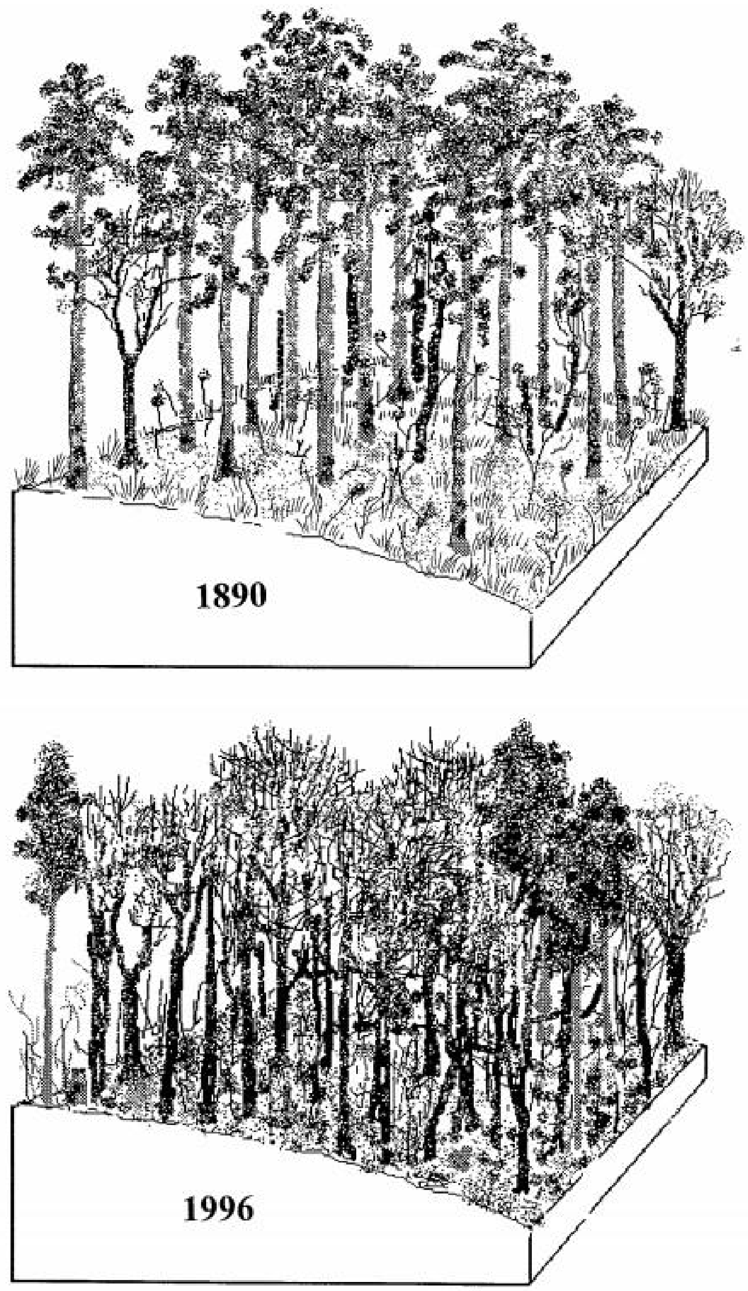


Figure 2. Artist concept of changes at site 8 of the Missouri Ozark Forest Ecosystem Project (Guyette and Dey 1997).

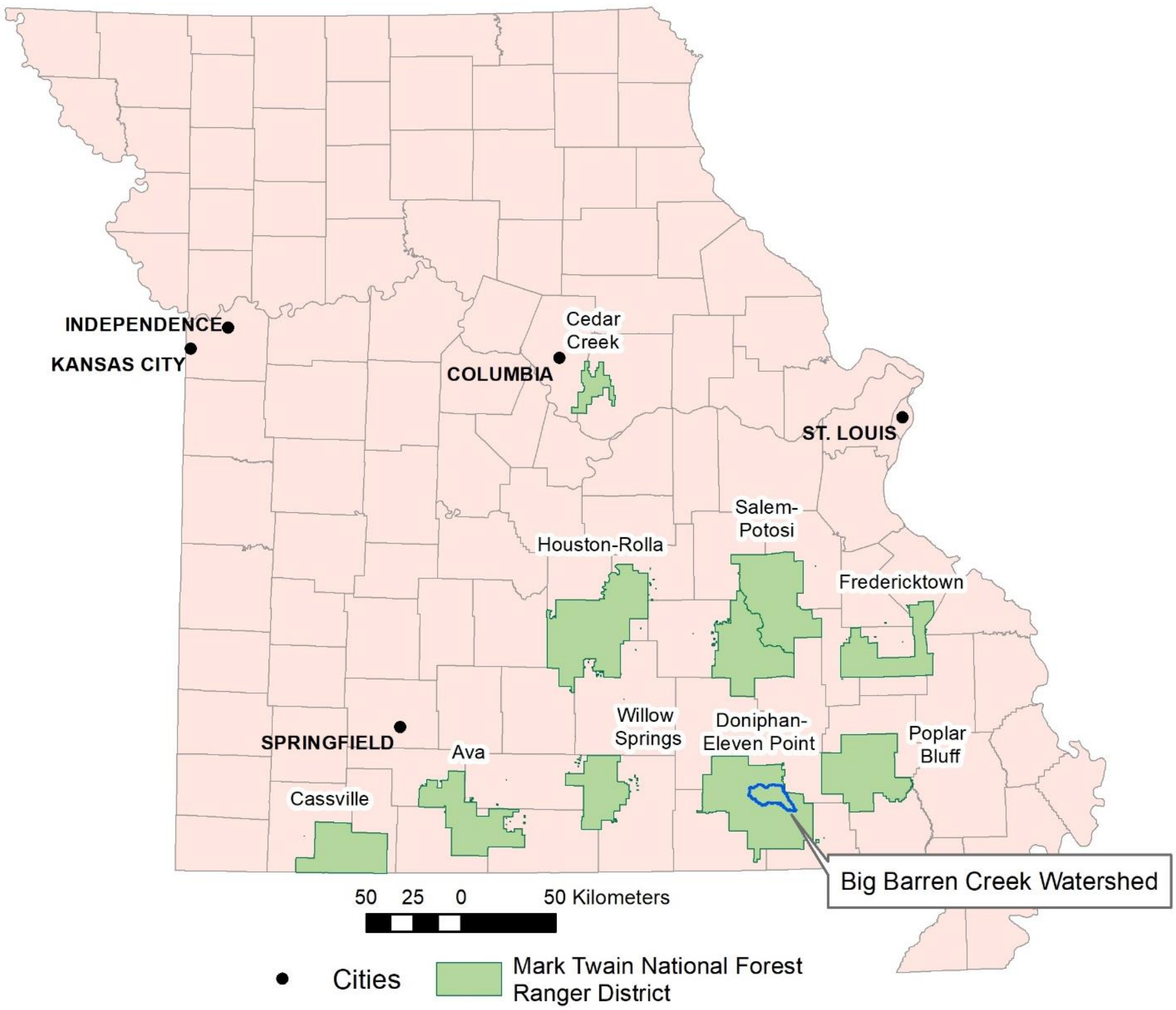


Figure 3. Study area map of Mark Twain National Forest and Big Barren Creek.

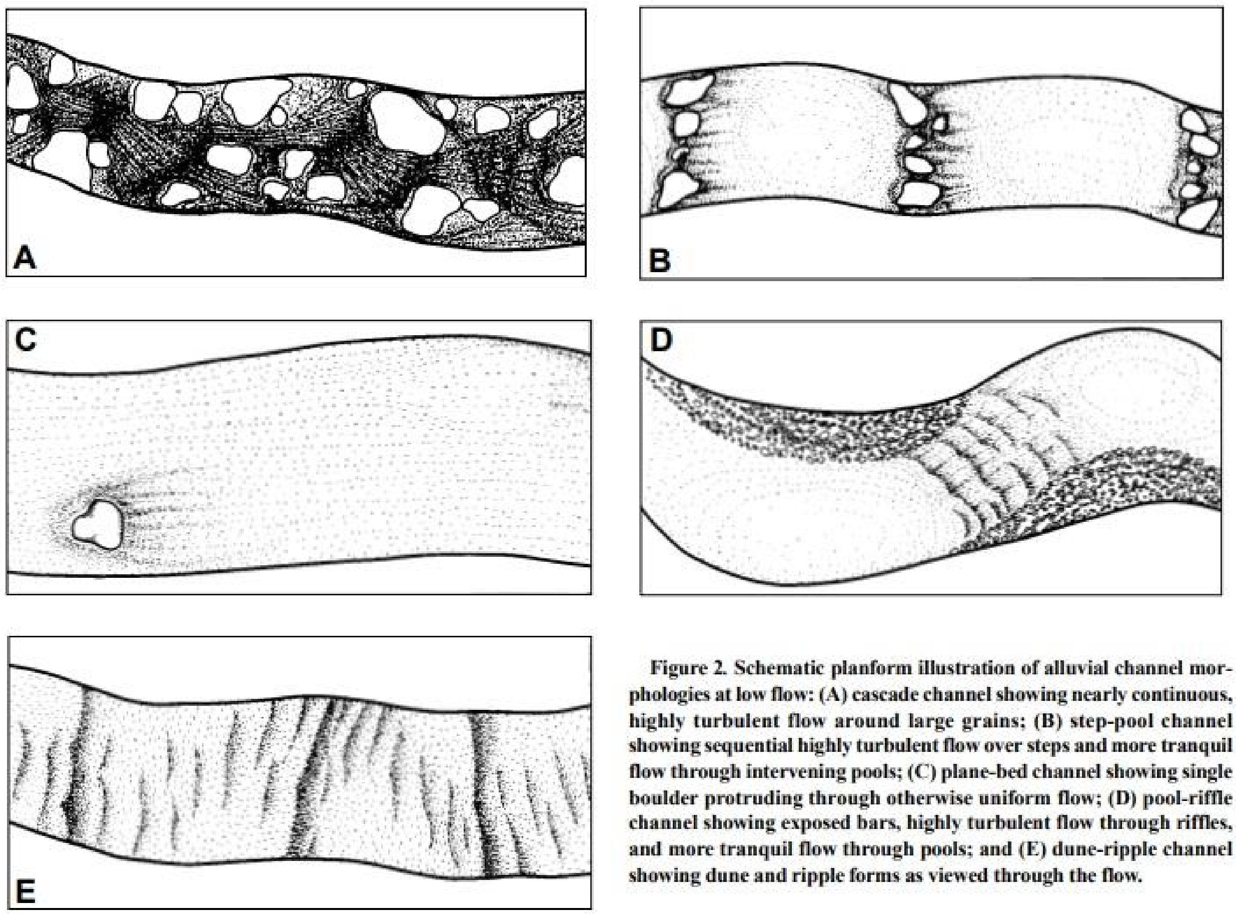


Figure 4. Stream classification of mountain drainage basins (Montgomery and Buffington 1997).

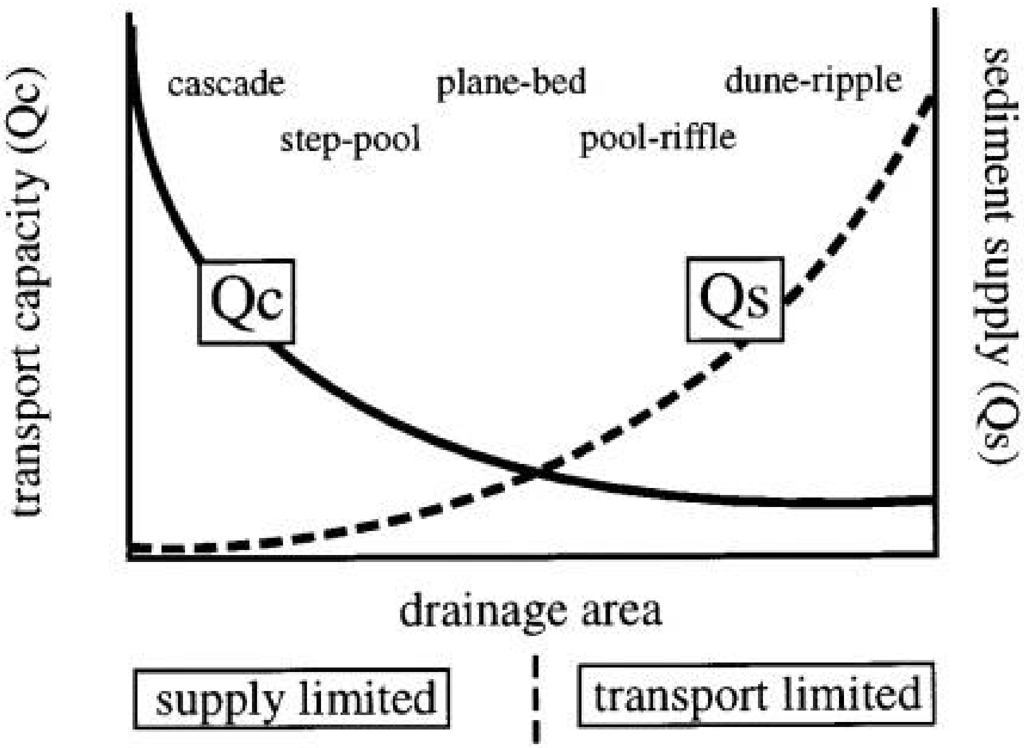
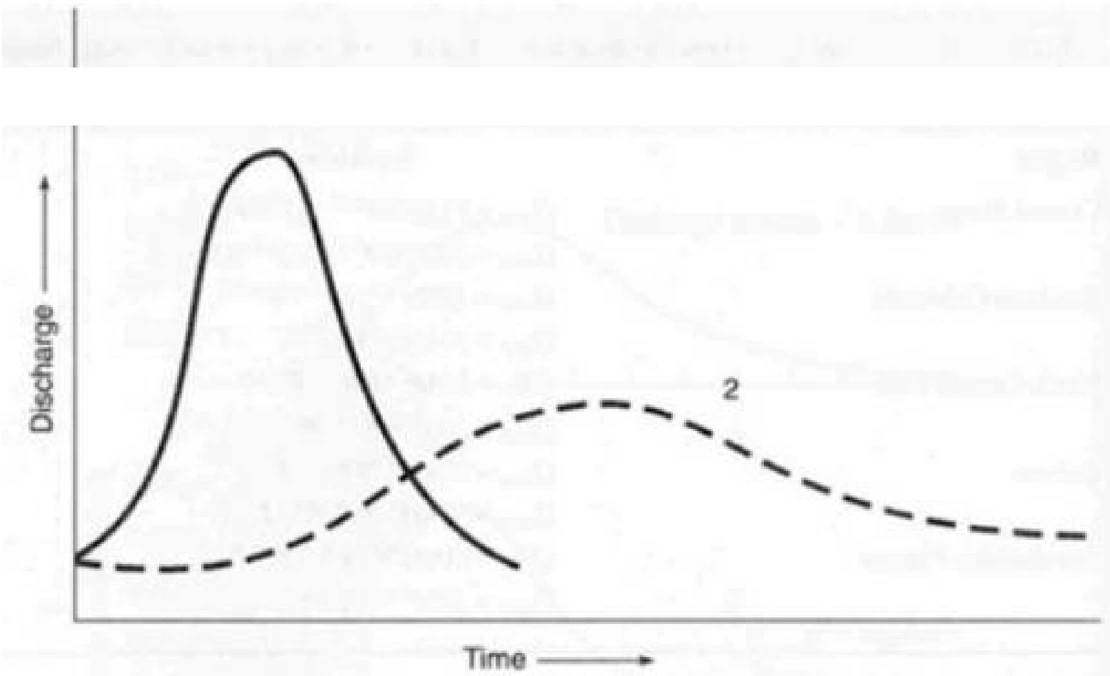


Figure 5. "Schematic illustration of generalized relative trends in sediment supply (Q_s) and transport capacity (Q_c) in mountain drainage basins," (Montgomery and Buffington 1997).



Characteristic	Flashy (hydrograph 1)	Sluggish (hydrograph 2)
Basin area	Small	Large
Drainage density	High	Low
Basin magnitude	High	Low
Relief	High	Low
Ruggedness number	High	Low
Basin shape	Equidimensional	Elongate
Soils	Thin	Thick
Vegetation	Sparse	Dense
Storm track	Down the basin	Up the basin

Figure 6. "Idealized flood hydrograph and generalized responses to drainage basin characteristics. The effect of an individual characteristic is shown assuming the other characteristics are held constant," (Ritter et al. 1995).

STUDY AREA

This project was conducted in the Big Barren Creek watershed located in the Eleven Point Ranger District of Mark Twain National Forest (MTNF). The Big Barren Creek watershed has a drainage area of 190.6 km^2 and is a tributary to the Current River (Figure 7). In August of 1974, congress designated portions of the Current River and adjacent land as the Ozark National Scenic Riverways (Barks 1978). The was done to conserve and preserve Missouri free—flowing streams, springs, caves, and wildlife, as well as establish outdoor recreation resources (Barks 1978). The Big Barren Creek watershed drains portions of Ripley, Oregon, and Carter County in southeast Missouri. The headwaters of Big Barren Creek are located in southwest Carter County and the main channel flows east-southeast toward the northwest corner of Ripley County where it reaches its confluence with the Current River. The Current River then extends down into Arkansas where it converges with the Black River, a tributary to the White River, that which eventually drains into the Mississippi River in east-central Arkansas (Panfil and Jacobson 2001) (Figure 7). Big Barren Creek tributaries include Cedar Bluff Creek (30.6 km^2), Fools Catch Creek (9.9 km^2), Devil's Run (17.0 km^2), Polecat Hollow (6.5 km^2), Wolf Pond Hollow (8.7 km^2), Coward's Hollow (9.2 km^2), and Cave Fork (13.9 km^2) (Figure 7). Headwater streams drain the majority of Big Barren Creek watershed and account for approximately 87% of total stream length in the watershed.

Geology and Soils

Geology. The Big Barren Creek Watershed is located in the Salem Plateau subdivision of the Ozark Highlands physiographic province. The Salem Plateau consists of rolling uplands dominated by dolomite and other carbonate rocks (Panfil and Jacobson 2001). These rocks are of Mississippian age and were originally deposited in shallow seas throughout the Ozark Highlands physiographic province (Orndorff et al. 2001). The Salem Plateau is underlain by a structural dome comprised of Precambrian metamorphic and igneous rocks that come to the surface to form the St. Francois Mountains (Adamski et al. 1995). This plateau contains five major formations, and from youngest to oldest they include: Jefferson City dolomite, Roubidoux Formation, Gasconade Formation, Eminence Formation, and Potosi dolomite (Orndorff et al. 2001). Within the Current River Basin the Roubidoux Formation is found in small amounts and tends to cap ridges, the Gasconade Formation extensively underlies dissected uplands and steep hillslopes, and river valley bottoms consist mainly of the Eminence Formation and Potosi dolomite (Panfil and Jacobson 2001) (Figure 8). However, in eastern and middle portions of the Current Basin, where Big Barren Creek is located, the older geologic formations are more dominant (Panfil and Jacobson 2001).

Within the Big Barren Creek watershed, the Roubidoux Formation and Gasconade Formation are the prominent formation types, with Jefferson City dolomite occurring occasionally. Headwater streams in the Big Barren Creek watershed predominately reside in areas underlain by the Roubidoux Formation. The Roubidoux Formation lies between the Gasconade Formation and the Jefferson City dolomite and is 100 to 300 feet thick (Repetski et al. 1998). The formation is composed of dolomite and sandy dolomite with interlaid beds of sandstone and cherty dolomite (Repetski et al. 1998). In the Ozarks, this formation caps the divides between most streams (Barks 1978). In Carter County, the Roubidoux Formation weathers rapidly and has reduced to layers of clay, sandstone, and chert (Butler 1990). Due to the rapid weathering of the Roubidoux, resulting slopes can be characterized by loose blocks of sandstone (Repetski et al. 1998). Chert float blocks from the middle section of the formation are also common (Repetski et al. 1998).

Soils. Soils in the Ozark Highlands form primarily in loess, hillslope colluvium, residuum, or gravelly alluvium (Kabrick et al. 2000). Within the Current River basin Quaternary loess deposits occur on flat, stable landforms (Kabrick et al. 2000). However, most upland soils are composed of alfisol and ultisol soil orders that are highly weathered and vary in texture, gravel content, and range in depth to bedrock (Adamski et al. 1995). These soil types can be described as deciduous forest soils that are found in semiarid to humid areas with a clay enriched subsoil and moderately low amounts of organic matter (Vander Veen and Preston 2006). Most bottomland soils are not as weathered, formed in alluvium, and include inceptisols and entisols soil order types (Kabrick et al 2000; Vander Veen and Preston 2006). Although soil types in this area are diverse, in general most of these soils have a high potential for nutrient leaching into groundwater and runoff (Adamski et al. 1995).

