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Step-Pool Channel Morphology, Forcing Effects, and Geomorphic Classification in the Ozark Highlands, SE Missouri

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STEP-POOL CHANNEL MORPHOLOGY, FORCING EFFECTS, AND GEOMORPHIC CLASSIFICATION IN THE OZARK HIGHLANDS, SE MISSOURI

A Master's Thesis
Presented to
The Graduate College of
Missouri State University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science, Geography and Geology

By
Triston Ralland Rice
December 2019

STEP-POOL CHANNEL MORPHOLOGY, FORCING EFFECTS, AND GEOMORPHIC CLASSIFICATION IN THE OZARK HIGHLANDS, SE MISSOURI

Geography, Geology, and Planning

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ABSTRACT

Understanding headwater streams and their morphology is inherently difficult in contrast to larger streams in downstream valleys. Geomorphic forcing can occur over short distances (<10 m) and influence channel geometry due to geologic factors such as colluvial inputs and resistant bedrock or biologic factors such as fluvial wood inputs and tree growth in the channel. How and where these geomorphic variables effect step-pool channel characteristics is poorly understood in the Ozark Highlands. Step-pool channel form is typically controlled by gradient, substrate characteristics, and sediment supply.This study reports on a geomorphic assessment of step-pool characteristics and classifies channel form using two different geomorphic classification frameworks in Deer Camp Hollow (0.2 km^2) draining the Salem Plateau in Mark Twain National Forest in southeastern Missouri. Topographic surveys, pebble counts, and step measurements were used to assess channel form and forcing effects, along with 0.5 m resolution LiDAR data provided by the U.S. Forest Service. Step-pool forms occur along >80% of the stream length with an average bed slope of 11.5 %, average D90 of 185 mm, and 89 of 122 total steps indicating forcing. Step-spacing typically varies from 1.2 to 3.2 m and decreases with the frequency of forcing. Both classification frameworks suggest that hillslope processes greatly influence channel form, due to their inherently steep slopes and high valley confinement. Furthermore, forced steps had significantly greater step heights (~2x) and H/L ratios (~1.5x). Overall, forcing tends to develop more steps per reach length and higher steps in step-pool channels.

KEYWORDS: step-pool morphology, forcing effects, headwater streams, Ozark Highlands, bedrock influence, geomorphic classification

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I dedicate this thesis to Maverick.

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CHAPTER ONE: INTRODUCTION

Understanding headwater streams and the variables that control their form is critical for increasing our knowledge of watershed processes and to support management and restoration purposes (Adams and Spotila, 2005; Chartrand and Whiting, 2000; Gomi et al., 2002). Unlike larger rivers where channel form remains relatively uniform with distance downstream, headwater channel form and substrate characteristics can vary significantly at the reach-scale (Montgomery, 1999). Fluvial processes occur in the channel such as incision, sediment transport, and aggradation, and colluvial processes occur on adjacent hillslopes such as landslides and slumps, and raindrop erosion. However, slope, sediment supply, channel confinement, and riparian vegetation all can control the channel type present in headwater watersheds (Maxwell and Papanicolaou, 2001; Montgomery and Macdonald, 2002). Higher gradient streams in headwater catchments are influenced greatly by low-frequency colluvial processes involving high and low energy events, such as landslides, soil creep, and debris flows (Fig. 1). Channel forms are initiated where runoff is concentrated above the thresholds of bed erosion and sediment transport (Gomi et al., 2002). Additionally, steep headwater valley floors tend to be narrow and contain obstacles to channel formation due to bedrock and trees that often force unexpected channel forms (Adams and Spotila, 2005; Montgomery et al., 1995). Therefore, there is a gap in our understanding of how colluvial, fluvial, and forcing processes are integrated downstream to influence channel form in steep headwater streams (Bonell, 1998). This thesis will investigate a steep headwater stream in the Ozark Highlands of Missouri to address the relationships between geomorphic forcing and channel forms, focusing on step-pool channel morphology.