Within the Big Barren Creek watershed, the most common soil series include Macedonia silt loam, Captina silt loam, Clarksville very gravelly silt loam, Coulstone gravelly sandy loam, Doniphan gravelly silt loam, Wilderness gravelly silt loam, Poynor very gravelly silt loam, and Viraton silt loam (Hente 2017). The majority of headwater streams located within the Big Barren Creek watershed are found in areas that contain Macedonia silt loam, Captina silt loam, Clarksville very gravelly silt loam, and Coulstone very gravelly sandy loam (Table 1; Figure 9). The majority of these soil series are part of the Ultisol soil order. The Macedonia, Clarksville, and Coulstone soil series are all typic paleudults while the Captina silt loam is a typic fragiudult. The distribution of soil series in the watershed shows that the Clarksville very gravelly silt loam is more commonly found near larger stream sections and is more ubiquitous throughout the entire watershed than the other soil types. The Captina silt loam is more common in the eastern portion of the watershed, while the Macedonia silt loam and Coulstone very gravelly sandy loam tend to be located in the western half of the watershed. For headwater areas in this watershed, the Clarksville very gravelly silt loam appears to be situated at lower elevations than the other soil series (Figure 9).

Climate and Hydrology

Climate. The Missouri Ozark Highlands region has a temperate climate with humid-continental and humid subtropical weather conditions that are consistent with mid-continent and middle latitude locations (Stambaugh and Guyette 2004). General circulation patterns dominate local climate with major weather systems typically moving across the region from west to east (Adamski et al. 1995). In early spring and throughout the summer months this region is influenced by moisture-laden air masses that move into the area from the Gulf of Mexico. These air masses can produce severe weather including thunderstorms, tornadoes, and intense rainfall (Adamski et al. 1995).

In the Missouri Ozarks, mean monthly precipitation, generally in the form of rain, is approximately 9.25 cm (3.64 inches) (Adamski et. al 1995). Mean annual precipitation in the Big Barren Creek watershed is estimated to be 119.8 cm (47.2 in) for 1956 – 2014. This estimation is based on an inverse distance-weighted average of six stations within 70 km of the Big Barren Creek watershed (Pavlowsky et al. 2016). Annual rainfall has been increasing 0.22 cm (0.09 in) every year on average over the last 60 years (Pavlowsky et al. 2016). Similar to regional trends, in the Big Barren Creek watershed the highest rainfall totals tend to occur in the fall and spring (Pavlowsky et al. 2016). Historically, high magnitude rainfall events account for a large portion of annual rainfall in the region and in recent years 7.5 cm (3”) per day events have become more common (Stambaugh and Guyette 2004; Pavlowsky et al. 2016). Overall, high magnitude rainfall events are becoming more intense and occurring more frequently in this region (Pavlowsky et al. 2016).

Hydrology. Due to the abundance of carbonate rocks in the Missouri Ozarks, this region is dominated by karst terrain (Panfil and Jacobson 2001). Karst topography in this region allows for the development of subsurface drainage systems. These systems channel upland precipitation and runoff flow underground where it can be transported and resurface in valley bottom springs (Jacobson and Primm 1997). Extensive karst terrain gives the Ozarks defining features of sinkholes, losing streams, caves, and spring fed streams (Panfil and Jacobson 2001).

In the Big Barren Creek watershed, segments of the main channel are dry almost all year due to extensive underground karst systems, while other segments are supplied with perennial baseflow from springs (Orndorff et al. 2001). For example, in the designated Big Barren Creek Natural Area, established in 1989 by the Missouri Department of Conservation, Big Barren Creek is fed by springs that provide continuous flow (Whitacre 2008). Upstream and downstream of this natural area, Big Barren Creek is a losing, ephemeral creek that runs dry for the majority of the year (Bradley RA 2017). The Missouri Department of Natural Resources has designated 36.7 km of Big Barren Creek as a losing stream. However, field visits have determined that the 2.4 km of Big Barren Creek that flows through the Big Barren Creek Natural Area was mis-categorized and is a gaining stream. The local topography and Big Barren Creek’s extensive connection to karst drainage systems contributes to the ephemeral nature of headwater channels in the watershed.

Land Use and Vegetation

Land Use. Prior to European settlement in the Missouri Ozarks region, the people that occupied this area relied on hunting and gathering for subsistence and dwelled in caves or in small villages on river terraces. European settlement led to land clearing in order to establish row crops and pasture lands (Panfil and Jacobson 2001). From 1880 to 1920 commercial timber harvesting operations decimated the native short leaf pine forests in this region. A decrease in forested area made room for increased livestock grazing, row crop farming, and development which has continued into recent years (Adamski et al. 1995). Wildfires were relatively frequent in the Ozarks region before European settlement and contributed to fire dependent ecological structures. Wildfires persist in this area today but are almost exclusively human-initiated surface fires with rare cases of stand replacing fires (Stambaugh and Guyette 2006). Intentional use of controlled fires has been documented in this area since before European settlement. Historical accounts exist of fires that were set by Native Americans who inhabited the region as a way to improve grasslands for grazing by large game, aid in hunting, and to harass enemies (Jacobson and Primm 1997). When Ozark residents returned to farming practices after the timber harvest boom, annual burning of uplands was also common to increase grazing on open ranges (Panfil and Jacobson 2001). However, this practice was discontinued after regulations were set on open range grazing practices.

The use of fire to alter the landscape in the Missouri Ozarks was not used again until prescribed burns became an integral part of land management practices in the late 1990s and early 2000s (Dey and Hartman 2005; Stambaugh and Guyette 2006). Currently, general land use practices common in this watershed include using land for timber production and agricultural purposes (Vander Veen and Preston 2006). Approximately 75% of the watershed is also owned and operated by the National Forest Service as part of MTNF (Figure 7). Of the eastern public forest lands and according to the U.S. Forest Service website, MTNF is the largest government-owned forest in Missouri (MTNF – Points of Pride).

Vegetation. Historic accounts describe the pre-settlement Ozark landscape as one with abundant prairies, oak savannahs, and oak-pine forests with open, grassy undergrowth (Jacobson and Primm 1997). More than 4 million acres of Missouri Ozarks was dominated by pine species prior to European settlement (Ladd et al. 2007). Pre-settlement vegetation consisted of pine dominated woodlands, an open canopy, and a diverse yet consistent assemblage of perennial upland herbaceous vascular taxa associated with pine-based ecological systems (Ladd et al. 2007). During the extensive timber harvest period in the late 1800s through early 1900s, poor transportation in the Reynolds, Carter, Shannon, and Ripley County areas led to the development of railroads and small tram ways to facilitate logging operations (Guyette and Larsen 2000). The spatial arrangement of this logging infrastructure played a large part in developing current forest vegetation structure as well as local geomorphology (Guyette and Larsen 2000; Bradley NS 2017).

Intensive land clearing from the timber harvest boom as well as fire suppression throughout the majority of the 20th century allowed for invasive species to infiltrate, thrive, and outcompete native species such as the shortleaf pine (Cunningham 2007). Due to this, forest structure has shifted more towards an oak-hickory dominated landscape as opposed to oak-pine dominated forest stands. Ozark regional forest health problems associated with oak decline and red oak borer have made pine restoration efforts critical to maintaining sustainable oak-pine forest types (Stambaugh and Guyette 2004).

Prescribed Fire Use in Mark Twain National Forest

In the Ozarks during the late 1990s and early 2000s, prescribed fire treatments started to be used as a restoration and conservation tool by land management agencies (Dey and Hartman 2005; Stambaugh and Guyette 2006). In 2012 the Eleven Point Ranger District of MTNF, including the Big Barren Creek watershed, was selected to be one of the Collaborative Forest Landscape Restoration Program's (CFLRP) projects. The CFLRP was developed by the Omnibus Public Land Management Act of 2009 and is intended to help restore priority forest landscapes with the help of landowners and community partners (MTNF – Forest's Collaborative Forest Landscape Restoration Project 2012-2022). The objectives of this project are to be carried out by the U.S. Forest Service and include encouraging ecological, economic, and social sustainability; leveraging local resources with national and private resources to meet forest management goals; facilitating the reduction of wildfire management costs and re-establish natural fire regimes; demonstrating which ecological restoration techniques are most efficient; and encouraging restoration practices that will lead to outcomes that offset treatment costs (Schultz et al. 2012). In the Eleven Point Ranger District of MTNF the CFLRP has focused on instituting a combination of appropriate silviculture and prescribed burning treatments to help restore the forest to its original shortleaf pine-oak woodlands habitat (MTNF – Forest's Collaborative Forest Landscape Restoration Project 2012-2022).

In the Big Barren Creek watershed located within the Eleven Point Ranger District of MTNF, the use of prescribed burns was first documented in 2002. After the Eleven Point Ranger District was instituted as a CFLRP project, the use of prescribed burns increased. As of 2018, approximately 21,300 acres of forest within the Big Barren Creek watershed has been subjected to prescribe burn treatments (Figure 10). Some of these areas, especially units in the northwest portion of the watershed, are regularly burned on an approximate two to three year basis. Overall, these burns are used to mimic historic fire regimes in order to reduce fuel loading in hardwood ecosystems while stimulating grass and forb plant communities by maintaining open areas in glade and prairie ecosystems (MTNF – Prescribed burning on the Mark Twain National Forest).

Table 1. Soil Properties (USDA-WSS, 2019).

Soil Series	Landform	Slope Classes	Parent Material	Chert Fragments in Top Layer of Soil (%)	Depth to Bt (in)	Depth to Bx (in)
Macedonia	Ridges, hillslopes, interfluves, and divides.	3 to 8 and 8 to 15 percent slopes	Loess over residuum weathered from cherty limestone.	0	9	-
Captina	Hillslopes	3 to 8 percent slopes	Loess over pedisediment over residuum weathered from cherty limestone.	0	5	25
Doniphan	Interfluves and Hillslopes	3 to 8 and 15 to 35 percent slopes	Slope alluvium over residuum weathered from dolomite.	7	13	-
Clarksville	Hillslopes	8 to 15 and 15 to 35 percent slopes	Slope alluvium over residuum weathered from dolomite.	0-5	13	-
Coulstone	Hillslopes, interfluves, and ridges.	3 to 8, 15 to 35, and 35 to 60 percent slopes	Slope alluvium over residuum weathered from sandstone.	5-15	8	-
Tilk-Secesh	Drainageways	1 to 3 percent slopes	Gravelly alluvium	0	8	-

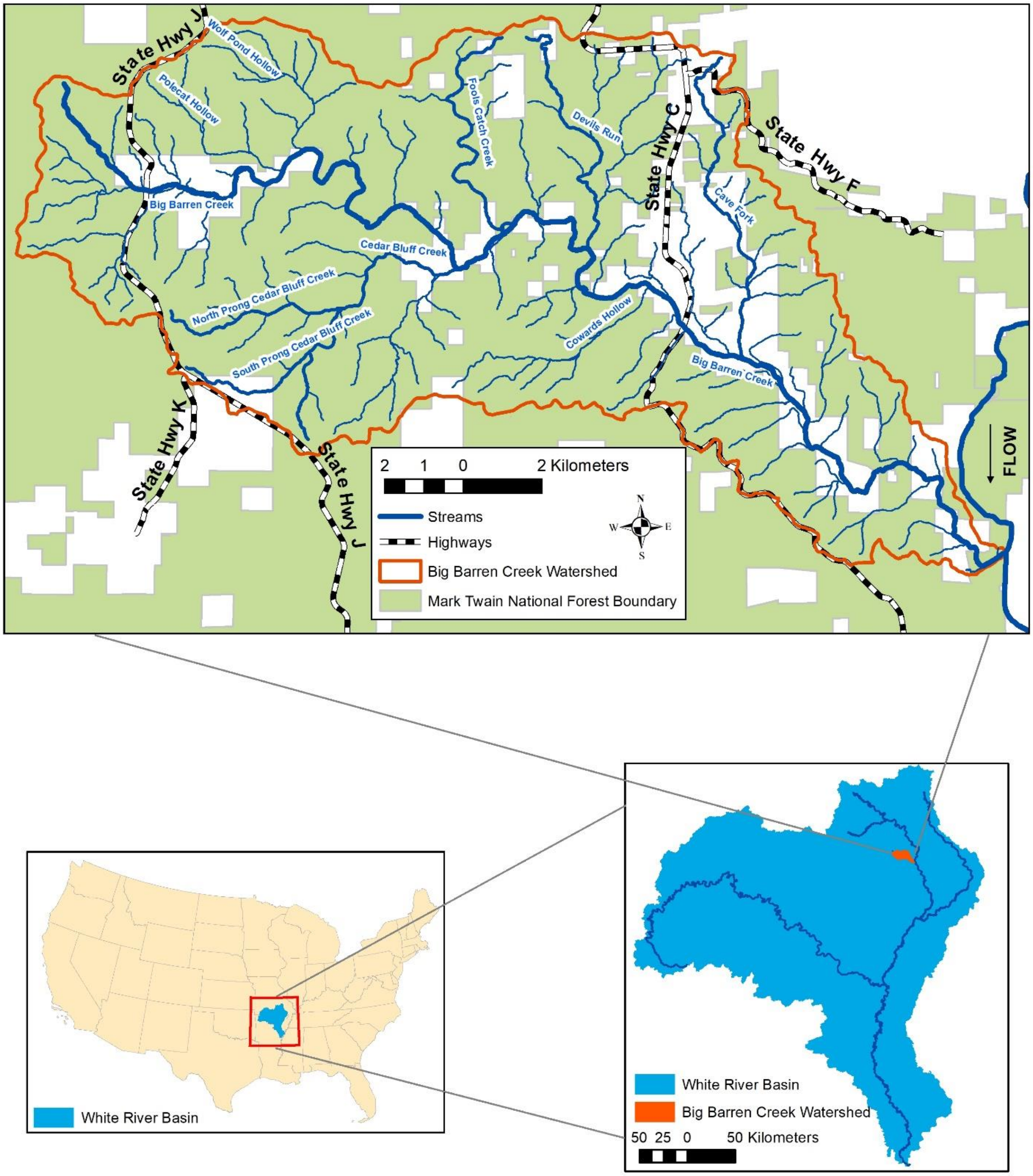


Figure 7. The Big Barren Creek watershed location and tributary streams.

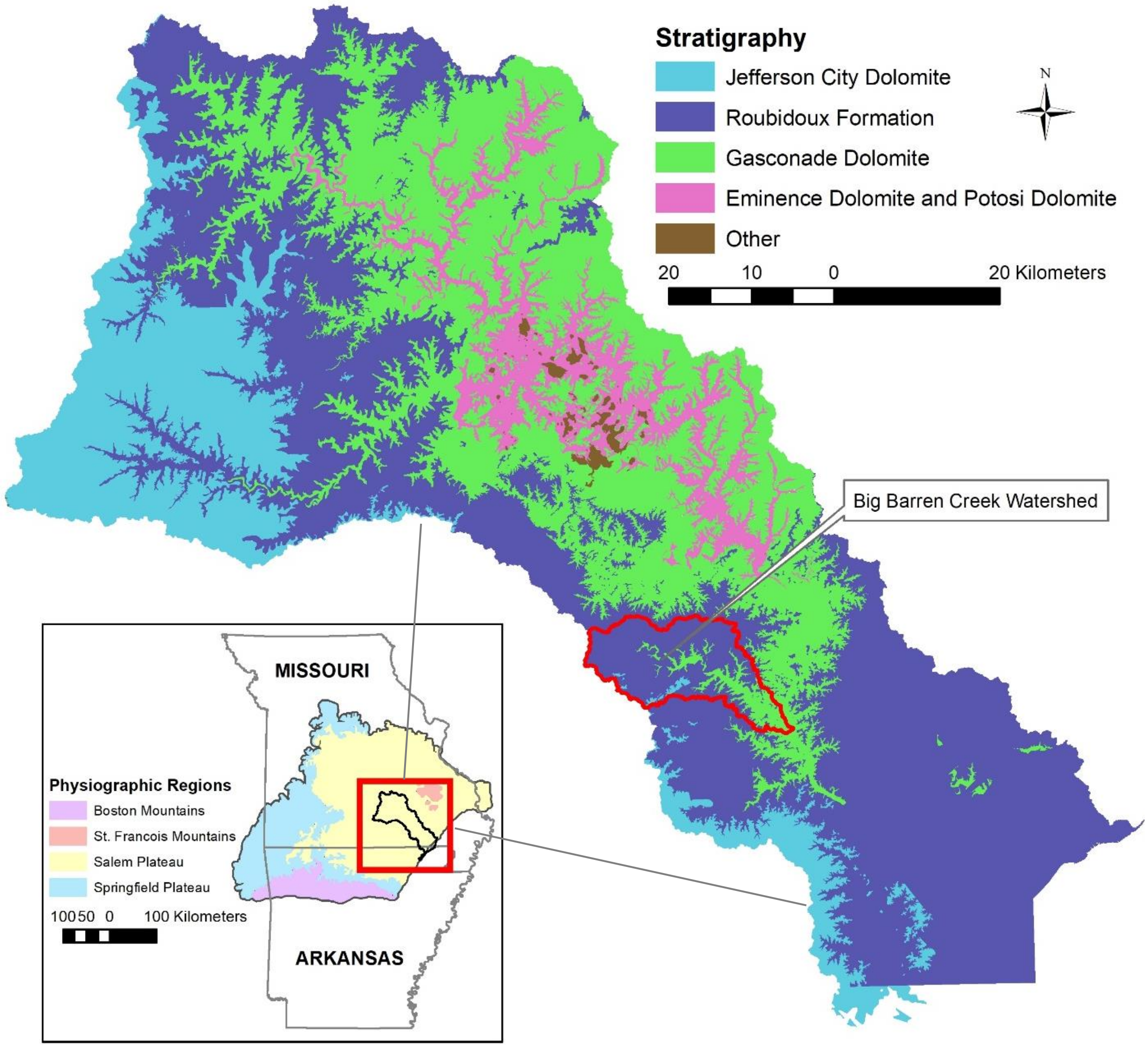


Figure 8. Geology and location of the Current River Basin.

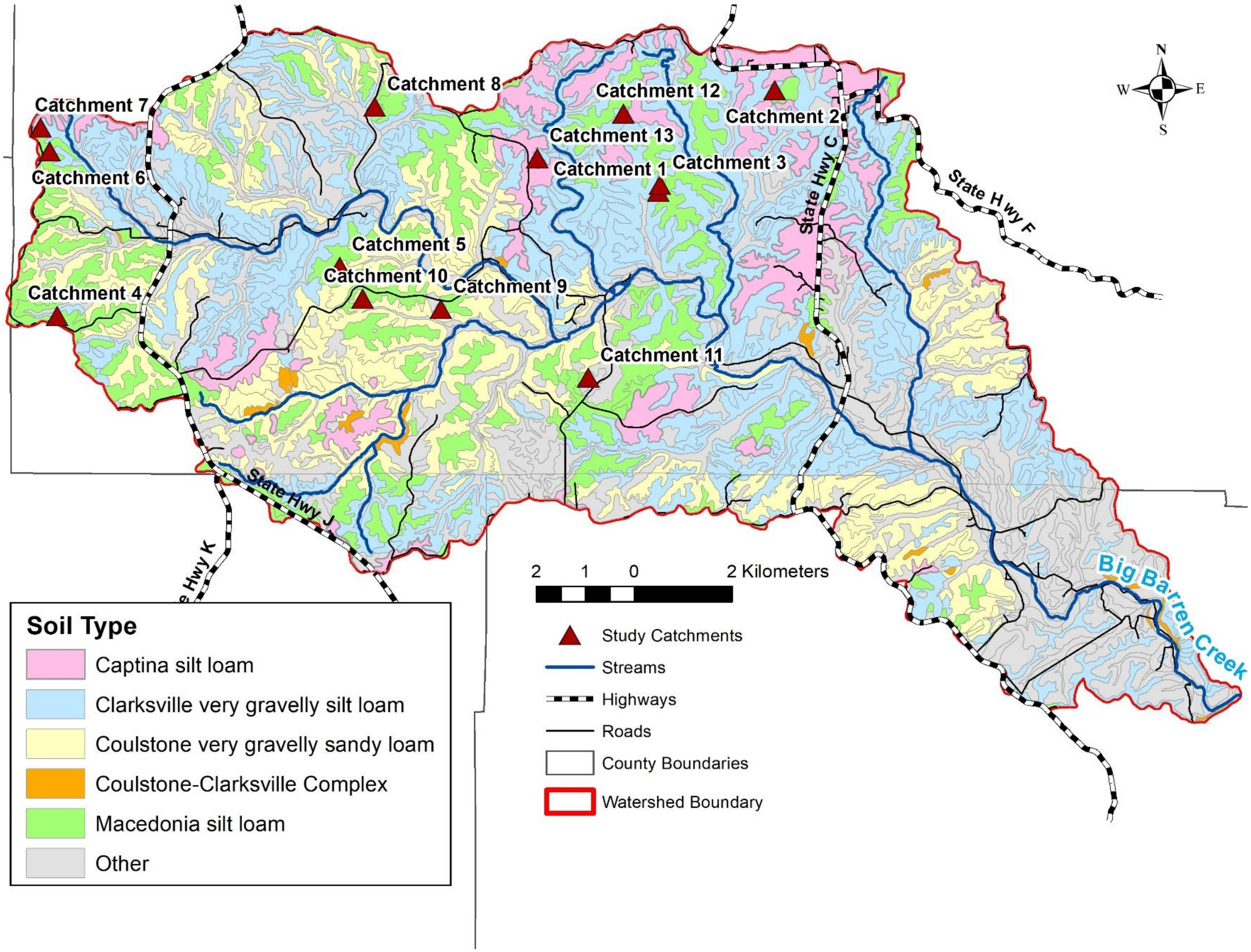


Figure 9. Common upland soil types associated with headwater streams in the Big Barren Creek watershed.