Headwater Stream Morphology

Headwater streams are generally sediment supply-limited, meaning that the channels are capable of moving more sediment than is being supplied and often exhibit an intermittent or ephemeral nature (Gomi et al., 2002). These supply-limited and low-discharge environments mean that flood events that control channel size and shape are rare (recurrence interval between 20-50 years) and produce high energy and relative discharge rates (Chartrand and Whiting, 2000; Grant and Mizuyama, 1991). Steep hillslope processes like debris flows and landslides are also relatively rare compared to dominant processes in downstream lowland rivers. However, these are known to supply the boulders associated with flow obstructions and bedform development seen in steep headwater streams (Whiting and Bradley, 1993).

Due to the large variety in channel form and process of headwaters streams, classification frameworks are often used to aid in understanding their fluvial processes. However, this is relatively difficult due to their complexity (Buffington and Montgomery, 2013). Several attempts have been made to create classification schemes for headwater streams, based on geomorphic processes e.g., (Whiting and Bradley, 1993) and form e.g., (Rosgen, 1994). However, a combination of both process- and form-based approaches may be best suited in most stream studies (Montgomery and Buffington, 1997). Montgomery and Buffington (1997) present five types of alluvial channels in mountain drainages in order of decreasing bed slope (m/m): cascade (>0.065), step-pool (0.03-0.065), plane-bed (0.015-0.03), pool-riffle (<0.015), and dune-ripple. As drainage area increases, bed slope, sediment size, and flow resistance are expected to decrease, and valley confinement is expected to decrease as floodplains become wider (Kasprak et al., 2016). However, geomorphic classification systems also must account for local factors that can deviate from the general trend. Forcing-effects from a variety of geologic and biologic processes can drastically alter the characteristics used for classifying reach segments (Fig. 2). In steep first- and second-order streams, relatively high valley confinement, small channel widths, and lower sinuosity, allow for increased effects of forcing and channel spanning colluvial blocks and large wood (LW), compared to that of its downstream counterparts (Piégay and Gurnell, 1997). Also, the underlying geology of the watershed can affect the erosion potential and substrate characteristics of the channel (MacFarlane and Wohl, 2003). Bedrock lithology can also have a significant influence on sediment size of the channel where more resistant rocks tend to supply larger sediment (Levson and Rutter, 2000).

The combination of high energy flows, large sediment, and large wood in confined valleys lends itself to create bedforms in headwater catchments. Bedforms are channel unit scale features formed on the beds of headwater streams which serve a significant role in retaining sediment and organic material and preventing sediment from being transported immediately out of the system. Regularly spaced LW is associated with the formation of bedforms such as pools, riffles, and steps (Kraft and Warren, 2003; Montgomery et al., 1995). Bedforms also function as segments of energy dissipation, creating pools that promote aquatic ecosystems within the channel (Montgomery, 1999). Also, high spatial and temporal variations in headwater catchment processes cause them to be exceptionally susceptible to anthropogenic disturbances (Wohl, 2006). Human disturbances through urbanization and deforestation in these environments have been shown to remove the influence of forcing factors on channel form, due to construction physically removing forcing factors (Montgomery et al., 1995; Shepherd et al., 2010).

Step Pool Morphology

Research related to step-pool streams began in the late 1980s (Chin, 1989; Grant and Mizuyama, 1991). Chin (1989) was one of the first to categorize step-pool streams and assess their unique geomorphic role in steep headwater environments. Variables describing channel and bedform geometry are often used to classify step-pool streams (Chartrand and Whiting, 2000; Montgomery et al., 1995; Montgomery and Buffington, 1997). Subtle differences in lithology, relief, and slope between regions and even adjacent basins can often lead to changes in step-pool channel morphology (Duckson and Duckson, 2001; Wilcox et al., 2011). Studies have shown that pool-size attributes such as length, depth, and area can be associated with changes in rock type (Duckson and Duckson, 2001, 1995).