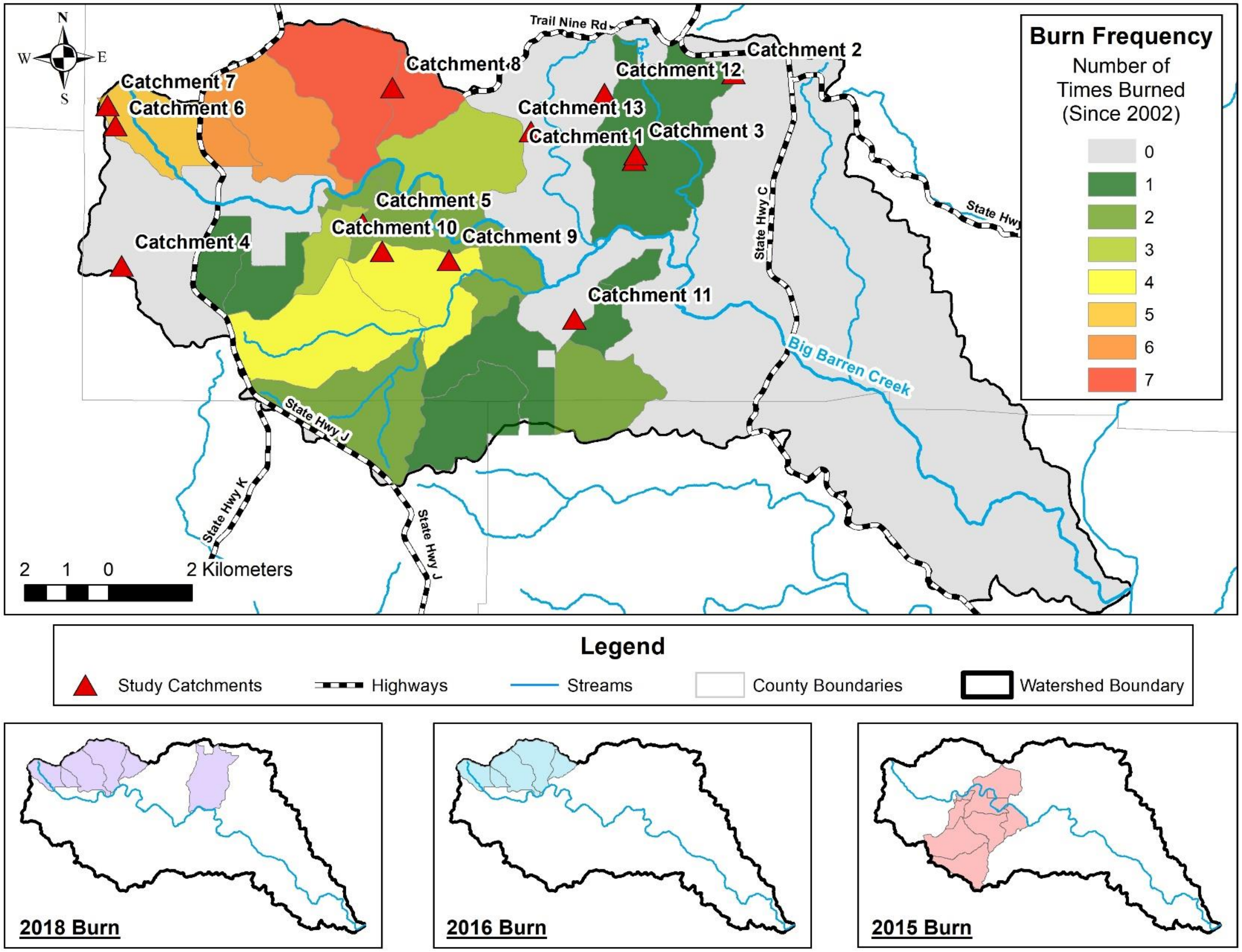


Figure 10. Prescribed burn history and burned areas from past years in the Big Barren Creek watershed.
Note: No units in the Big Barren Creek watershed were burned in 2017.

METHODS

The main goal of this project was to assess the geomorphic characteristics and channel properties of headwater streams. Additionally, these features will be compared among reaches with differing prescribe burn histories. In order to meet this goal a variety of methods were utilized. Geographic Information System (GIS) was used in site selection and to determine headwater catchment properties. Geomorphic assessments were also used in the field to collect data on the geomorphic, substrate, and vegetative characteristics of the selected stream channels. The rational equation as well as a precipitation database allowed for reference discharges to be estimated for each headwater channel to approximate the bank-full stage. The estimated reference discharges and cross-sectional survey data were entered into Hydraflow Express software for hydraulic modeling. Modeling outputs estimated channel geometry including width, depth, and velocity at bank-full discharge. Statistical analysis using linear regression was then used to evaluate the geomorphic characteristics and catchment relationships of headwater stream channels in the Big Barren Creek watershed and to determine if any statistically significant variation exits between reaches with different prescribe burn history.

Site Selection

A total of 38 headwater channel reach sites were evaluated in 13 different headwater catchments. Channel sites were generally nested in catchments where two or more first order streams converged to form a second order stream. A total of 26 first order channel sites were selected and have drainage areas that range from 0.29 to 14.73 ha. In addition, a total of 12 second order channel sites were selected that have drainage areas that range from 3.11 to 20.9 ha.

Study catchments were generally selected based on their association to an ongoing Ozarks Environmental and Water Resources Institute monitoring program with permanent sites on uplands areas in Big Barren Creek watershed (Hente 2017; Roman et al. 2019).

The channel reach sites and catchments used in this research were also selected based on four different factors. Firstly, study channel sites were selected in areas that drained soil series with loess parent material or with relatively high silt content such as the Macedonia soil series. Catchments that consist of soils with loess parent material and high silt contents are more vulnerable to erosion than catchments with different soil types (Ward et al. 2003). Secondly, catchments and sites were selected based on their prescribed burn histories. Sites selected represent a gradient of burn frequencies with burned sites having burn frequencies that range from 0 to 7 times burned since 2002. The burn history of the Big Barren Creek watershed was assessed using digitized burn unit polygons in ArcGIS as well as burn unit burn frequency records, both of which were provided by the U.S. Forest Service, to develop a burn index map (Figure 10). A total of 21 burn units have been established in the Big Barren Creek watershed by the U.S. Forest Service equating to 45.3% of the total area of the watershed. Thirdly, the study channel sites selected also represent a gradient of slopes. Slope can ultimately influence a reach’s stream power and ability to transport sediment (Benda et al. 2005). Therefore, sites with varying slopes may experience natural differences in geomorphology and may also be affected by prescribed burns in different ways. The fourth factor that was considered in site selection was forest stand type. Catchment hydrology and erosive potential can be affected by forest stand type by influencing rates of interception and forest floor composition (Lee 1980; Ward et al. 2003). Study catchments were populated by eight different forest stand types, with shortleaf pine being the most abundant followed by white oak. All four of these factors were considered during the site selection process in order to generate a representative sample of headwater streams within the Big Barren Creek watershed.

Field Methods

Field data was collected during March, July, September, and December of 2018. Preliminary field surveys of catchments were performed in order to establish that an area had substantial headwater channel development and that further surveying was possible. If the potential study catchment was deemed suitable, a geomorphic assessment was completed on at least one or more first order streams and typically on a second order stream as well. GPS locations were recorded for each reach using a Trimble GPS tool and TerraSync software. GPS points were taken at the furthest upstream and downstream points of the reach, at the beginning and ends of the cross-section, and where the cross-section crossed the thalweg of the stream. GPS points were taken for the dual purpose of future GIS analysis and to record the location of the study site in case it needed to be revisited. Pictures were also taken to document the landscape of the reach when it was sampled and to validate cross-sectional surveys.

Geomorphic assessments were completed at each channel reach site including a cross-sectional survey, a pebble count, and large woody debris (LWD) and standing tree tallies (Wolman 1954; Harrelson et al. 1994; Rosgen 1996; Schuett-Hames et al. 1999). Channel cross-sections were collected perpendicular to the channel in an area that most closely resembled a riffle or glide. A 100 meter tape was stretched across the cross-section and often extended to the valley walls so that geomorphic landforms could be surveyed. The reach width was estimated as the width of the active channel and was used to determine the reach length as five channel widths upstream and five channel widths downstream from the cross-section (Harrelson et al. 1994). A

100 meter tape was also stretched down the center line of the channel as a visual aid. An auto level, tripod, and stadia rod were then used to conduct the cross-sectional survey in a way that geomorphic landforms, such as channel banks, benches, and floodplains, could be distinguished (Harrelson et al. 1994). Points were also taken at surface slope breaks where landforms could not be discerned. The amount of survey points taken at each cross-section ranged from 7 - 15 with an average of 11 survey points per cross-section. The total stream length assessed was 1,200 meters with the average sample reach length being 31.6 m long with an average channel width of 3.2 m. Longitudinal profiles of each reach were later assessed using ArcGIS software and LiDAR imagery.

Pebble counts were also conducted at each site in accordance with the Wolman (1954) method to classify substrate material for each reach. A total of 30 pebble count measurements were taken at each site using a gravelometer (Rosgen 1996). Depending on the length of the site, the number of transects as well as the number of pebbles counted at each transect varied. Typically sites were either 30 or 40 meters in length. For reaches 30 meters long, five pebbles would be counted along six evenly-spaced transects. For reaches 40 meters long, six pebbles would be counted along five transects. Particle size measurements collected in situ were then later used to develop grain size distributions for each headwater stream reach.

A LWD and standing tree inventory was also completed for each reach. For this study, LWD was defined as any piece of wood equal to or larger than 10 cm in diameter for a length of 1.5 m (Schuett-Hames et al. 1999). Any standing tree 13 cm in diameter at DBH or larger was also documented. All LWD and standing trees sampled were contained within the active width of the channel reach. For LWD, the diameter and length of each piece was measured and qualitative properties including type, orientation, age, anchor type, and geomorphic effect was recorded for each piece. The DBH for each standing tree was also measured in addition to tree location in the channel and distance along the longitudinal tape.

Geospatial Methods.

Stream and Watershed Delineation. Streams in the Big Barren Creek watershed were delineated using a half-meter spatial resolution, LiDAR derived DEM provided by the U.S. Forest Service. This DEM and the ArcGIS hydrologic set of spatial analyst tools were used to create flow direction and flow accumulation rasters. These rasters were then used to classify pixels as either stream and non-stream pixels. Pixels that drain approximately 2,500 m^2 were classified as stream pixels and collected to form a stream network. The stream network derived at this scale was used because it was most similar to stream systems observed in the field. The derived stream network was then ordered according to the Strahler method (Strahler 1957) using ArcGIS's 'stream order' tool. Stream channels surveyed in the field were then verified as headwater channels using GPS locations. The flow direction and flow accumulation rasters were also used to delineate the headwater catchments associated with each study reach surveyed. The GPS location at the point where the cross-section and thalweg intersected was used as a reference point to delineate the surrounding catchments of each reach. Once a catchment for each study reach was created, the drainage area of each catchment was calculated using ArcGIS.

Upland Forest Properties. Geospatial methods were also used to assess upland forest properties in the Big Barren Creek watershed. Overall watershed land use was determined using ArcGIS software and land use data sourced by the Multi-Resolution Land Characteristics Consortium. The land use for all headwater catchments included in this study is forested. The underlying geology of the area was also assessed using the Missouri Spatial Data Information

Service's 500K scale bedrock geology data. All headwater catchments in this study tend to be underlain by the Roubidoux Formation. Soil data for the Big Barren Creek watershed was also retrieved from the Web Soil Survey operated by the USDA Natural Resources Conservation Service. This soil data was used to determine the composition and distribution of soil types in the Big Barren Creek watershed, especially in headwater areas and in each study catchment. The forest stand type and site management for each headwater catchment was also determined using ecological spatial data provided by the FSGeodata Clearinghouse. All of the data associated with Big Barren Creek watershed's upland forest properties was stored in geodatabases on the OEWRI server.

Channel and Basin Slope. Channel slope as well as basin slope were also calculated using ArcGIS for each study reach and catchment. The previously delineated stream network and ArcGIS's 'generate points along lines' tool was then used to create longitudinal profiles of headwater streams surveyed. A point was placed every two meters along the stream feature for fifty meters above and below each cross-section. Elevation values from the half-meter DEM were then extracted to each point along the stream. Point elevations and distances were plotted in Microsoft Excel in order to develop the longitudinal profile of each stream. Channel slope was then calculated from these plots using linear trendlines. Basin slope was calculated using the methods described by Alexander and Wilson (1995). This method divides the difference in elevations at the points that are 10% and 85% of the distance from the reach's cross-section to the basin divide, by the distance between the two points. Overall, these methods were used as an objective way to consistently derive channel and basin slope for each study reach.

Hydraulic Modeling

Rational Equation. All headwater streams assessed by this study were ungaged, and so the rational method was used to estimate peak flow. The rational method was first developed by Kuichling (1889) for small urban drainage basins, but is the basic design for many small catchments**.** The ration equation is one of the simplest methods and is based on the assumptions that 1) rainfall is distributed uniformly over a drainage area; 2) peak rate of runoff is representative of the rainfall intensity averaged over the time of concentration for a drainage area; 3) time of concentration is the time required for flow to reach a specific point from the most out-lying part of the watershed; and 4) frequency of runoff is equal to the frequency of rainfall used (Ward et al., 2016). The rational equation is defined as q = kCiA. For this equation, q is the peak flow (ft3/s), k is 1.008 for q in ft^3/s or 0.0028 for q in m^3/s, C is an empirical runoff coefficient, i is the average rainfall intensity (in./h) during the time of concentration, and A is the drainage area (acres) (Ward et al. 2003).

The methods outlined by Pavlowsky et al. (2016) and precipitation data collected from the Midwestern Regional Climate Center's (MRCC) cli-MATE website were used to calculate the average rainfall intensity for headwater streams in the Big Barren Creek watershed. A total of 30 years of data was selected to calculate the two-year precipitation recurrence interval. Considering the rational method assumes that the frequencies of peak runoff and rainfall are equal, the two-year precipitation recurrence interval was used to simulate the two-year discharge recurrence interval that is associated with bank-full, channel-forming flow in higher ordered streams (Wolman and Miller 1960). The time of concentration for each headwater drainage area was determined by using the Kirpich (1940) method and equation. The Kirpich Equation states that $t_c = kL^{0.77}S^{-0.385}$, where t_c is the time of concentration, L is the hydraulic length, S is the mean slope along the hydraulic length, and k is a numerical constant. Empirical runoff coefficients can be selected from a published table and were selected from Table 5.5 in Ward et al. (2003). This runoff coefficient table uses the hydrologic soil group, slope range of a reach's underlying soil type, and dominant land use to produce a value. For each headwater watershed, the empirical runoff coefficient, the average rainfall intensity during the time of concentration, previously calculated drainage areas, and the constant k were used to determine peak two-year recurrence interval discharges.

Hydraulic Analysis of Channel Data. Hydraflow Express hydraulic modeling software was used to simulate how the calculated two-year recurrence interval discharge fills each headwater channel (Intelisolve 2006). The user-defined channel feature of Hydraflow Express was used to model discharge for each study reach site. Discharge values, cross-sectional survey measurements, and a manning's n value, were used as the inputs for the Hydraflow software. For all headwater channel sites, a Manning's n value was determined using the table developed by Chow (1959). The outputs of Hydraflow include water depth, cross-sectional area of flow, velocity, wetted perimeter, critical depth of flow, top width, and the energy grade line for a particular discharge. The Hydraflow software uses the know discharge and a series of hydraulic equations in order to determine the output values. These Hydraflow calculated variables were then used for statistical analysis.

Statistical Analysis

Channel reach (21) and watershed (25) variables were compiled into an Excel spreadsheet database. From this database linear regression models were developed using the IMB Statistical Package for the Social Sciences (SPSS) software in order to describe headwater stream geomorphology. Single and multiple parameter linear regression models were developed to described channel morphology. Single regression models were used to assess the relationship between two variables based on the coefficient of determination (r^2) which quantifies the percent of variance of the Y-variable explained by the regression equation with an r^2 of 1 explaining 100% of the variance and 0 explaining none (Rogerson 2001). Correlation matrixes were evaluated based on the correlation coefficient (Pearson r) ranging from -1 (perfect inverse relationship), to 0 (no correlation), and to +1 (perfect positive relationship) (Rogerson 2001). Multiple regression models, developed using step-wise regression methods, were also produced to understand what variables most influence and or best predict the dependent variable. A large amount of geomorphic variables were entered into the step-wise regression process using SPSS. To verify the results of the step-wise regression modeling, a hierarchical approach of adding and removing primary and secondary watershed variables to regression models was done to affirm variable relationships. Variables were retained in this process when the p-value associated with an F-test was 0.05 or below as to be significant at the 95% significance level. Final models were accepted when all variables met this criteria and the overall model was significant ($p \leq 0.05$) (Mundry and Nunn 2009).

If more than one predictive variable was used for each regression model, a multicollinearity test was also completed by assessing variance inflation factor (VIF) scores. If VIF scores were above five then it was assumed that variables experienced multicollinearity problems and the model was revised (Rogerson 2001). Models were also further assessed by examining the standardized residuals of each observation. A model residual is an error component that represent the deviation from the observed and the predicted values ($Y_i - Y_p$) of the model (Fernandez 1992). Residuals can be standardized by diving each individual residual by the standard deviation of all residuals produced by the model (Anscombe and Tukey 1963). By standardizing and analyzing residuals, the amount of unexplained variance within a model can be indicated. Individual observations with standardized residuals of an absolute value greater than or equal to two were deemed influential outliers and removed from the regression model (Atkinson 1994). This was done in order to improve the strength and robustness of each linear regression model. In addition, some single and multiple linear regression models were also produced as power function (log-log) regression models in order to improve relationships between variables.

Rosgen Channel Classification

The Rosgen channel classification method is morphology-based and can be used to infer the processes that influence the pattern and character of a river system. This classification method has also been used in a variety of applications including hydraulic geometry analysis and channel restoration (Rosgen 1996). The Rosgen method categorizes stream reaches into seven major stream types based on differences in channel morphology (Figure 11). The seven stream types differ in entrenchment, gradient, width-depth ratio, and sinuosity in various landforms at the bank-full stage (Rosgen 1996). Each of the seven stream types can then be further delineated into six categories based on dominate channel substrate including the median diameter of bed material. Entrenchment ratio is defined as the ratio of the width of the flood-prone area at two-times the maximum bank-full depth to the bank-full surface water width of the channel. It describes the vertical containment of a river channel and the degree to which it is incised in the valley floor (Rosgen 1996). Slope is used in this method due to its importance to the morphological character of the channel and its sediment, hydraulic, and biological function (Rosgen 1996). Width-depth ratio is defined as the bank-full channel width to bank-full mean depth and is representative of the frequency and magnitude of bank-full discharge (Rosgen 1996). Sinuosity, the ratio of stream length to valley length, is also used described the ratio of valley slope to channel slope.

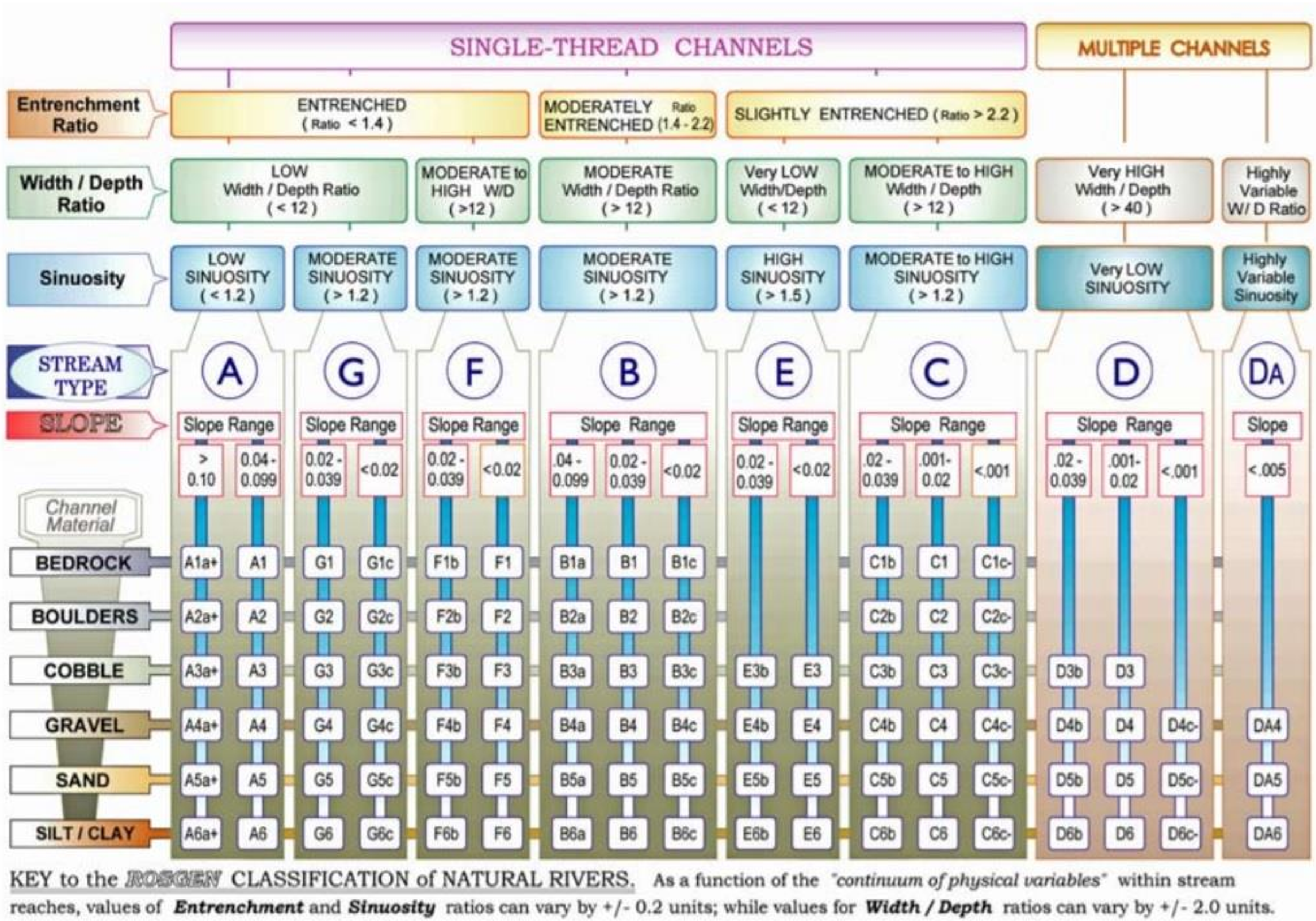


Figure 11. Rosgen Classification method key for natural rivers.

RESULTS AND DISCUSSION

Channel Assessment and Classification

Thirty-eight channel reach sites were surveyed among13 catchments with 2-4 sites per catchment (Figure 9; Appendix A-2). Sampling sites were selected to include catchments characteristics across a range of relatively low and high relief (Figure 9) and burned and unburned sites (Figure 10) within four areas in Big Barren Creek watershed above Hwy C: (i) western headwaters (nos. 4, 6, & 7); (ii) central tributaries (nos. 5, 9, 10, & 11); (iii) north-central headwaters (nos, 1 & 8); and (iv) north-east tributaries (nos. 1, 2, 3, 12, & 13) (Figure 9; Appendix A-2). Multiple watershed, hydraulic, channel, and substrate variables were calculated for each site (Appendix A-1, A-3, A-4, & A-5).

Channel morphology metrics at bank-full conditions for 38 headwater stream sites in Big Barren Creek had average values and ranges as follows: width, 3.24 m (0.41 - 10.1 m); average depth, 0.09 m (0.02 - 0.29 m); channel area, 0.41 m^2 (0.01 – 2.17 m^2); width-depth ratio, 43.0 (7.2 - 158.8); and entrenchment ratio, 1.8 (1.09) (Appendix A-2). Width, mean depth, and channel area gradually increased with drainage area (Table 2). Velocity does this as well, but velocity slightly decreases for channels draining 3-5 ha. However this could be due to the small number of channel sites sampled in this range (n=2). Over 40% of the stream sites evaluated for this study had width-depth ratios >40 indicating that multiple channel D-types are both present and common in this area of the Ozark Highlands (Table 3) (Rosgen 1996). It also appears that these headwater streams become less entrenched with increasing drainage area, except for the smallest channels with drainage basins smaller than 1 ha which were less entrenched (Table 2). The smallest channels occur in topographic settings associated with colluvial channel types.

Colluvial channels typically form in drainage-ways on soil materials where incision is limited by low stream power or bedrock (Montgomery and Buffington 1997).

The Rosgen channel classification was used in this study to better understand the variability of different headwater channel types in Big Barren Creek watershed (Rosgen 1996) (Table 3; Appendix A-2). Multiple channels (D type) were the most common channel form observed (16 out of 38 sites, 42.1%). As described by Rosgen (1996), the “D” stream type often exhibits a braided or bar-braided pattern with high sediment supply and can be laterally confined by narrow valleys (Rosgen 1996). However, the D channels in the Big Barren Creek watershed were more stable with low sediment load and high bank stability. Therefore, maybe those in this study better represent the characteristics of a DA-type channel with 2-3 channels separated by stable islands with trees growing in the active channel zone (note: they may be a form of anastomosing channel in mountain setting) (Rosgen 1996). The second most common channel type found in the study was the single channel “B” stream type (36.8%) (Table 3). The “B” stream type can be found in transitional colluvial-alluvial segments that are structurally-controlled by valley side-slopes, in relatively narrow valleys, with low sinuosity, and a limited floodplain (Rosgen 1996) (Table 3).

Other stream types in headwater channels were categorized as “F” (13.2%), “C” (5.3%), and “E” (2.6%). As observed in this study, these streams are probably an early transitional form of the riffle-pool configuration more common in larger channels farther downstream. According to Rosgen (1996), the “F” stream type describes entrenched meandering riffle/pool channels that occur on low gradients with high width depth ratios. The “C” and “E” stream types are defined as low gradient, meandering riffle/pool alluvial channels that tend to be very stable (Rosgen 1996). While the Rosgen channel classification was helpful in the identification of similar channel types in this study, not all channels fit precisely into a Rosgen channel class. Channel sinuosity was not directly measured during this study, however it is assumed that all headwater channels assessed have a reach sinuosity <1.2 which was too low for the riffle-pool stream types described in the Rosgen classification system (Rosgen 1996). Further, headwater channel slope was generally too steep to fit the Rosgen channel criteria. However, the Rosgen classification method was not designed for such small headwater streams which tend to have steeper slopes and less sinuous channels than streams with much larger drainage areas (Knighton 1984).

Some trends are apparent from the Rosgen classification of headwater stream channels (Table 3). The majority of streams with drainage areas below 1 ha all were classified as type “B” streams. Streams with smaller drainage areas may be closer to the point of channel initiation which tend to be more controlled by hillslope processes and colluvial channel characteristics often associated with type “B” channels (Rosgen 1996; Montgomery and Buffington 1997). Nevertheless, headwater stream channels may be expected to exhibit considerable variability in the Rosgen classification procedure. Adams and Spotila (2005) found that headwater streams in the Appalachian Mountains lack predictable trends or functional relationships among hydraulic variables due to the close coupling of channel form and function with local boundary conditions. Generally, headwater streams in Big Barren Creek watershed were able to be classified using the Rosgen classification method which distinguished headwater channel types based mainly on degree of entrenchment and width-depth ratios. However, headwater channels in this study had slope values which were too high and sinuosity values that were too low to fit into the Rosgen system. Therefore, a more process-based approach specifically developed for headwater streams, such as proposed by Whiting and Bradley (1993) and Montgomery and Buffington (1998), may be more applicable to Ozark streams.

Channel Substrate and Vegetation

Sediment size distribution was also assessed using grain size measurements from pebble counts conducted in the field (Table 4; Appendix A-6). Median particle sizes for headwater streams ranged from fine gravel to large cobble averaging 39 mm with a range from 5 – 240 mm (Table 4). The D_{84} particle size ranged from coarse gravel to small boulder averaging 103 mm with a range from 16 – 343 mm (Table 4). The largest mobile clast size (average of 5 samples) ranged from small cobble to medium boulder in headwater channels with an average of 211 mm and range of 83 - 612 mm (Table 4). Adams and Spotila (2005) found similar ranges in sediment size distribution for their smallest headwater streams. Sediment size and distribution do not necessarily trend with drainage area, except for the largest mobile clast size which increases as drainage areas becomes larger. However, headwater streams with drainage areas between 1 and 3 ha consistently have the largest sized sediment for all sediment parameters. This may be the result of geological control on weathering and sediment supply from nearly-horizontal bedrock units outcropping at similar elevations in the region (Repetski et al. 1998).

Other sediment characteristics show downstream trends in headwater channels within the Big Barren Creek watershed (Table 4). In-channel fine sediment area (%) ranged from 0.0% – 46.7%, bedrock area (%) ranged from 0.0% – 26.7%, and percent embeddedness ranged from 0.0% - 30.0%. Fine sediment generally decreased with increasing drainage area, while percent bedrock increased with drainage area, and embeddedness showed no trend. This could imply that as drainage area increases the sediment transport capacity of headwater streams also increases and removes fine grained sediment and exposes bedrock. Further, colluvial channels at higher elevations may produce finer beds which coarsen downstream as alluvial channels become more common (Montgomery and Buffington 1997). Additionally, wider channels typically have largest mobile clast sizes above 200 mm, most likely as a result of the local influx of large boulders from hillslopes. Higher percentages of fine-grain sediment on the channel bed above 15% were often found in channels with v-shaped or incised forms (Tables 3 and 4) as also noted by Whiting and Bradley (1993).

The number of standing trees and their locations within the channel were also recorded for the 38 headwater sites (Table 4; Appendix A-6). The number of in-channel trees averaged 4.6 per site ranging from 0 - 16 trees. Basal area averaged 39.3 m^2/ha and ranged from 0.0 - 206.0 m^2/ha. The number of trees present in the active channel does not appear to trend with drainage area, although basal area decreases with increasing drainage area (Table 4). Basal area in upland forest stands of the Big Barren Creek watershed was assessed by Roman et al. (2019) who reported an average of 130 m^2/ha basal area for pine-dominated forests and 90 m^2/ha for oak/mixed hardwood forests. The range of basal area for headwater streams overlaps with the range of basal area for upland areas, but headwater channels tend to have more variable basal areas than upland areas with a CV of 122.9% versus 45.1% for upland areas. Considering basal area decreases with increasing drainage area, basal area may be associated with increased disturbance caused by increased discharge for headwater channels with larger drainage areas.

LWD in headwater reaches was also assessed to determine its geomorphic contribution (Table 4; Appendix A-6). LWD volume per channel bed area had a range of 0 – 0.029 m^3/m^2 and a mean of 0.005 m^3/m^2. The length of a single piece of LWD averaged 4.1 m and the average diameter was 0.16 m among all sites. LWD loads were fairly consistent among headwater streams with different drainage areas, although streams with drainage areas greater than 10 ha showed reduced LWD loads. This again, could be due to increased transport capacity as drainage area increases and moves LWD downstream or due to lower inputs considering basal area decreases downstream (Montgomery and Buffington 1997). Roman et al. (2019) also evaluated coarse woody debris (CWD) in upland areas of the Big Barren Creek watershed. Average CWD for burned and unburned pine sites was 0.007 m^3/ha and 0.010 m^3/ha and for burned and unburned oak/mixed sites was 0.005 m^3/ha and 0.006 m^3/ha, respectively. In comparison, volumes of LWD and CWD tend to be similar among headwater channels and upland forest stands, although sites dominated by pines may produce more CWD. The majority of LWD in headwater streams was found perpendicular to the stream and in the middle stages of decomposition. The dominant geomorphic effect of LWD in headwater channels was the deposition of organic debris and fine-grained sediment immediately upstream of the obstruction. This was closely followed by the geomorphic effect of creating a forced riffle. Other geomorphic consequences of LWD that were noted included scour pool formation, thalweg deflection, and bank armoring. These results are consistent with those found for other Ozark streams reporting that LWD facilitates pool formation, alters stream flow, forces local scour, stabilizes banks, increases bed roughness and heterogeneity, and helps retain sediment and coarse organic matter (Mitchell et al. 2012).

Hydraulic Geometry Relationships

Hydraulic geometry was first described by Leopold and Maddock (1953) to relate mean stream channel form and discharge both at a cross-section and downstream along a stream network. When width, mean depth, and velocity are plotted against discharge, each relationship can be expressed by nearly straight lines as simple power functions (Leopold and Maddock 1953). This type of analysis describes the regulation of flow adjustments by channel form in response to increasing discharge downstream (Singh 2003). It is thought that hydraulic geometry analysis can help to understand how channel form undergoes systematic change towards a quasi-equilibrium state as a function of the combined influences of flow regime and channel boundary conditions (Knighton 1977; Singh 2003)

In Big Barren Creek watershed, headwater channels indicate the strong influence of hydraulic geometry on describing downstream variations in width (r^2=0.73), mean depth (r^2=0.88), and velocity (r^2=0.45) as a function of bank-full discharge (Table 5; Figure 12). Recall, the relationships of discharge to these properties in natural rivers can be expressed as w = aQb, d = cQf, and v = kQm, where w is width, d is mean depth, v is mean velocity, Q is discharge. In this study, the intercept coefficients have the following values: a= 4.97, c= 0.145, and k= 0.139 and their product is 1 (Table 5). The slope coefficients have the following values: b=0.423, f=0.432, and m=0.1465 and sum to 1 (Table 5). Coefficient unity verifies the theoretical significance of hydraulic geometry analysis as an indicator of equilibrium between form and discharge regime for headwaters streams in Big Barren Creek watershed.

Parker (1979) has stated that the exponent values, a, c, and k, tend to vary more from site to site, but the exponents, b, f, and m, exhibit more consistency and appear to be independent of location and only weakly dependent on channel type. This is consistent with the results obtained from the headwater streams assessed by this study. The sensitivity of velocity to variations in channel form may have been reduced by assuming a constant Manning's n value in hydraulic calculations. It has also been noted by Klein (1981) who analyzed the variation of channel width with downstream discharge that b = 0.5 was an appropriate average. For headwater streams in the Big Barren Creek watershed b = 0.423, however Klein (1981) states that low b values normally occur for smaller catchment sizes such as those being evaluated in this study.

Drainage Area-Channel Form Relationships

Drainage area is often an important independent variable used to describe spatial trends in channel morphology since it controls the amount of precipitation collected annually, characteristics of rainfall-runoff relationships, and the number of channels contributing to runoff and sediment load at the watershed outlet (Horton 1945; Montgomery and Buffington 1997; Ward et al. 2003). For example, bank-full discharge typically increases with drainage area along with systematic trends in other channel variables such as increasing width and mean depth and decreasing slope and bed material size (Leopold et al. 1964). In this study, the arithmetic and logged relationships of drainage area to other watershed-scale variables were evaluated to investigate drainage area-channel form relationships in the Big Barren Creek watershed (Appendix B-1, B-2, B-3, & B-4). Drainage area is strongly correlated (r= >0.6) with valley width, total stream length, and compactness (-), moderately correlated (r= >0.3) with basin slope (-), relief, ruggedness number, and form factor, and poorly correlated (r= <0.3) with elevation (-) (p=0.05 at r= 0.317) (Appendix B-1 & B-2). Variables related to upland and valley topography are also strongly correlated such as site elevation, basin slope, relief, and ruggedness number (Appendix B-1 & B-2). Splinter et al. (2010a) also found that ruggedness number increases with stream order and watershed size in the Ozark Highlands region of Oklahoma.

Drainage area relationships were also developed for other channel variables to quantify and evaluate headwater channel morphology in the Big Barren Creek watershed (Table 6, Figure 13). As expected, given the strong dependence of bank-full discharge calculations on drainage area in the rationale equation, strong positive relationships were found between log drainage area and channel variables of log width (r^2=0.707), log mean depth (r^2=0.850), and log area

(r^2=0.935) (Table 6). However, drainage area explained only 40% of the variance in channel slope (Table 6) since local relief tends to increase downstream along the main channel of Big Barren Creek as valley elevation decreases from the upland divide to its mouth on the Current River. In addition, width-depth ratio was not related to drainage area (r^2= 0.0004). The poor relationship may have been caused by the variable mixture of different channel types observed among the 38 headwater stream reaches including two channel pattern types and three entrenched types (Table 3; Rosgen 1996).

Interestingly, none of the bed material size classes derived from pebble counts were well explained by drainage area including D_{50} (r^2= 0.002), D_{85} (r^2= 0.006), and largest mobile clast size (r^2= 0.070) (Table 6; Figure 13). These poor relationships may relate to variable local slope controls and sediment supply conditions within these catchments, however, evaluating these factors is beyond the scope of this study. Nevertheless, Benda and Dunne (1997) state that sediment influx to channel networks in low order streams is stochastic because it is driven by debris flow from rainstorms and other complex processes that trigger hillslope erosion. This can create considerable sediment distribution variability in headwater streams that cannot be described solely by drainage area.

Sediment and vegetation properties were also evaluated to determine their relationship with watershed factors (Appendix B-3 & B-4). Channel slope was found to be most strongly correlated with sediment size variables including the D_{50} particle size (r=0.58) and D_{84} particle size (r=0.67). Basin slope was also correlated with D_{50} and D_{84} particle size, but not to the same extent. These relationships were also found when values were logged. This may indicate that local factors are more influential in sediment distribution than larger watershed factors. For example, Benda and Dunne (1977) commented that sediment influx to channel networks in low order streams is driven more by local hillslope processes. Largest mobile clast size was also evaluated and correlates best with elevation (r= -0.32) and LWD volume (r= -0.30). However, when values were logged it was determined that the largest mobile clast size was more correlated with ruggedness number (r=0.39) than elevation (r= -0.28) or LWD (r= -0.31). Vegetation properties appear to be better related to watershed factors in that LWD was most correlated with basin slope (r=0.59) and basal area was most correlated with compactness coefficient (r=0.58). Yet, when these values were logged it was found that valley width also correlated with both LWD (r= -0.67) and basal area (r= -0.59).

Thies (2017) also reported drainage area regression models for sites along the main stem of Big Barren Creek for drainage areas from 1-100 km^2 that examined channel relationships at bank-full discharge including width, mean depth, channel area, width-depth ratio, largest mobile clast size, and channel slope (Table 7). The relationships in Thies (2017) were displayed with the results of this study (Figure 13). While Thies' study included natural, channelized, incised, and aggraded channel conditions, only channels recognized as in natural or aggraded condition were evaluated here (Figure 13). Even though, the main stream and large tributary sites in the Thies analysis have drainage areas from one to two orders of magnitude larger than in the present headwater channel study, similar hydraulic geometry trends are indicated (Table 7). Further, all trends appear to be consistent across drainage area-scale given allowance for different channel types, bank-full discharge analysis methods, and differences in sample size. Mean depth shows the largest difference in trend between the two studies, which may reflect differences in the use of field channel indicators in 2017 compared to hydraulically modeled stage in the present study (Figure 13).