Step-Pool Formation. Step-pool channels will form anywhere the following conditions are present: (1) steep slopes, (2) a heterogeneous coarse bed with the largest material immobile except under forming conditions, (3) high magnitude/low frequency flow events, (4) near-critical to supercritical flow, and (5) low sediment supply environments with low transport rates (Chartrand and Whiting, 2000). As a result, the locations where these conditions exist are located primarily in mountainous areas due to their inherently steep slopes, coarse sediment supply, and mass wasting dominated processes. Under ideal conditions, natural channel form balances flow resistance, slope, and high flow events to create step-pool channel geometry, which best reflects the local environment (Abrahams et al., 1995).

Step-Pool Characteristics. Step-pool streams consist of alternating step and pool features where large clasts or wood form the steps and smaller clasts are deposited in the bottom of pools (Fig. 3). Steps are composed of the largest clasts in the reach, which separate pools and can span the entire channel width. Plunge pools and steps increase flow resistance and dissipate hydraulic energy (Grant and Mizuyama, 1991; Wilcox and Wohl, 2006). Step-pools are associated with larger grain sizes than other stream types, so they are subject to increased bed roughness and relatively low depth of flow (Chin, 1989; Grant et al., 1990; Montgomery and Buffington, 1997). Step-spacing is the distance from one step to the next and is equal to the reach length divided by the total number of steps. Typical step-spacing for step-pool channels is one to four channel widths in length (Montgomery and Buffington, 1997).

Gradients of step-pool channels are typically steeper than most other headwater streams (i.e., plane-bed and pool-riffles), with gradients ranging between 3 to 7% (Montgomery and Buffington, 1997). Step-pool channels also have larger relative roughness (the ratio of the largest sediment to channel depth) ranging from 0.3 to 0.8 (Montgomery and Buffington, 1997). Where the 90th percentile of sediment sizes on the bed (D_{90}) from a sample of bed clasts is approximately equal to the average grain size of the step, and step height approximates the D_{84} of the entire channel (Chin, 1999; Chin and Wohl, 2005; Grant et al., 1990; Nickolotsky and Pavlowsky, 2007). Studies have shown that given height/length/slope ratios (H/L/S) remain relatively consistent between 1-2, even with variability in slope and region (Abrahams et al., 1995; Wilcox and Wohl, 2006). Therefore, as slopes increases, step height must increase or step length must decrease to maintain maximum flow resistance.

Step-Pool Forcing. Geomorphic forcing effects can disturb natural channels and often have a significant impact on the morphology of step-pool streams by varying flow hydraulics to alter step-pool geometry (Duckson and Duckson, 2001, 1995; Montgomery et al., 1995; Montgomery and Buffington, 1997). Forcing types include: (1) episodic inputs of sediment by landslides and slumps, which increase sediment load and obstructs channel flow (Gomi et al., 2002); (2) bedrock obstacles from channel degradation which can control channel morphology through structural and lithological influences (Nickolotsky and Pavlowsky, 2007); (3) colluvial block input via diffusional hillslope processes, that supply large material to the channel; (4) LW supplied by the landscape, forcing steps and pools in reach segments which may not naturally observe them (Piégay and Gurnell, 1997); and (5) living trees in the channel which can obstruct flow, forcing pockets of excess deposition or erosion (Opperman et al., 2008). Laboratory flume studies have assessed the effects of different forcing factors on flow resistance, where effects of forcing factors such as boulders from either landslides or colluvium, bedrock obstacles, LW in the channel, and living organic material have been shown to increase flow resistance and accumulation of material in the channel (Montgomery, 1999; Wilcox and Wohl, 2006). However, areas with large amounts of urbanization and other anthropogenic effects like logging have been shown to decrease flow resistance and increase stream power in the channel from the removal of these resisting factors (Montgomery et al., 1995; Shepherd et al., 2010).

Purpose

The purpose of this research is to classify and quantify step-pool channel form and evaluate forcing effects in the Mark Twain National Forest of the Salem Plateau of the Ozark Highlands. The Ozark Highlands of southeast Missouri is a physiographic region which is characterized by spring-fed streams, rolling hills, and moderately steep hillsides. The landscape consists of dendritic and radial channel networks cutting into the high plateaus of the region with local relief >100 m along major tributaries (Gott, 1975). Known for its karst topography, the state of Missouri has over 6,000 caves, a majority of which are in the Ozarks. Representative features also associated with the karst topography of the region include losing streams, estavellas, and sinkholes (Gott, 1975). Characterized by pine-oak forest, the Current River subsection of the Ozark Highlands has moderately steep hills, and local relief ranging between 50 to 100 meters (Kabrick et al., 2000). As referred to by this author, Deer Camp Hollow (DCH) (0.18 km^2) a headwater watershed of Big Barren Creek in Mark Twain National Forest is the focus of this research (Fig. 4).

Objectives and Hypotheses

The Ozarks are a region in the southern portion of the Midwest few geomorphologic studies of mountain streams. The Mark Twain National Forest experienced heavy logging in the past and is currently undergoing efforts to restore the ecosystem to its natural state (Jacobson and Primm, 1997). This research focuses on evaluating morphologic relationships unique to the Ozarks which may help inform restoration and other management efforts and provide insight to preventative efforts to maintain channel stability in forest stream systems. The objectives of this study are to: (1) classify channel types and evaluate the distribution of in-channel networks in relation to the effects of slope, sediment size, and geological and biological forcing; (2) complete a geomorphic assessment of step-pool channels; and (3) evaluate the influence of forcing factors on step-pool morphology. Morphologic variables include effects from slope variance, bed size/average grain size, and forcing relationships inherent in the channel. Assessing how DCH fits within the prevailing understanding of step-pool channel forms can help evaluate the effects of forcing factors relevant to the Ozarks. Deviation from expected geomorphic relationships can explain the effects of watershed processes and their forcing conditions. The hypotheses for this study are based on findings and studies of step-pool morphology in other regions are: (1) step-pool channels will tend to have bed slopes between 3 to 6.5%, step-spacing between 1-4 channel widths, and step length to height ratios between 15:1 and 2:1 (Montgomery and Buffington, 1997); (2) sediment size and step-spacing will correlate with slope, but possibly also be influenced by local bedrock lithology which may affect step-forming clast size (Duckson and Duckson, 2001); and (3) forcing factors such as LW, bedrock boulders, and trees will increase step-spacing and average step-clast size, and decrease channel width (Montgomery et al., 1995).