Drainage area was a better predictor of channel morphology in the headwaters compared to lower valley streams (Tables 6 & 7). Headwater channels typically have higher drainage density than larger downstream reaches due to the close coupling of reaches to hillslope hydrology (Gomi et al. 2002; Adams and Spotila 2005). Montgomery and Buffington (1997) reported that slope-drainage area equations for alluvial channels tend to have slope exponent values of 0.26 ± 0.05 (r^2 = 0.58), while colluvial channels tend to have exponent values of 0.72 ± 0.08 (r^2 = 0.72). Thies' (2017) data show that main stem channels have a slope exponent value of 0.19 which is more consistent with alluvial channels. However, the slope exponent for headwater channels is 0.42 and falls in the transition area between colluvial and alluvial channel types in the Big Barren Creek watershed (Montgomery and Buffington 1997).

Geomorphic Analysis of Channel Morphology

In order to more completely understand the controls of headwater stream morphology, best-fitting linear regression models were created using step-wise linear regression methods (Table 8). A combination of large-scale watershed factors, upland forest and soil properties, and reach-scale variables were used to model hydraulic geometry, sediment, and roughness variables. Models were improved by removing observations that were deemed as outliers. Outliers were determined by examining each observation's standardized residual value and observations with values greater than or equal to two standard errors of the Y-estimate were removed from the model (Atkinson 1994).

Channel width and mean depth. The hydraulic geometry variables that were given a more in depth examination include width, depth, channel area, and width-depth ratio. Channel width variability was best explained by both valley width and drainage area independently. It was determined that log-linear models described both relationships best. With the removal of three outlying observations, valley width explained 94% of the variance in channel width. Valley width was able to explain more variation in channel width than drainage area which only explained 86% of the variance in channel width. The drainage area-channel width model also excluded six observations and still had standardized residuals greater than two. This indicates that valley width is a better parameter to use when modeling channel width for these headwater streams. Due to drainage area and valley width being highly correlated, the two variables could not be combined into a single model in order to describe channel width. Comparatively, drainage area was the single best predictor of channel mean depth for the headwater sites assessed. A total of five observations were removed as outliers in order to improve the model. As a result it was determined that drainage area explains 96% of the variation of mean depth.

Channel area and width-depth ratio. Two models with equal r^2 values were developed with each explaining 98% of the variance in channel cross-section area (Table 8). Drainage area (+), basin relief (-), and basin form factor (-) were the significant variables in the first model. This model shows an overriding control of drainage area on channel cross-section area with secondary effects of decreasing area in catchments with higher relief and/or more circular shape. In the second model, channel area is explained by total stream length (+) and channel elevation (+) which links channel conveyance and upland drainage area to channel size. Width-depth ratios were also evaluated to describe headwater channels. However, no acceptable models could be produced to explain the width-depth ratio variation in headwater streams in the Big Barren Creek watershed. Considering that drainage area has been used as a surrogate for discharge in ungagged streams in this study, it is expected that drainage area would explain a large amount of hydraulic geometric variability (Dunne and Leopold 1978). Valley width is also a good predictor of channel widths ($r^2 = 0.94$) which is expected in this study since many channels with a v-shaped valley are narrow and have similar channel and valley width measurements. It also appears that the variability of channel area is better explained with the addition of a variable that describes the local setting of the channel within the watershed like elevation or relief.

Sediment size. Linear regression models were also used to evaluate sediment size of the channel bed (Table 8). Excluding three outliers, channel slope (+) explained 63% of the variance in the D_{50} (median particle size). However, for this model not all observations with residuals over two could be excluded without a significant removal of observations. Channel slope (+) and basin ruggedness number (+) explained 56% of the variance in the D_{84} particle size. Excluding three outliers, elevation (-) explained 35% of the variance in the maximum mobile clast size, and not all observations with residuals above two could be removed. This equation suggested that larger clasts are released to the channel or deposited in the channel at relatively lower elevations, possibly reflecting geology factors controlling the source of the largest particles in the channel. Overall, sediment regression models were not as well suited for explaining spatial variability as the hydraulic geometry models, but showed clear relationships between watershed factors and channel sediment characteristics. Bed material size is typically explained by slope relationships and source factors in headwater streams (Whiting and Bradley 1993; Benda and Dunne 1997).

In-channel large woody debris (LWD) and tree basal area. After the removal of four outliers, basin slope (+), largest mobile clast size (+), and burn frequency (-) were able to explain 41% of the variance in LWD volume (Table 8). Logically, it would be expected for LWD input to increase with steeper slopes, larger bed material to obstruct and collect wood, and less burning that weakens and removes wood (Mitchell et al. 2012; Roman et al. 2019). Basal area was best explained using the compactness coefficient. After removal of seven outliers, it was determined that compactness coefficient can explain 54% of the variation of basal area. This model relationship may be a spurious result. Considering the amount of observations excluded from the model and the fact that not all observations with residuals over two could be removed, this may not be an appropriate model to describe all headwater streams in the Big Barren Creek watershed.

Influence of channel planform on model prediction. In the Rosgen classification system, channel pattern is one of the first characteristics assessed by using width-depth ratio to distinguish between single (w/d <40) and multi-threaded (w/d >40) channels (Rosgen 1996). When drainage area relationships are stratified by channel planform according to multi-threaded and single channel sites, slope coefficients tend to remain similar, but Y-intercept values shift up and down (Parker 1979) (Figure 14). In almost all cases, relationships between channel form and drainage area improved in the stratified models (compare Table 6 and Figure 13 to Figure 14). For single channel streams, the percent of variance explained by drainage area increased by 10% for width (r^2=0.84), 8% for mean depth (r^2=0.93), 2% for channel area (r^2=0.96), and 0.6% for width-depth ratio (r^2=0.006). For multiple channel streams, the percent of variance explained by drainage area increased by 10% for width (r^2=0.80), 1.4% for mean depth (r^2=0.86), and 0.1% for width-depth ratio (r^2=0.001), but decreased by -2.5 % for channel area (r^2=0.91). As expected according to the Rosgen criteria for multi-threaded (D/DA) channels, multi-channel types are wider and shallower compared to single-channel types, but drainage area-channel area relationships are similar (Figure 14). The lack of variability between single and multiple channel types may result from co-variation by using drainage area in the rationale equation to determine the 2-year "bank-full" equivalent discharge. Future studies are needed to evaluate the geomorphic evolution, distribution, and behavior of multi-threaded headwater streams in comparison to single-channel types in the Ozark Highlands.

To test for the influences of other watershed- and reach-scale variables on channel types, average standardized residuals from the geomorphic models were compared between headwater streams classified as multi-channel type “D” channels and those classified as single channel types (Figure 15). For each geomorphic model it was determined that average standardized residuals for “D” streams were generally larger than the average standardized residuals of other stream types, except for mean depth. Additionally, there was little difference between average standardized residuals for the largest mobile clast size, LWD, and basal area geomorphic models. This may indicate that multi-threaded stream pattern morphology is not as well explained by the models as single threaded morphology, however more investigation is needed.

Valley Topography Effects on Channel Morphology. For a given drainage area of a headwater stream, relative relief tends to increase for catchments located further downstream along the main valley as the valley floor elevation of Big Barren Creek drops to meet the base-level control of the Current River. To evaluate the effect of valley relief on channel morphology, regression analysis was used to test for the relationship between (i) standardized residuals from geomorphic models over (ii) physiographic variables including basin slope, relative relief, ruggedness number, and form factor (Tables 8 & 9). Almost all the 40 regression tests between geomorphic model residuals and physiographic variables generally indicated no relationship (50% with $r^2 = 0.00$) with only one significant negative relationship between mean depth residuals and basin slope ($r^2 = 0.14$, $p = 0.03$) (Table 9). While explaining 14% of the remaining (residual) variance in depth, basin slope actually explains <1% of the total variance in depth since the original geomorphic depth model explained almost 96% of the variance in depth (Table

8). Therefore, changes in down-valley physiography had little influence on headwater channel form variables as evaluated in this study for drainage areas < 1 km^2.

Land Use Effects on Headwater Channel Morphology. It is well know that land use practices can affect runoff and sediment condition in forested watersheds being managed for timber production (Davies and Nelson 1994; Megahan et al. 1995; Roberts et al. 2007). To check for land use effects on headwater channel morphology, geomorphic model residuals were again regressed over several land use variables to test for significant effects (Table 9). The land use effects examined include prescribed burn frequency (no. of years), timber harvest area (% of drainage area), pine cover (% of drainage area), and percentage of road area (% of drainage area). In general, while land use effects were better related to geomorphic model residuals compared to physiographic variables, the relationships were still relatively very weak and largely insignificant. Eighty-five percent of the 40 regression tests between geomorphic model residuals and land use variables had r^2 values <0.06 (30% with r^2 = 0.00) (Table 9). Timber harvest and pine cover variables did not indicate a significant relationship with any geomorphic model, however, road area and burn frequency did show some effects.

Road area (%) trended with the residuals of the D_{50} geomorphic model with a negative slope, r^2 = 0.13, and p = 0.03 (Table 9). When the original model is considered, road area explains an additional 5% of the total variance in D_{50}. This finding suggests that channel beds might be slightly finer in drainage areas draining relatively more road area. In MTNF, road drainage tends to be directed by design from road sides into surrounding low areas where water can infiltrate into the forest soil. However, in some instances, road drain channels extend downstream by erosion into the drainage network and deliver fine-grained sediment to headwater channels. The potential effect of roads on increased fine-sediment supply to headwater channels needs to be studied further. While not finding a strong relationship (explaining only 5% of the variance in fine sediment), the sampling design of the present study was not aimed at evaluating road hydrology and sediment effects.

Prescribed fire burn frequency correlated with the residuals of three geomorphic models: (i) width (A) with a positive slope, $r^2 = 0.14$, and $p = 0.03$; (ii) D_{50} with a negative slope, $r^2 = 0.13$, and $p = 0.03$; and (iii) basal area with a negative slope, $r^2 = 0.15$, and $p = 0.03$. (Table 9). It is logical to expect that catchments burned more frequently might have slightly wider channels due to minor increases in runoff since litter depth is temporarily reduced for several months after burn events (Robichaud 2000; Vega et al. 2005, Roman et al., 2018). However, burn frequency explains <1% of the total variance in width, and therefore, its effect on channel form is not significant or measureable in this study. Interestingly, while of low significance, burn frequency may be associated with a decrease in sediment size on the channel bed since it explains 5% of the total variance in D_{50} (Tables 8 & 9). The reduction of soil litter and ground cover by controlled burning may be expected to increase soil erosion and the delivery of fine-grained sediment to headwater channel beds, thus reducing the D_{50} (Elliott et al. 1999; Hartman and Heumann 2003; Lane et al. 2006; Singh et al. 2017). Finally, burn frequency indicates a weak inverse-relationship and explains only 7% of the total variance in basal area of trees within the active channel. This outcome may be expected due to the overall influence of stem removal due to silvicultural practices and occasional seedling/sapling mortality by fire in these managed stands. Road and burn variables only explain 13-15% of the remaining variance and 5-7% of the total variance in three of the ten geomorphic models developed for this study. Recall, the effects of these land use variables were not significant enough to be included in models developed by the stepwise regression process. Therefore, future studies may be needed using sampling plans and methods aimed to specifically test and/or verify hypothesized burn frequency and road area effects. Nevertheless, using statistical analysis, this study did not find significant effects of prescribed burn frequency on headwater channel morphology.

Table 2. Average channel properties of headwater channels by drainage area.

Drainage Area	Reach #	Width (m)	Mean Depth	Velocity (m/s)	Channel Area (m^2)	Width-Depth Ratio	Entrenchment Ratio
<1 ha	7	0.79	0.03	0.86	0.02	31.00	1.90
1-3 ha	16	2.06	0.05	1.08	0.10	47.36	1.58
3-5 ha	2	4.21	0.07	0.88	0.27	65.73	1.61
5-10 ha	7	5.26	0.12	1.10	0.58	50.96	1.89
>10 ha	6	6.57	0.24	1.78	1.54	28.45	2.16

Table 3. Rosgen classification of headwater channels.

Drainage Area	Single Thread						Multiple Channel
	Entrenched			Moderately Entrenched	Slightly Entrenched		
	A	G	F	B	E	C	D
<1 ha	-	-	-	71.4%	-	-	28.6%
1-3 ha	-	-	18.8%	25.0%	-	12.5%	43.8%
3-5 ha	-	-	-	-	-	-	100%
5-10 ha	-	-	14.3%	28.6%	-	-	57.1
>10 ha	-	-	16.7%	50.0%	16.7%	-	16.7%
Total	-	-	13.2%	36.8%	2.6%	5.3%	42.1%

Table 4. Substrate and vegetation characteristics of headwater channels.

Drainage Area	D_{50} (mm)	D_{84} (mm)	D_{95} (mm)	Largest Mobile Clast Size (mm)	Percent Fines (%)	Percent Embedded (%)	Percent Bedrock (%)	LWD (m^3/m^2)	Tree Count (#)	Basal Area (m^2/ha)
<1 ha	25.2	80.5	167.8	183.9	25.2	9.0	0.0	0.008	4	87.6
1-3 ha	59.7	139.0	253.4	209.6	14.4	11.5	0.2	0.005	4	42.8
3-5 ha	33.8	84.5	138.6	189.0	11.7	6.7	0.0	0.004	8	18.8
5-10 ha	20.0	66.4	149.0	217.1	9.0	2.4	0.5	0.005	4	15.1
>10 ha	25.7	80.6	144.7	244.3	3.9	7.8	4.4	0.001	6	9.0

Table 5. Log-log linear regression model equations for headwater channel relations among width, mean depth, velocity and discharge.

Hydraulic Geometry Variable	R^2 (n = 38)	s.e. (Er. of Y est.)	Y-int b_o	b_1 coef.	p-value
Width (m)	0.726	1.55	4.97	0.423	1.1E-11*
Mean Depth (m)	0.883	1.31	0.145	0.432	2.6E-18*
Velocity (m/s)	0.449	1.32	1.39	0.1465	4.3E-06*

Fitted regression equation : $\text{Log } Y = b_o \log X1^{b1}$
Significant relations are denoted by *

Table 6. Log-linear regression model equations for headwater channel relations among geomorphic variables and drainage area.

Geomorphic Variable	R^2 (n = 38)	s.e. (Er. of Y est.)	Y-int b_o	b_1 coef.	p-value
Width (m)	0.707	1.57	20.84	0.596	3.9E-11*
Mean Depth (m)	0.850	1.35	0.62	0.607	2.0E-16*
Channel Area (m^2)	0.935	1.46	12.98	1.202	6.7E-23*
Channel Slope (%)	0.405	1.83	1.58	-0.423	1.7E-05*
Width-Depth Ratio	0.0004	1.46	33.48	-0.011	0.906
D_{50} (mm)	0.002	2.14	25.35	-0.029	0.789
D_{85} (mm)	0.006	1.84	74.68	-0.039	0.649
Largest Mobile Clast Size (mm)	0.070	1.45	266.88	0.084	0.118

Fitted regression equation: Log Y = b_o log X1 ^{b1}
Significant relations are denoted by *.

Table 7. Thies (2017) log-linear regression model equations for Big Barren Creek relations among geomorphic variables and drainage area.

Geomorphic Variable (Drainage Area = independent var.)	R^2 (n = 14)	s.e. (Er. Of Y est.)	Y-int b_o	b_1 coef.	p-value
Width (m)	0.116	1.55	16.37	0.1200	0.233
Mean Depth (m)	0.623	1.40	0.22	0.3292	7.8E-04*
Channel Area (m^2)	0.710	1.45	3.80	0.4412	1.5E-04*
Channel Slope (%)	0.218	1.65	0.82	-0.1897	0.126
Width-Depth Ratio	0.135	1.96	70.85	-0.2020	0.196
D_{50} (mm)	0.012	6.09	5.98	0.1440	0.726
Largest Mobile Clast Size (mm)	0.280	1.60	117.22	0.2148	0.063

Fitted regression equation: Log Y = b_o log X1 ^{b1}
Significant relations are denoted by *.

Table 8. Geomorphic analysis of linear regression models.

Model Number	Y-variable	X-variable(s)	n	R^2	s.e. (Er. of Y est.)	Y-int b_o	b_1 coef.	b_2 coef.	b_3 coef.	p-value
1	Width (m) - Model 1	Valley Width	35	0.943	1.23	0.60	1.026	-	-	3.77E-22*
2	Width (m) - Model 2	Drainage Area	32	0.856	1.34	19.44	0.585	-	-	3.78E-14*
3	Mean Depth (m)	Drainage Area	33	0.959	0.01	0.03	1.267	-	-	4.24E-23*
4	Channel Area (m^2) - Model 1	Drainage Area, Relief, Basin Form Factor	37	0.975	1.27	1.98	1.453	-0.651	-0.509	2.41E-26*
5	Channel Area (m^2) - Model 2	Total Stream Length, Elevation	35	0.975	1.26	17.15	1.260	3.978	-	2.30E-26*
6	D_{50} (mm)	Channel Slope	35	0.629	29.52	-10.58	5.970	-	-	1.32E-08*
7	D_{84} (mm)	Channel Slope, Ruggedness	38	0.560	1.51	29.05	0.449	0.380	-	5.75E-07*
8	Largest Mobile Clast Size (mm)	Elevation	33	0.347	47.20	571.88	-1421.530	-	-	3.10E-04*
9	LWD (m^3/m^2)	Basin Slope, Largest Mobile Clast Size, Burn	32	0.414	2.3E-03	0.00	0.0004	0.00001	-0.0003	1.70E-03*
10	Basal Area (m^2/hectare)	Compactness Coefficient	31	0.543	17.39	-5.81	4.395	-	-	2.26E-06*

Underlined models are log-linear regression models.
Significant relations are denoted by *.

Table 9. Residual analysis results.

Geomorphic Model	Basin Slope (%)			Relative Relief (m/m)			Ruggedness Number (m/m)			Form Factor (m^2/m^2)		
	r^2	b1 coef.	p-value	r^2	b1 coef.	p-value	r^2	b1 coef.	p-value	r^2	b1 coef.	p-value
Width (A)	0.00	-0.01	0.79	0.00	2.53	0.84	0.05	0.22	0.18	0.02	-0.63	0.44
Width (B)	0.06	-0.05	0.18	0.05	-15.45	0.23	0.02	-0.11	0.50	0.01	-0.30	0.69
Mean Depth	0.14	-0.07	0.03*	0.08	-19.97	0.10	0.03	-0.16	0.37	0.00	-0.14	0.85
Channel Area (A)	0.02	-0.02	0.46	0.00	-4.89	0.69	0.00	-0.02	0.88	0.00	-0.16	0.82
Channel Area (B)	0.00	-0.01	0.83	0.00	-2.77	0.82	0.00	0.06	0.71	0.00	-0.22	0.76
D50	0.00	0.00	0.97	0.00	-3.55	0.80	0.04	0.19	0.23	0.00	0.02	0.97
D84	0.04	-0.04	0.24	0.03	-12.54	0.29	0.01	-0.07	0.65	0.00	-0.11	0.88
Largest Mobile Clast Size	0.02	-0.03	0.49	0.00	-2.26	0.88	0.07	0.28	0.13	0.03	-0.69	0.37
LWD	4E-08	0.00	1.00	0.01	6.19	0.67	0.02	0.13	0.49	0.07	-1.07	0.14
Basal Area	5E-05	0.00	0.97	0.00	-4.90	0.74	0.01	0.06	0.70	0.00	0.26	0.74

Geomorphic Model	Burn Frequency (#)			Area Affected by Timber Harvest (%)			Percent Pine (%)			Percent Roads (%)		
	r^2	b1 coef.	p-value	r^2	b1 coef.	p-value	r^2	b1 coef.	p-value	r^2	b1 coef.	p-value
Width (A)	0.14	0.15	0.03*	0.04	0.00	0.26	0.02	0.00	0.39	0.00	0.01	0.88
Width (B)	0.05	-0.09	0.23	0.01	0.00	0.66	0.00	0.00	0.72	0.01	0.05	0.61
Mean Depth	0.05	0.09	0.20	0.02	0.00	0.46	0.00	0.00	0.93	0.00	-0.02	0.86
Channel Area (A)	0.01	0.04	0.54	0.02	0.00	0.41	0.00	0.00	0.84	0.01	0.06	0.50
Channel Area (B)	0.01	-0.03	0.65	0.03	0.00	0.28	0.07	-0.01	0.13	0.00	-0.02	0.84
D50	0.13	-0.14	0.03*	0.01	0.00	0.61	0.03	0.00	0.31	0.13	-0.19	0.03*
D84	0.09	-0.12	0.06	0.00	0.00	0.93	0.00	0.00	0.85	0.04	-0.11	0.20
Largest Mobile Clast Size	0.04	0.08	0.28	0.03	0.00	0.30	0.02	0.00	0.42	0.03	-0.08	0.37
LWD	0.00	0.00	1.00	0.00	0.00	0.94	0.00	0.00	0.99	0.01	0.06	0.52
Basal Area	0.15	-0.14	0.03*	0.01	0.00	0.52	0.03	0.00	0.35	0.00	0.00	0.99

Significant relations are denoted by *.

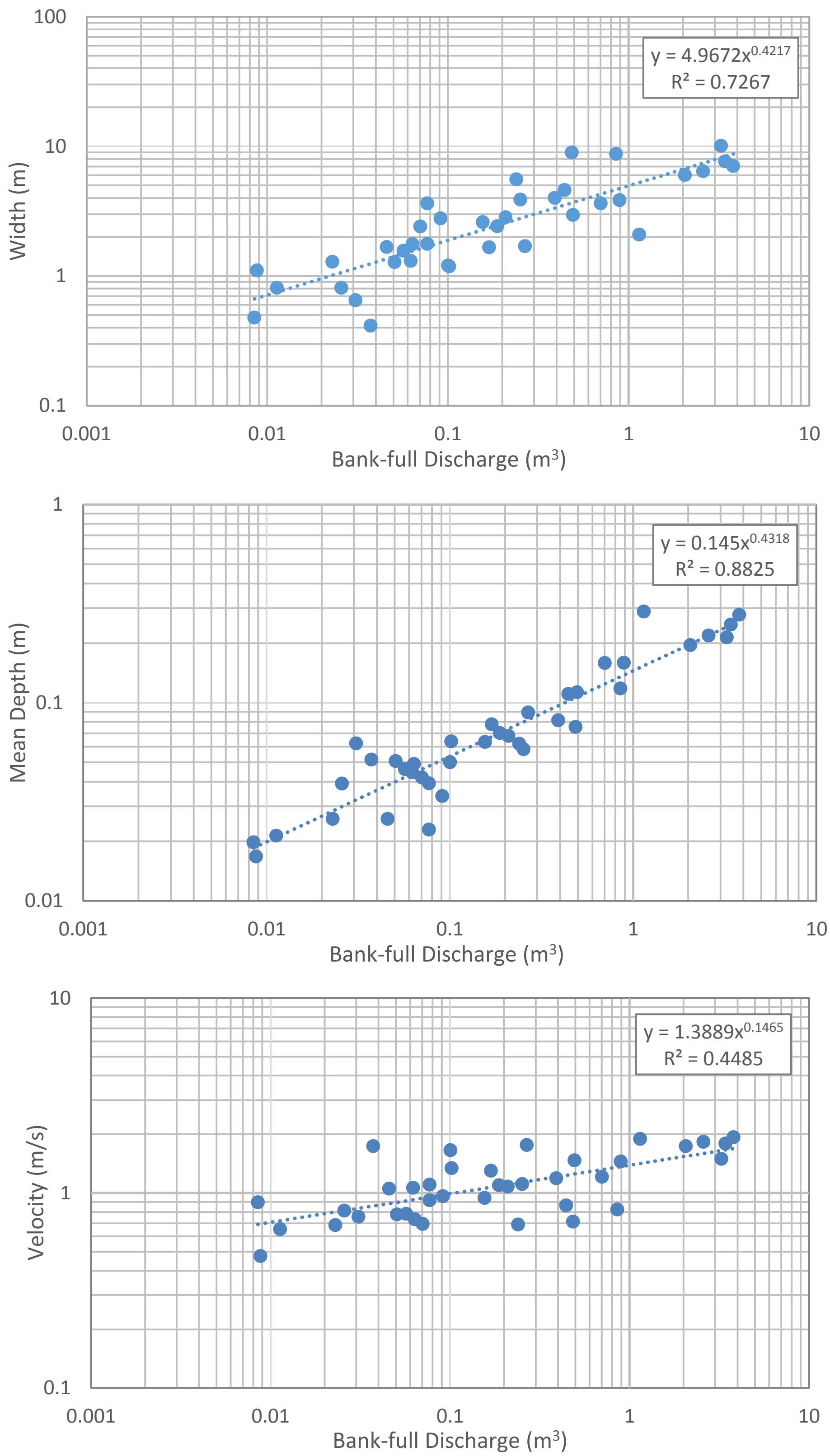


Figure 12. Log-linear regression model equations for headwater channel relations among width, mean depth, velocity and discharge.

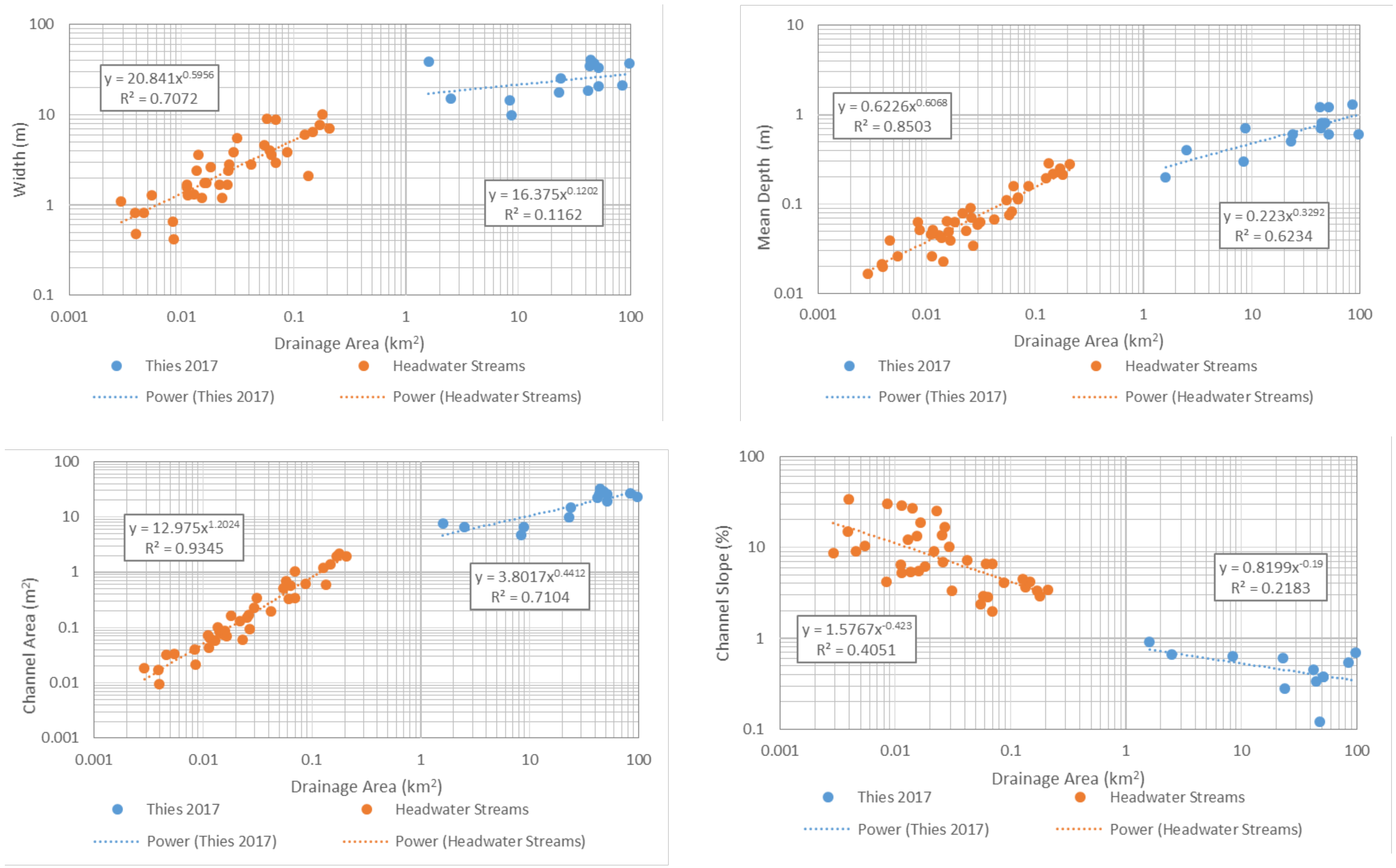


Figure 13. Comparison of Thies 2017 main stem and headwater channel log-linear regression models for geomorphic variables and drainage area.

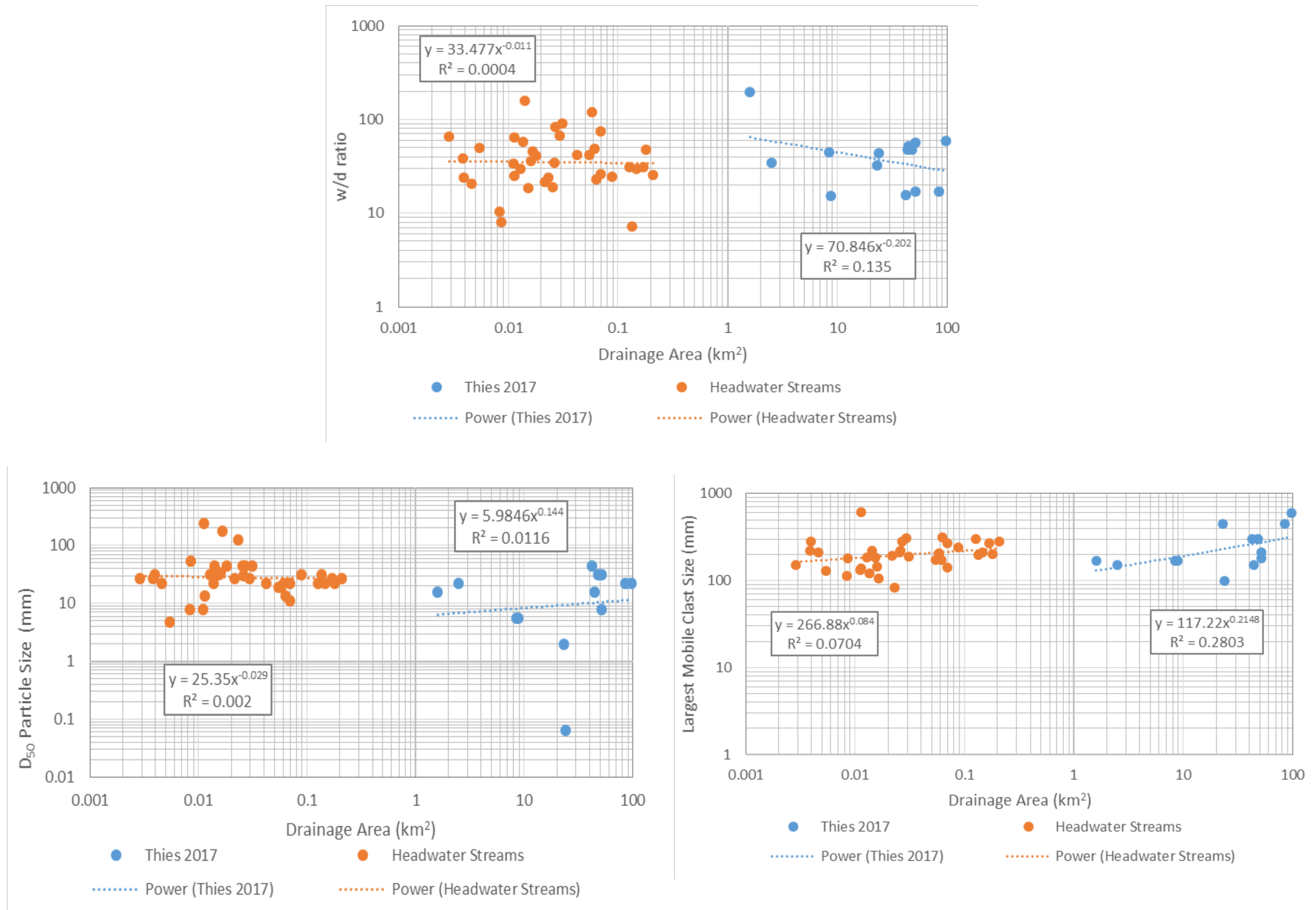


Figure 13 continued. Comparison of Thies 2017 main stem and headwater channel log-linear regression models for geomorphic variables and drainage area.

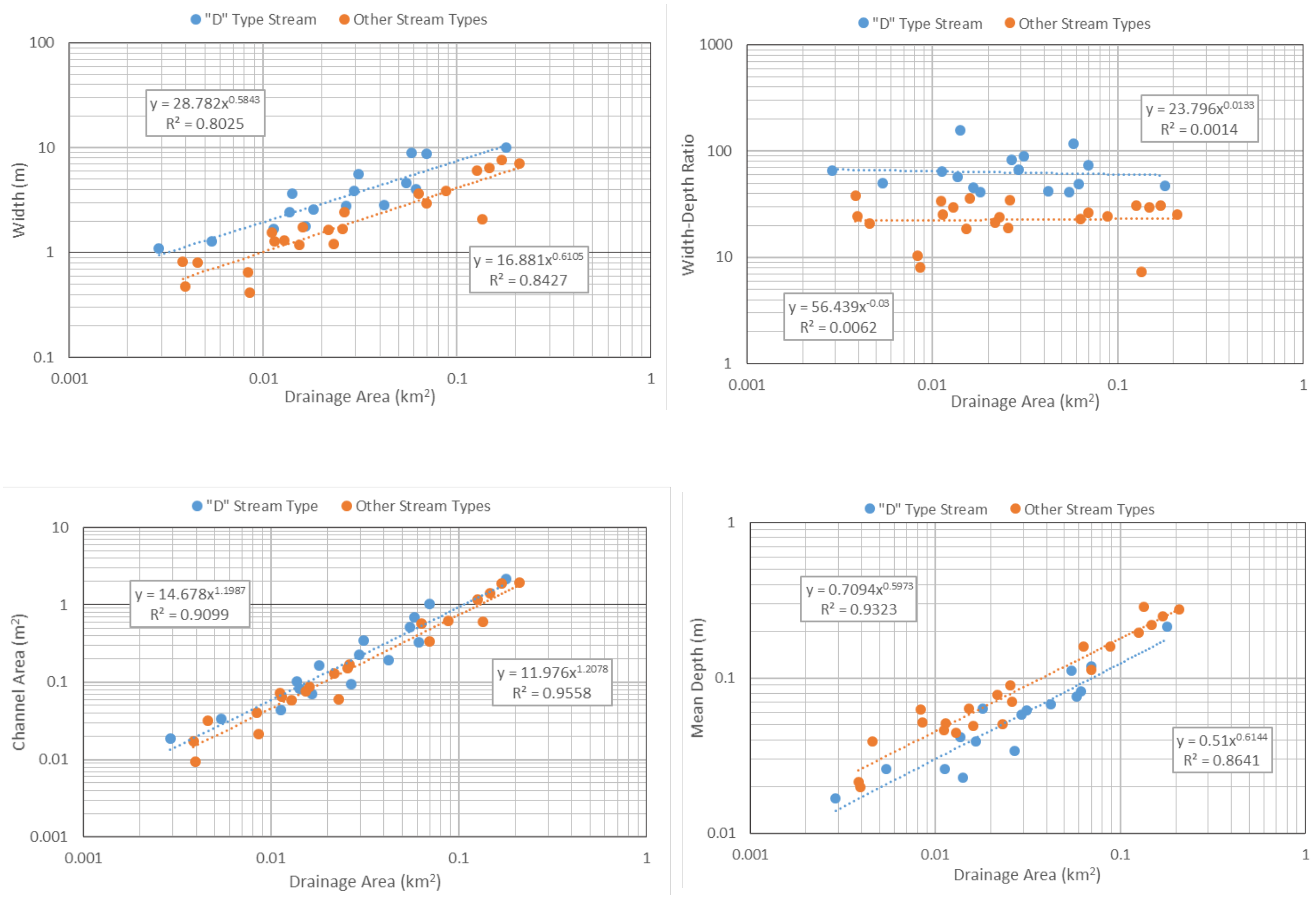


Figure 14. Rosgen channel type log-linear relationships for geomorphic variables and drainage area.

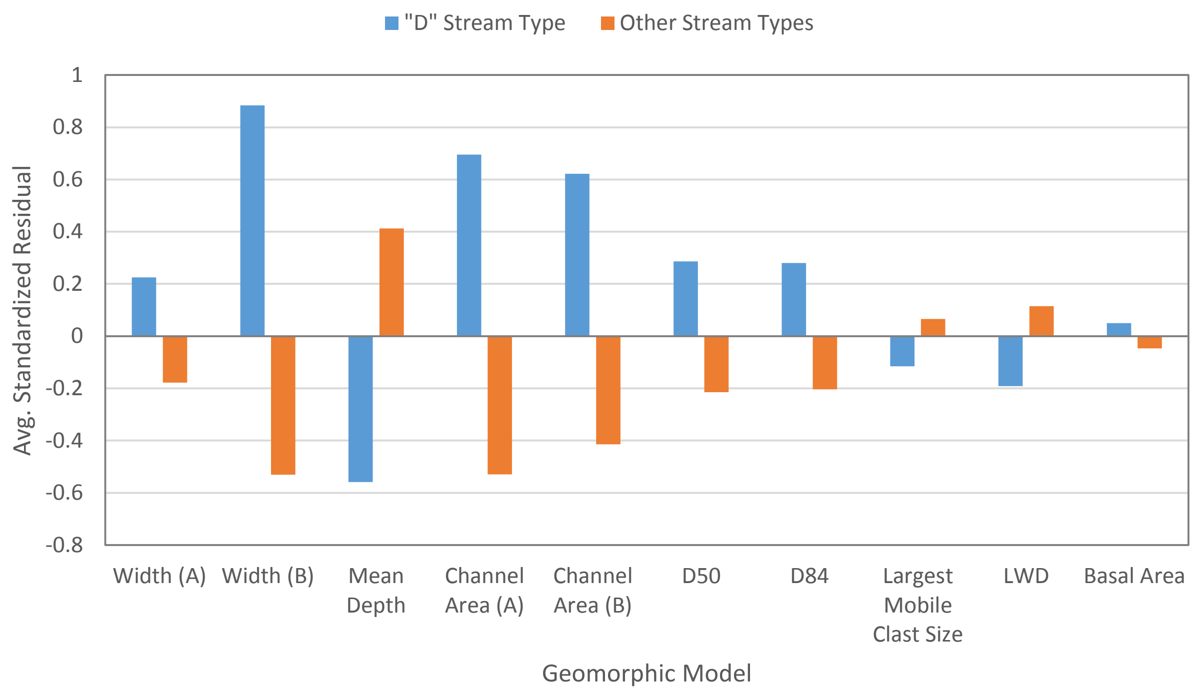


Figure 15. Comparison of Rosgen channel types to the average standardized residuals of the geomorphic models.

CONCLUSION

Most previous research on channel morphology has focused on understanding form and process relationships in larger, downstream channels of a watershed and their response to disturbance events. However, headwater streams can account for more than two thirds of total stream length in a watershed, are sensitive to local hydro-geomorphic conditions including land use effects, and can be effective indicators of watershed health (Leopold et al. 1964; Whiting and Bradley 1993; Sidle et al. 2000; Gomi et al. 2002). Understanding what watershed factors are strongly associated with channel form, substrate, and vegetation can be beneficial for land managers trying to preserve the integrity and hydrologic connectivity of headwater streams. Results of this study can help managers to understand stream processes and causes of spatial variability. Moreover, while prescribed burning has become a popular forest management tool in the United States, the environmental effects of frequent prescribed burning are not yet well understood. In MTNF, frequent treatments of prescribed fire are being used to restore the forest landscape to its original shortleaf pine-oak composition. In this study, a combination of field, geospatial, hydraulic modeling, and statistical methods were used to assess what geomorphic watershed factors are connected to headwater channel form, substrate, and vegetation properties. Relationships among these factors were analyzed by regression analysis and the residuals were assessed to evaluate if prescribed fire influences headwater stream channel form, sediment, or vegetation. There are four key findings of this study:

1. **The rational method can be used to simulate bank-full discharges to evaluate bank-full stage headwater channel morphology in forested watersheds.** A precipitation database was created for the Big Barren Creek watershed and analyzed to determine the two year 24-hour recurrence interval rainfall event. Using the rational method and the Kirpich (1940) equation to determine time of concentration, an estimated two year recurrence interval bank-full discharge was calculated. Channel morphology of the bank-

full stage was then determined by using Hydraflow Express hydraulic modeling software. When channel geometry values were evaluated by increasing discharge it was determined that discharge and width, mean depth, and velocity relationships can be described by simple power functions first described by Leopold and Maddock (1953). The product of b, f, and m coefficients and the sum of a, c, and k coefficients of the power function equations were both equal to one. These relationships imply that headwater streams in Big Barren Creek follow the geomorphic principle that width, mean depth, and velocity increase systematically downstream with discharge. Comparison of exponent values with other studies indicates that headwater channel morphology is in transition between colluvial and alluvial process-dominated systems.