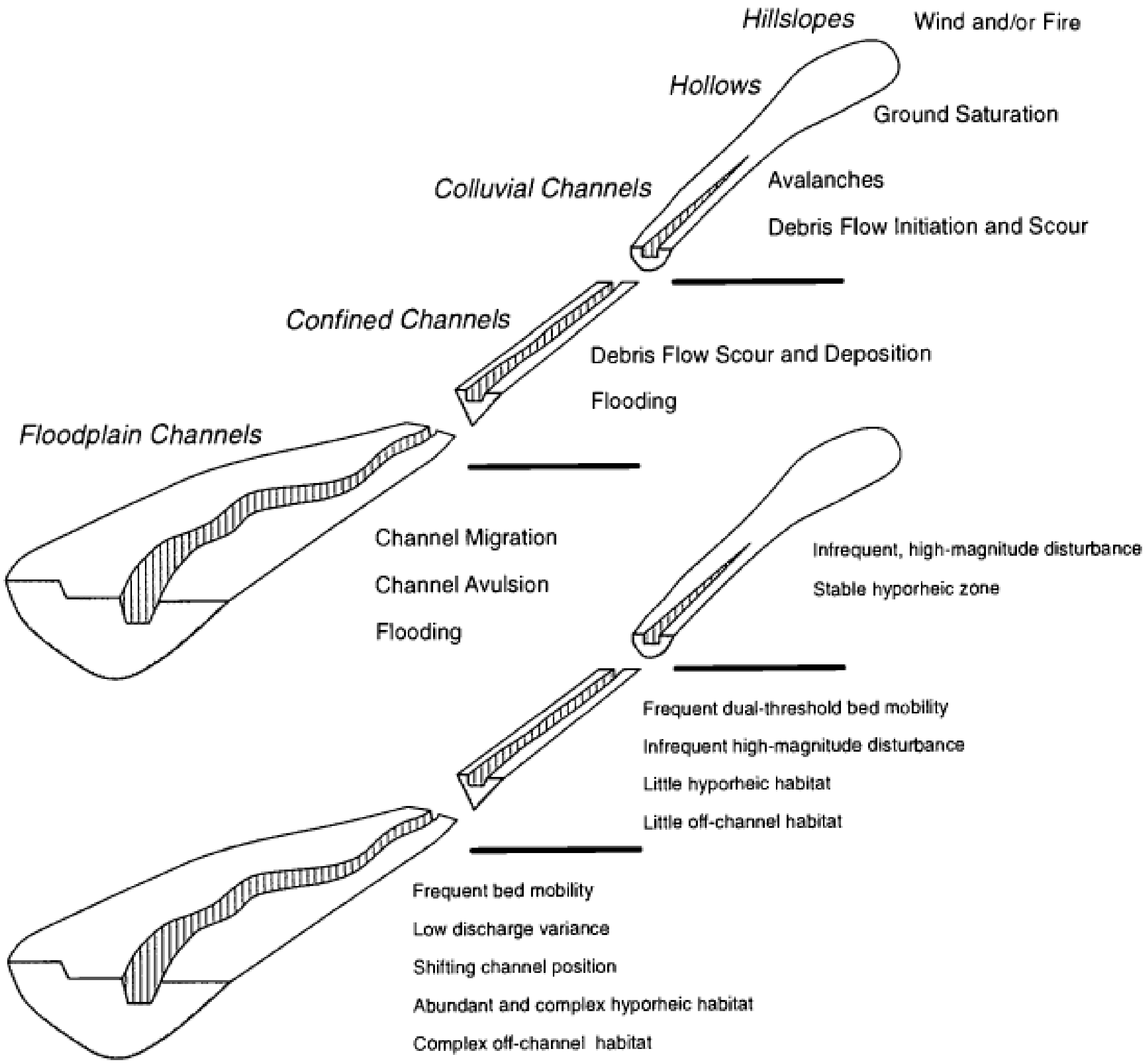


Fig. 1. Mountain channel network and geomorphic processes. (Montgomery, 1999)