2. **The Rosgen Classification method can be used to categorize headwater streams within the Big Barren Creek watershed.** The Rosgen classification method was also applied to headwater streams in the Big Barren Creek watershed in an attempt to compare channel morphology. The majority of headwater stream channels assessed were classified as either type “B” (36.8%) or type “D” streams (42.1%). Type “B” streams represent single-threaded channels that exist on moderately steep slopes and are structurally controlled by narrow valleys and side-slopes. The “D” stream type describes multi-threaded braided or bar-braided channels with very high width-depth ratios. The Rosgen classification method was able to adequately classify and describe headwater stream channels. However, headwater channel sinuosity values were occasionally lower and slopes were usually greater than Rosgen criteria. Thus, a process-based classification approach specifically developed for headwater streams may be a more appropriate option for future classification. In general, headwater streams were classified as having either single or multi-threaded channels. Those that are single-threaded can be further sub-classified by entrenchment ratios. Moreover, residual analysis and re-examination of channel form-drainage area relationships based on single or multi-threaded channel pattern showed some geomorphic differences present between streams with single and multi-threaded channels. Specifically, multi-threaded channels typically have more variable geomorphic features and substrate distributions than single-threaded channels.

3. **Headwater channel properties are best explained by drainage area of the basin and channel slope.** Correlation matrices, drainage area relationships, and geomorphic analysis models indicate that drainage area and basin/channel slope consistently explain the highest percent of variance for in channel-reach form, substrate, and vegetation variables. Two groups of primary watershed variables were found to correlate with headwater channel variables including those that describe the size or shape of the drainage system such as drainage area, total stream length, valley width, and compactness coefficient and those that describe the local topographic situation of the headwater watershed such as elevation, relief, basin slope, and ruggedness number. Geomorphic analysis models developed using step-wise linear regression confirm that these variables are good predictors of headwater stream channel form, sediment, and vegetation characteristics. The best models produced show that drainage area was the best overall predictor of hydraulic geometry variables, sediment characteristics were best predicted by channel slope and local factors, and vegetation factors such as LWD volume and basal area were best explained by basin characteristics including basin slope and compactness.

4. **Analysis of headwater channel models and their outliers reveals that frequent prescribed burning has little effect on headwater stream geomorphology.** Stepwise regression did not include burn frequency, or any other land use variable, in final model selection. To investigate further, the standardized residuals for each channel variable were plotted against burn frequency and weak relationships were found with channel width, sediment size (D_{50}), and in-channel tree basal area. Although these residual-over-burn frequency relationships were significant, they only explained 1-7% of the total variance in the geomorphic models developed for this study. Given this low level of statistical effect on only a few variables, it was concluded that channel morphology has not responded to prescribed burn frequency over the 16 year period of burning in the watershed. However, the LWD geomorphic model indicated that as burn frequency increases, the volume of LWD decreases. This effect and the implications of LWD reduction may be the only potential geomorphic consequence on headwater streams due to prescribed burning in the Big Barren Creek watershed.

In conclusion, based on field channel surveys and modeled bank-full discharges, headwater streams (draining <0.2 km^2) in the Big Barren Creek watershed occur in narrow valleys (0.8-16.1 m), with moderately steep slopes (2-34%), channel widths averaging 3.2 m ranging from 0.4-10 m, and low reach sinuosity (<1.2). Two planform types occur in headwater catchments: (i) multi-threaded channels (w/d >40) with a low-relief braided pattern stabilized with vegetation and bedrock/boulder resistance (42% of study sites); and (i) single channels including entrenched (13%), moderately entrenched (37%), and slightly entrenched (8%) forms. These channels occupy narrow valleys with limited floodplain development and have variable substrates composed of colluvial and alluvial deposits, and bedrock in some places. Similar to larger alluvial channels, headwater stream morphology is significantly related to drainage area and slope, as well as other watershed and reach variables. More research is encouraged to follow up on some possible effects of land use disturbances on headwater stream stability. However, in the Big Barren Creek watershed, catchments treated frequently (once every 1-2 years) by prescribed fire do not have channel form or sediment properties that vary significantly from sites that were never burned.

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APPENDICES

Appendix A. Headwater Channel Site Information

Appendix A-1. Geomorphic variable descriptions

Variable	Description
Drainage Area (km^2)	Total area drained upstream of site location.
Channel Slope (%)	Slope of the channel along the site reach. (Rise/Run x 100)
Basin Slope (%)	Slope of the drainage area. Calculated as the difference in elevations at points 10 and 85 percent of the distance along the main channel site location to basin divide, divided by the distance between the two points (Alexander and Wilson, 1995)
Relief (km)	Difference in elevation from the watershed divide to the channel site.
Burn Frequency (#)	Number of times a site has been treated with prescribed fire since 2002.
Percent Pine (%)	Percent area of the drainage area dominated by shortleaf-pine forest.
Area Affected by Timber Harvest (%)	Percent area of the drainage area affected by timber harvesting since 1980.

Appendix A-1 continued. Geomorphic variable descriptions

Variable	Description
D_{95} (mm)	Size of the particle that is greater than 95% of the sediment distribution.
D_{84} (mm)	Size of the particle that is greater than 84% of the sediment distribution.
D_{50} (mm)	Size of the particle that is greater than 50% of the sediment distribution.
Percent Bedrock (%)	Percentage of bedrock present along the length of the reach.
Percent Embedded (%)	Percentage of embedded sediment present along the length of the reach.
Percent Fines (%)	Percentage of fine grained material along the length of the reach.
Largest Mobile Clast Size (mm)	Average of the five largest mobile clasts found within the reach.

Appendix A-1 continued. Geomorphic variable descriptions

Variable	Description
LWD (m^3/m^2)	Total volume of large woody debris found within the reach.
Basal Area (m^2/ha)	Total basal area of standing trees found within the active channel of the reach.
Tree Count (#)	The amount of trees within the active channel of the reach.
Percent Silt (%)	Percent area of the drainage area containing soil types with high silt content.
Depth to Bt (in)	Area weighted depth to the Bt soil horizon from USDA-NRCS Web Soil Survey.
Elevation (m)	Distance above sea level.
Perimeter (km)	Perimeter of the drainage area.

Appendix A-1 continued. Geomorphic variable descriptions

Variable	Description
Relative Relief (m/m)	The relief of the drainage area divided by the perimeter.
Channel Length (km)	Length of the main channel from the site location to the watershed divide.
Basin Shape (m^2/m^2)	Channel length squared divided by the drainage area.
Basin Sinuosity (km/km)	Channel length divided by basin length.
Valley Width (m)	Width of the valley occupied by the channel.
Maximum Capacity of the Most Limiting Layer to Transmit Water (in/hr)	Water transmission capacity of the most limiting soil layer from USDA-NRCS Web Soil Survey.
Total Stream Length (km)	Total length of all streams within the drainage area.

Appendix A-1 continued. Geomorphic variable descriptions

Variable	Description
Drainage Density (km/km^2)	Total stream length divided by drainage area.
Circulatory Ratio (m^2/m^2)	The ratio of drainage area to the area of a circle having the same perimeter as the basin.
Ruggedness Number (m/m)	Drainage density multiplied by drainage area relief.
Basin Length (km)	Straight-line length of the basin along the main channel.
Form Factor (m^2/m^2)	Drainage area divided by the square of basin length.
Compactness Coefficient (m/m)	The ratio of the perimeter to the circumference of a circular area which equals the drainage area.
Elongation Ratio (m/m)	The ratio of the diameter of a circle of the same area as the basin to the maximum basin length.

Appendix A-1 continued. Geomorphic variable descriptions

Variable	Description
Percent Roads (%)	Percent area of the drainage area occupied by roads.
Max Depth (m)	The maximum depth of bank-full discharge.
Q (m^3)	Bank-full discharge as estimated by the 2-year 24hr rainfall using the rational equation.
Channel Area (m^2)	The cross-sectional area of bank-full discharge.
Velocity (m/s)	Average velocity of bank-full discharge.
Wetted Perimeter (m)	The wetted perimeter of the channel at bank-full discharge.
Yc	Critical depth of flow of bank-full dishcarge.

Appendix A-1 continued. Geomorphic variable descriptions

Variable	Description
Width (m)	Distance across the top of the water surface at bank-full discharge.
Energy (m)	The energy grade line.
Mean Depth (m)	Mean depth bank-full discharge.
Width-Depth Ratio	The ratio of channel width to mean depth at bank-full discharge.
Entrenchment Ratio	The ratio of channel width to valley width at bank-full discharge.

Appendix A-2. General site information

Channel Site	Catchment	Stream Order	Rosgen Classification	Latitude	Longitude
1	1	1st	D3b	-91.074709	36.875192
2	1	1st	D3b	-91.075441	36.875201
3	1	1st	B3a	-91.075289	36.875329
4	2	2nd	B4	-91.049042	36.893349
5	2	1st	D4b	-91.047433	36.893882
6	2	1st	B4a	-91.047248	36.893276
7	1	2nd	D4b	-91.075608	36.87548
8	3	2nd	D4b	-91.075419	36.876058
9	3	1st	B4a	-91.074737	36.876816
10	3	1st	D4b	-91.07418	36.876685
11	4	2nd	D4	-91.213979	36.854893
12	4	1st	D4b	-91.213591	36.854122
13	4	1st	D4b	-91.213045	36.854094
14	5	1st	F4b	-91.14986	36.862059
15	5	2nd	B4a	-91.147751	36.862421
16	5	1st	B4a	-91.148399	36.862882
17	5	1st	B4a	-91.148672	36.862788
18	6	2nd	D4b	-91.213603	36.884992
19	6	1st	B4a	-91.214723	36.884385
20	6	1st	D4b	-91.215294	36.884503
21	6	1st	B4a	-91.215185	36.885219
22	7	2nd	D4b	-91.215671	36.889249
23	7	1st	B4a	-91.217319	36.889514
24	8	1st	F4b	-91.139344	36.892163
25	8	1st	D4b	-91.139431	36.891672
26	8	2nd	F4b	-91.140502	36.891927
27	9	1st	C4b	-91.124825	36.854564
28	9	1st	D4b	-91.125874	36.854577
29	9	1st	B4a	-91.126187	36.854504
30	9	2nd	B4a	-91.12584	36.854077
31	10	1st	F4b	-91.143409	36.85715
32	10	2nd	E4b	-91.091899	36.840783
33	11	1st	C4b	-91.143251	36.856005
34	11	2nd	D4b	-91.09249	36.841669
35	12	1st	D4	-91.082788	36.889674
36	13	1st	F4b	-91.103083	36.881214
37	13	1st	B4a	-91.102669	36.882024
38	13	2nd	B4	-91.102124	36.882434

Appendix A-3.Primary watershed variables

Channel Site	Catchment	Drainage Area (ha)	Channel Slope (%)	Basin Slope (%)	Elevation (m)	Relief (m)	Perimeter (km)	Relative Relief (m/m)	Channel Length (km)	Basin Shape (m^2/m^2)	Basin Sinuosity	Valley Width (m)	Total Stream Length (km)	Drainage Density (km/km^2)	Circulatory Ratio	Ruggedness Number	Basin Length (km)	Form Factor	Compactness Coefficient	Elongation Ratio
1	1	1.13	28.7	14.5	233.0	30.5	0.78	0.04	0.21	4.1	1.20	2.0	0.8	67.1	0.18	2.0	0.18	0.35	9.9	0.67
2	1	1.65	18.5	17.9	216.5	47.0	0.93	0.05	0.29	5.0	1.18	3.1	1.4	81.9	0.22	3.8	0.24	0.28	8.0	0.60
3	1	2.30	25.2	19.0	215.5	48.0	0.95	0.05	0.28	3.3	1.19	2.1	1.6	71.1	0.30	3.4	0.23	0.42	5.9	0.73
4	2	16.98	3.3	2.9	254.5	22.3	2.78	0.01	0.80	3.7	1.45	12.5	13.3	78.5	0.77	1.7	0.55	0.57	2.3	0.85
5	2	1.81	6.1	6.5	262.0	23.3	1.11	0.02	0.37	7.7	1.28	3.6	1.6	90.4	0.20	2.1	0.29	0.21	8.7	0.52
6	2	0.46	9.0	7.3	265.1	16.3	0.65	0.02	0.22	10.7	1.12	1.3	0.3	73.0	0.09	1.2	0.20	0.12	20.2	0.38
7	1	4.21	7.3	19.0	210.5	53.0	1.17	0.05	0.33	2.5	1.23	4.0	3.1	73.6	0.45	3.9	0.26	0.60	4.0	0.87
8	3	6.15	6.6	15.6	215.1	49.9	1.55	0.03	0.41	2.7	1.38	8.6	4.0	64.8	0.50	3.2	0.29	0.71	3.6	0.95
9	3	0.86	30.0	12.8	235.8	29.3	0.64	0.05	0.22	5.9	1.26	0.8	0.6	72.6	0.17	2.1	0.18	0.27	10.6	0.59
10	3	1.42	26.9	9.4	238.6	26.4	0.87	0.03	0.25	4.5	1.48	5.0	0.8	55.4	0.21	1.5	0.17	0.49	8.7	0.79
11	4	3.11	3.4	5.1	287.4	13.6	1.11	0.01	0.31	3.1	1.30	10.2	2.0	62.7	0.35	0.9	0.24	0.55	5.1	0.84
12	4	0.29	8.7	8.1	294.2	8.3	0.35	0.02	0.11	3.9	1.21	2.1	0.2	56.3	0.10	0.5	0.09	0.37	17.1	0.69
13	4	1.37	5.4	4.4	294.7	6.3	0.82	0.01	0.16	1.8	1.30	4.0	0.9	65.5	0.21	0.4	0.12	0.96	8.6	1.11
14	5	2.61	6.8	6.2	265.3	17.2	0.97	0.02	0.30	3.5	1.36	3.2	2.3	87.4	0.34	1.5	0.22	0.53	5.3	0.82
15	5	8.80	4.1	6.7	250.2	32.3	1.98	0.02	0.55	3.4	1.34	8.0	7.2	82.2	0.56	2.7	0.41	0.53	3.2	0.82
16	5	1.29	12.2	9.9	259.6	21.5	0.84	0.03	0.24	4.3	1.16	2.1	1.1	82.4	0.19	1.8	0.20	0.31	9.3	0.63
17	5	0.38	14.9	12.5	261.5	18.5	0.43	0.04	0.15	6.0	1.09	1.5	0.4	92.7	0.11	1.7	0.14	0.20	15.9	0.50
18	6	5.80	2.9	6.5	283.3	23.8	1.60	0.01	0.42	3.1	1.40	11.2	3.6	61.5	0.46	1.5	0.30	0.63	3.9	0.89
19	6	1.60	5.4	9.5	290.1	14.6	0.75	0.02	0.18	2.1	1.23	2.7	0.9	57.5	0.27	0.8	0.15	0.71	6.7	0.95
20	6	0.54	10.4	7.3	294.2	11.3	0.45	0.02	0.16	4.4	1.43	2.4	0.3	52.3	0.15	0.6	0.11	0.46	11.9	0.77
21	6	1.11	6.5	8.3	291.2	15.9	0.75	0.02	0.22	4.5	1.50	2.3	0.7	65.9	0.19	1.0	0.15	0.50	9.6	0.80
22	7	6.97	2.0	3.9	284.1	19.2	1.74	0.01	0.53	4.0	1.61	11.7	4.3	62.3	0.50	1.2	0.33	0.65	3.5	0.91
23	7	0.83	4.2	6.1	289.4	7.2	0.57	0.01	0.13	2.2	1.22	1.3	0.4	47.4	0.19	0.3	0.11	0.69	9.6	0.94
24	8	2.17	9.0	11.7	249.6	41.4	1.07	0.04	0.40	7.2	1.20	2.0	1.8	81.6	0.25	3.4	0.33	0.20	7.0	0.50
25	8	2.93	10.0	11.0	248.8	41.5	1.07	0.04	0.43	6.3	1.36	4.2	2.6	87.4	0.34	3.6	0.32	0.29	5.2	0.61
26	8	6.32	2.8	10.9	240.1	50.3	1.54	0.03	0.57	5.2	1.33	4.8	4.9	77.3	0.52	3.9	0.43	0.34	3.5	0.66
27	9	1.53	13.3	6.1	241.1	16.6	0.79	0.02	0.27	4.7	1.74	3.2	1.2	76.0	0.24	1.3	0.15	0.64	7.3	0.90
28	9	2.67	16.8	16.3	226.8	29.5	1.09	0.03	0.20	1.5	1.12	4.6	2.0	74.2	0.31	2.2	0.18	0.84	5.8	1.04
29	9	0.40	33.6	21.1	230.4	25.2	0.44	0.06	0.13	4.0	1.14	1.0	0.3	81.8	0.11	2.1	0.11	0.32	15.6	0.64
30	9	6.95	6.5	10.3	220.1	37.6	1.75	0.02	0.43	2.7	1.76	4.8	5.3	76.8	0.50	2.9	0.24	1.16	3.6	1.22
31	10	2.56	13.7	3.2	259.5	14.8	1.13	0.01	0.37	5.3	1.88	2.2	1.7	66.8	0.29	1.0	0.20	0.67	6.3	0.92
32	10	13.49	3.6	9.0	242.6	43.3	2.45	0.02	0.52	2.0	1.28	9.8	7.3	53.9	0.69	2.3	0.40	0.83	2.6	1.03
33	11	1.14	5.3	11.4	238.0	17.9	0.72	0.02	0.18	3.0	1.42	3.1	0.6	54.0	0.20	1.0	0.13	0.68	9.0	0.93
34	11	17.91	2.9	5.8	229.0	41.5	2.60	0.02	0.74	3.1	1.39	14.0	12.6	70.2	0.87	2.9	0.54	0.63	2.1	0.89
35	12	5.48	2.4	6.0	269.5	21.8	1.63	0.01	0.38	2.6	1.38	16.1	4.1	74.9	0.42	1.6	0.27	0.73	4.2	0.96
36	13	12.64	4.5	3.1	251.0	20.8	2.35	0.01	0.67	3.6	1.70	7.4	9.6	76.0	0.68	1.6	0.40	0.80	2.6	1.01
37	13	14.73	4.2	3.5	245.2	26.6	2.58	0.01	0.80	4.3	1.70	12.3	11.3	76.7	0.72	2.0	0.47	0.66	2.5	0.92
38	13	20.94	3.4	3.7	242.5	29.3	3.51	0.01	0.88	3.7	1.57	15.2	15.9	75.8	0.75	2.2	0.56	0.67	2.4	0.92
	Average	4.83	10.0	9.3	253.3	26.7	1.28	0.02	0.36	4.1	1.37	5.5	3.5	71.3	0.36	1.9	0.26	0.54	7.1	0.81
	Minimum	0.29	2.0	2.9	210.5	6.3	0.35	0.01	0.11	1.5	1.09	0.8	0.2	47.4	0.09	0.3	0.09	0.12	2.1	0.38
	Maximum	20.94	33.6	21.1	294.7	53.0	3.51	0.06	0.88	10.7	1.88	16.1	15.9	92.7	0.87	3.9	0.56	1.16	20.2	1.22

Appendix A-4. Secondary watershed variables

Channel Site	Catchment	Burn Frequency	Percent Pine (%)	Area Affected by Timber Harvest (%)	Percent Silt (%)	Depth to Bt (in)	Maximum Capacity of the Most Limiting Layer to Transmit Water (in/hr)	Percent Roads (%)
1	1	0	18.1	0.0	68.4	10.3	0.76	0.0
2	1	0	0.0	0.0	61.8	10.5	0.88	0.0
3	1	0	28.2	0.0	48.5	11.1	1.12	0.0
4	2	0	29.8	62.8	74.3	9.0	0.66	1.5
5	2	0	53.4	46.6	87.6	9.5	0.42	1.7
6	2	0	57.8	39.8	97.8	9.1	0.24	3.7
7	1	0	0.2	0.0	50.8	11.0	1.07	0.0
8	3	0	98.2	0.0	52.9	10.9	1.04	2.4
9	3	0	100.0	0.0	61.9	10.5	0.88	0.5
10	3	0	95.7	0.0	74.7	10.0	0.65	5.3
11	4	0	0.0	100.0	78.2	9.9	1.45	0.5
12	4	0	0.0	100.0	100.0	9.0	0.20	0.2
13	4	0	0.0	100.0	100.0	9.0	0.20	1.2
14	5	2	100.0	0.0	84.9	8.8	0.47	2.4
15	5	2	97.0	3.0	63.4	8.6	0.85	1.8
16	5	2	79.5	20.5	78.1	8.8	0.59	2.7
17	5	2	100.0	0.0	61.4	8.6	0.89	0.0
18	6	5	43.0	95.4	60.1	10.6	2.49	2.0
19	6	5	100.0	100.0	72.8	10.1	1.77	1.8
20	6	5	46.5	80.9	99.1	9.0	0.25	6.7
21	6	5	0.0	85.1	87.5	9.5	0.92	7.6
22	7	5	0.1	90.5	71.6	9.3	1.83	2.1
23	7	5	0.0	100.0	99.5	5.2	0.23	2.0
24	8	7	100.0	0.0	100.0	9.0	0.20	0.0
25	8	7	100.0	0.0	100.0	9.0	0.20	0.0
26	8	7	100.0	0.0	99.8	9.0	0.20	0.0
27	9	4	0.0	100.0	88.5	8.9	0.40	0.0
28	9	4	0.0	41.1	21.7	10.6	0.67	3.0
29	9	4	0.0	21.8	0.0	11.6	0.61	0.0
30	9	4	0.0	69.7	37.7	9.6	0.85	2.2
31	10	4	0.0	77.1	79.4	8.8	0.57	4.8
32	10	4	17.1	51.9	57.8	8.6	0.95	2.1
33	11	0	0.0	100.0	0.0	13.0	0.06	0.0
34	11	0	0.0	91.3	51.7	10.9	0.13	0.6
35	12	0	0.0	0.0	78.0	8.2	1.46	1.5
36	13	0	12.2	86.1	92.6	5.6	0.62	0.5
37	13	0	17.7	84.0	89.3	5.9	0.82	0.5
38	13	0	39.0	69.0	84.4	6.3	1.10	0.7
	Average	2	37.7	47.8	71.5	9.3	0.76	1.6
	Minimum	0	0.0	0.0	0.0	5.2	0.06	0.0
	Maximum	7	100.0	100.0	100.0	13.0	2.49	7.6

Appendix A-5. Channel form variables

Channel Site	Catchment	Max Depth (m)	Q (m^3)	Channel Area (m^2)	Velocity (m/s)	Wetted Perimeter (m)	Yc	Width (m)	Energy (m)	Mean Depth (m)	Width-Depth Ratio	Entrenchment Ratio
1	1	0.04	0.05	0.04	1.1	1.7	0.1	1.68	0.09	0.03	64.6	1.19
2	1	0.11	0.08	0.07	1.1	1.8	0.1	1.78	0.17	0.04	45.3	1.74
3	1	0.10	0.10	0.06	1.7	1.2	0.1	1.21	0.24	0.05	24.0	1.74
4	2	0.38	3.42	1.91	1.8	7.7	0.4	7.66	0.55	0.25	30.8	1.63
5	2	0.09	0.16	0.17	0.9	2.6	0.1	2.61	0.14	0.06	41.1	1.37
6	2	0.07	0.03	0.03	0.8	0.8	0.1	0.81	0.10	0.04	20.7	1.63
7	1	0.11	0.21	0.19	1.1	2.9	0.1	2.85	0.17	0.07	41.8	1.39
8	3	0.16	0.39	0.33	1.2	4.0	0.2	4.01	0.23	0.08	49.0	2.15
9	3	0.10	0.04	0.02	1.7	0.5	0.1	0.41	0.26	0.05	8.0	2.00
10	3	0.09	0.08	0.08	0.9	3.7	0.1	3.65	0.13	0.02	158.8	1.38
11	4	0.15	0.24	0.35	0.7	5.6	0.1	5.58	0.17	0.06	89.6	1.82
12	4	0.03	0.01	0.02	0.5	1.1	0.0	1.10	0.05	0.02	65.9	1.91
13	4	0.08	0.07	0.10	0.7	2.4	0.1	2.41	0.10	0.04	57.5	1.65
14	5	0.11	0.19	0.17	1.1	2.4	0.1	2.43	0.17	0.07	34.5	1.30
15	5	0.33	0.89	0.62	1.5	3.9	0.4	3.86	0.44	0.16	24.2	2.09
16	5	0.09	0.06	0.06	1.1	1.3	0.1	1.31	0.14	0.04	29.3	1.57
17	5	0.04	0.01	0.02	0.7	0.8	0.1	0.81	0.06	0.02	38.1	1.88
18	6	0.28	0.49	0.68	0.7	9.1	0.3	8.99	0.31	0.08	118.8	1.24
19	6	0.09	0.06	0.09	0.7	1.8	0.1	1.76	0.12	0.05	35.9	1.52
20	6	0.05	0.02	0.03	0.7	1.3	0.1	1.29	0.08	0.03	49.7	1.87
21	6	0.09	0.06	0.07	0.8	1.6	0.1	1.57	0.12	0.05	33.9	1.49
22	7	0.16	0.85	1.04	0.8	8.8	0.1	8.75	0.20	0.12	74.0	1.34
23	7	0.12	0.03	0.04	0.8	0.7	0.1	0.65	0.16	0.06	10.4	2.00
24	8	0.13	0.17	0.13	1.3	1.7	0.2	1.67	0.22	0.08	21.4	1.22
25	8	0.09	0.25	0.23	1.1	3.9	0.1	3.89	0.15	0.06	66.5	1.09
26	8	0.23	0.70	0.58	1.2	3.7	0.2	3.65	0.31	0.16	22.9	1.32
27	9	0.13	0.10	0.08	1.3	1.2	0.2	1.19	0.22	0.06	18.6	2.66
28	9	0.07	0.09	0.09	1.0	2.8	0.1	2.79	0.12	0.03	82.2	1.64
29	9	0.04	0.01	0.01	0.9	0.5	0.1	0.48	0.08	0.02	24.2	2.00
30	9	0.20	0.49	0.34	1.5	3.0	0.2	2.97	0.31	0.11	26.2	1.62
31	10	0.15	0.27	0.15	1.8	1.7	0.2	1.70	0.31	0.09	19.0	1.31
32	10	0.49	1.15	0.60	1.9	2.4	0.5	2.09	0.67	0.29	7.2	4.69
33	11	0.11	0.05	0.07	0.8	1.3	0.1	1.28	0.14	0.05	25.1	2.40
34	11	0.43	3.25	2.17	1.5	10.3	0.4	10.13	0.54	0.21	47.2	1.38
35	12	0.31	0.44	0.51	0.9	4.7	0.3	4.61	0.35	0.11	41.6	3.48
36	13	0.25	2.06	1.18	1.7	6.1	0.3	6.02	0.40	0.20	30.7	1.22
37	13	0.35	2.59	1.41	1.8	6.6	0.4	6.45	0.52	0.22	29.5	1.91
38	13	0.51	3.80	1.96	1.9	7.2	0.5	7.05	0.70	0.28	25.3	2.15
	Average	0.17	0.60	0.41	1.1	3.3	0.2	3.24	0.24	0.09	43.0	1.79
	Minimum	0.03	0.01	0.01	0.5	0.5	0.0	0.41	0.05	0.02	7.2	1.09
	Maximum	0.51	3.80	2.17	1.9	10.3	0.5	10.13	0.70	0.29	158.8	4.69

Appendix A-6. Channel substrate and vegetation variables.

Channel Site	Catchment	D_{95} (mm)	D_{84} (mm)	D_{50} (mm)	Percent Bedrock (%)	Percent Embedded (%)	Percent Fines (%)	Largest Mobile Clast Size (mm)	LWD (m^3/m^2)	Basal Area (m^2/hectare)	Tree Count
1	1	640	343	240	0.0	0.0	0.0	612.0	0.000	118.3	5
2	1	450	301	180	0.0	0.0	3.3	105.2	0.011	21.1	0
3	1	353	281	128	0.0	0.0	16.7	83.4	0.029	34.9	15
4	2	90	90	27	26.7	0.0	3.3	272.0	0.004	28.4	7
5	2	128	90	45	0.0	10.0	10.0	-	0.006	54.9	4
6	2	151	90	23	0.0	13.3	30.0	212.0	0.007	115.3	3
7	1	128	78	23	0.0	10.0	6.7	-	0.008	8.2	3
8	3	350	90	23	3.3	0.0	6.7	172.8	0.027	26.6	1
9	3	286	128	55	0.0	16.7	10.0	180.0	0.006	141.9	6
10	3	323	128	45	0.0	20.0	6.7	220.0	0.001	36.3	4
11	4	149	92	45	0.0	3.3	16.7	189.0	0.000	29.3	13
12	4	107	64	27	0.0	3.3	23.3	151.6	0.020	61.7	4
13	4	90	64	23	3.3	13.3	30.0	120.4	0.006	21.4	5
14	5	300	128	30	0.0	10.0	23.3	222.0	0.000	99.2	2
15	5	93	64	32	0.0	0.0	3.3	240.0	0.000	14.2	2
16	5	234	128	32	0.0	3.3	16.7	186.0	0.008	120.5	3
17	5	223	92	27	0.0	13.3	40.0	221.0	0.000	206.0	5
18	6	128	90	19	0.0	0.0	20.0	208.0	0.001	5.4	12
19	6	128	92	34	0.0	16.7	16.7	145.6	0.001	38.3	8
20	6	90	46	5	0.0	6.7	46.7	130.0	0.004	59.3	1
21	6	54	33	8	0.0	0.0	30.0	132.8	0.006	0.0	0
22	7	54	45	11	0.0	0.0	6.7	141.2	0.000	0.5	5
23	7	45	16	8	0.0	0.0	20.0	112.8	0.000	16.3	0
24	8	180	128	27	0.0	13.3	3.3	192.0	0.006	0.0	6
25	8	254	128	27	0.0	30.0	10.0	310.0	0.002	0.0	2
26	8	151	46	14	0.0	3.3	13.3	315.0	0.004	0.0	5
27	9	323	90	32	0.0	30.0	20.0	186.2	0.001	109.7	0
28	9	273	128	45	0.0	16.7	0.0	280.0	0.003	24.4	4
29	9	273	128	32	0.0	10.0	6.7	280.0	0.017	12.3	8
30	9	160	65	23	0.0	0.0	0.0	270.0	0.002	41.9	0
31	10	273	130	45	0.0	16.7	6.7	210.0	0.000	0.0	0
32	10	151	65	32	0.0	3.3	0.0	196.0	0.000	0.0	5
33	11	54	33	14	0.0	3.3	36.7	138.4	0.007	5.5	10
34	11	107	64	23	0.0	10.0	16.7	202.0	0.001	0.0	5
35	12	107	65	19	0.0	13.3	13.3	172.8	0.001	17.1	0
36	13	212	90	23	0.0	10.0	3.3	300.0	0.002	9.5	16
37	13	180	128	23	0.0	13.3	0.0	211.6	0.001	11.5	4
38	13	128	47	27	0.0	10.0	0.0	284.0	0.000	4.3	1
	Average	195	103	39	0.9	8.5	13.6	211.3	0.005	39.3	5
	Minimum	45	16	5	0.0	0.0	0.0	83.4	0.000	0.0	0
	Maximum	640	343	240	26.7	30.0	46.7	612	0.029	206.0	16

Appendix B. Correlation Matrices among watershed and channel variable.

Appendix B-1. Correlation matrix for primary watershed variables.

	Drainage Area (ha)	Channel Slope (%)	Basin Slope (%)	Elevation (m)	Relief (m)	Valley Width (m)	Total Stream Length (km)	Ruggedness Number	Form Factor	Compactness Coefficient
Drainage Area (ha)	1.00									
Channel Slope (%)	-0.47	1.00								
Basin Slope (%)	-0.42	0.64	1.00							
Elevation (m)	-0.22	-0.41	-0.62	1.00						
Relief (m)	0.29	0.12	0.57	-0.81	1.00					
Valley Width (m)	0.82	-0.55	-0.48	-0.01	0.15	1.00				
Total Stream Length (km)	0.99	-0.46	-0.43	-0.23	0.27	0.80	1.00			
Ruggedness Number	0.24	0.13	0.56	-0.79	0.96	0.09	0.26	1.00		
Form Factor	0.39	-0.41	-0.30	0.00	-0.09	0.42	0.35	-0.20	1.00	
Compactness Coefficient	-0.68	0.47	0.26	0.27	-0.44	-0.68	-0.67	-0.39	-0.57	1.00

Appendix B-2. Correlation matrix for logged values of primary watershed.

	Logged Drainage Area (ha)	Logged Channel Slope (%)	Logged Basin Slope (%)	Logged Elevation (m)	Logged Relief (m)	Logged Valley Width (m)	Logged Total Stream Length (km)	Logged Ruggedness Number	Logged Form Factor	Logged Compactness Coefficient
Logged Drainage Area (ha)	1.00									
Logged Channel Slope (%)	-0.64	1.00								
Logged Basin Slope (%)	-0.44	0.61	1.00							
Logged Elevation (m)	-0.28	-0.38	-0.54	1.00						
Logged Relief (m)	0.48	0.11	0.48	-0.83	1.00					
Logged Valley Width (m)	0.87	-0.73	-0.50	-0.03	0.25	1.00				
Logged Total Stream Length (km)	0.99	-0.59	-0.41	-0.32	0.53	0.84	1.00			
Logged Ruggedness Number	0.46	0.14	0.44	-0.80	0.97	0.21	0.53	1.00		
Logged Form Factor	0.53	-0.43	-0.34	0.00	-0.12	0.56	0.46	-0.21	1.00	
Logged Compactness Coefficient	-0.99	0.64	0.40	0.28	-0.47	-0.86	-0.97	-0.44	-0.59	1.00

Appendix B-3. Correlation matrix for channel hydraulic geometry variables and primary watershed variables.

	Width (m)	Mean Depth (m)	Channel Area (m^2)	Channel Slope (%)	Width-Depth Ratio	D50 (mm)	D84 (mm)	Largest Mobile Clast Size (mm)	LWD (m^3/m^2)	Basal Area (m^2/hectare)	Drainage Area (ha)	Basin Slope (%)	Elevation (m)	Relief (m)	Valley Width (m)	Total Stream Length (km)	Ruggedness Number	Form Factor	Compactness Coefficient
Width (m)	1.00																		
Mean Depth (m)	0.62	1.00																	
Channel Area (m^2)	0.86	0.86	1.00																
Channel Slope (%)	-0.51	-0.52	-0.47	1.00															
Width-Depth Ratio	0.36	-0.30	-0.04	0.11	1.00														
D50 (mm)	-0.21	-0.23	-0.21	0.58	0.09	1.00													
D84 (mm)	-0.22	-0.28	-0.24	0.67	0.11	0.92	1.00												
Largest Mobile Clast Size (mm)	0.12	0.15	0.16	0.25	0.10	0.41	0.35	1.00											
LWD (m^3/m^2)	-0.31	-0.31	-0.28	0.33	-0.09	0.17	0.28	-0.30	1.00										
Basal Area (m^2/hectare)	-0.45	-0.41	-0.37	0.41	-0.10	0.23	0.25	0.15	-0.03	1.00									
Drainage Area (ha)	0.76	0.95	0.95	-0.47	-0.14	-0.19	-0.23	0.19	-0.26	-0.41	1.00								
Basin Slope (%)	-0.48	-0.47	-0.50	0.64	-0.02	0.44	0.50	0.09	0.59	0.12	-0.42	1.00							
Elevation (m)	0.02	-0.17	-0.10	-0.41	0.16	-0.38	-0.45	-0.32	-0.30	0.04	-0.22	-0.62	1.00						
Relief (m)	0.14	0.28	0.16	0.12	-0.09	0.28	0.34	0.22	0.30	-0.27	0.29	0.57	-0.81	1.00					
Valley Width (m)	0.87	0.74	0.83	-0.55	0.19	-0.23	-0.28	0.05	-0.28	-0.44	0.82	-0.48	-0.01	0.15	1.00				
Total Stream Length (km)	0.75	0.93	0.96	-0.46	-0.16	-0.18	-0.21	0.22	-0.25	-0.38	0.99	-0.43	-0.23	0.27	0.80	1.00			
Ruggedness Number	0.11	0.23	0.15	0.13	-0.14	0.28	0.37	0.25	0.27	-0.20	0.24	0.56	-0.79	0.96	0.09	0.26	1.00		
Form Factor	0.32	0.37	0.29	-0.41	0.04	-0.27	-0.35	-0.09	-0.22	-0.43	0.39	-0.30	0.00	-0.09	0.42	0.35	-0.20	1.00	
Compactness Coefficient	-0.67	-0.68	-0.61	0.47	-0.03	0.08	0.08	-0.09	0.27	0.58	-0.68	0.26	0.27	-0.44	-0.68	-0.67	-0.39	-0.57	1.00

Appendix B-4. Correlation matrix for the logged values of channel hydraulic geometry variables and primary watershed variables.

	Logged Width (m)	Logged Mean Depth (m)	Logged Channel Area (m^2)	Logged Channel Slope (%)	Logged Width-Depth Ratio	Logged D50 (mm)	Logged D84 (mm)	Logged Largest Mobile Clast Size (mm)	Logged LWD (m^3/m^2)	Logged Basal Area (m^2/hectare)	Logged Drainage Area (ha)	Logged Basin Slope (%)	Logged Elevation (m)	Logged Relief (m)	Logged Valley Width (m)	Logged Total Stream Length (km)	Logged Ruggedness Number	Logged Form Factor	Logged Compactness Coefficient
Logged Width (m)	1.00																		
Logged Mean Depth (m)	0.66	1.00																	
Logged Channel Area (m^2)	0.92	0.90	1.00																
Logged Channel Slope (%)	-0.68	-0.71	-0.76	1.00															
Logged Width-Depth Ratio	0.49	-0.34	0.10	-0.02	1.00														
Logged D50 (mm)	-0.11	-0.19	-0.16	0.56	0.08	1.00													
Logged D84 (mm)	-0.08	-0.25	-0.18	0.64	0.20	0.86	1.00												
Logged Largest Mobile Clast Size (mm)	0.26	0.18	0.24	0.06	0.11	0.22	0.25	1.00											
Logged LWD (m^3/m^2)	-0.60	-0.57	-0.64	0.56	-0.08	0.17	0.30	-0.31	1.00										
Logged Basal Area (m^2/hectare)	-0.58	-0.49	-0.58	0.58	-0.20	0.34	0.39	0.14	0.41	1.00									
Logged Drainage Area (ha)	0.84	0.92	0.97	-0.64	-0.02	-0.04	-0.08	0.27	-0.58	-0.55	1.00								
Logged Basin Slope (%)	-0.51	-0.55	-0.58	0.61	0.00	0.35	0.35	-0.04	0.62	0.29	-0.44	1.00							
Logged Elevation (m)	-0.01	-0.15	-0.09	-0.38	0.16	-0.49	-0.46	-0.28	-0.24	-0.02	-0.28	-0.54	1.00						
Logged Relief (m)	0.27	0.35	0.34	0.11	-0.07	0.37	0.42	0.33	0.05	-0.11	0.48	0.48	-0.83	1.00					
Logged Valley Width (m)	0.93	0.72	0.92	-0.73	0.33	-0.15	-0.17	0.16	-0.67	-0.59	0.87	-0.50	-0.03	0.25	1.00				
Logged Total Stream Length (km)	0.83	0.91	0.95	-0.59	-0.03	0.00	-0.01	0.31	-0.54	-0.49	0.99	-0.41	-0.32	0.53	0.84	1.00			
Logged Ruggedness Number	0.25	0.33	0.32	0.14	-0.07	0.41	0.48	0.39	0.09	-0.03	0.46	0.44	-0.80	0.97	0.21	0.53	1.00		
Logged Form Factor	0.46	0.43	0.49	-0.43	0.08	-0.24	-0.34	-0.08	-0.42	-0.51	0.53	-0.34	0.00	-0.12	0.56	0.46	-0.21	1.00	
Logged Compactness Coefficient	-0.83	-0.90	-0.95	0.64	0.01	0.08	0.10	-0.23	0.56	0.56	-0.99	0.40	0.28	-0.47	-0.86	-0.97	-0.44	-0.59	1.00