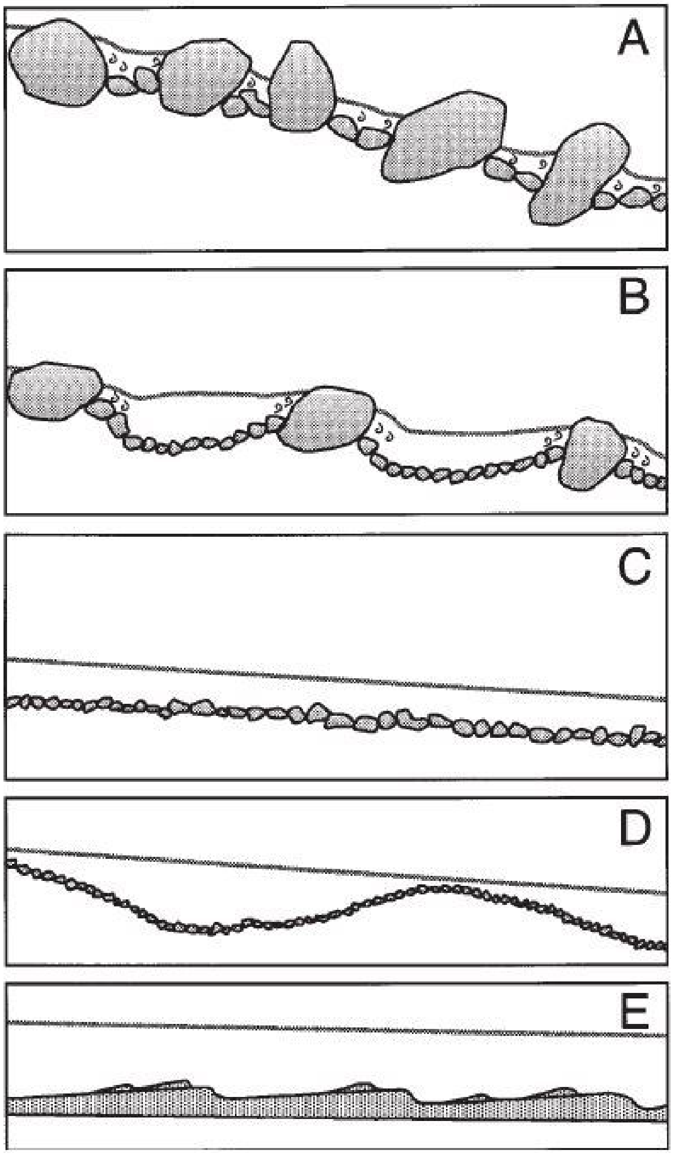


Fig. 2. Longitudinal profiles of the five types of mountain streams (Montgomery and Buffington, 1997)

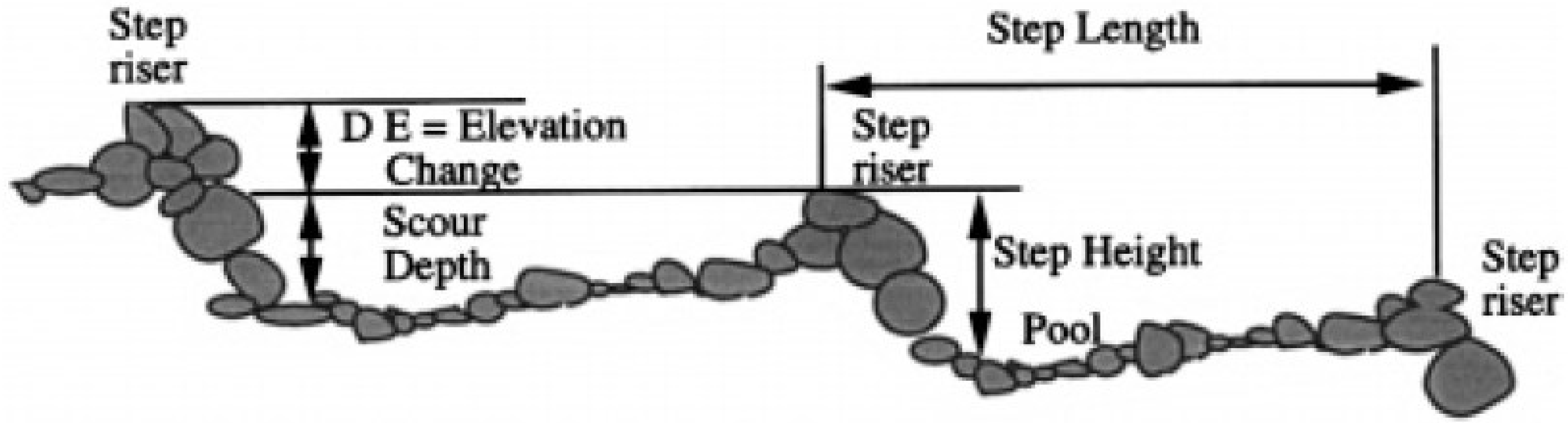


Fig. 3. Geometric characteristics step-pool beds (Chartrand and Whiting, 2000)

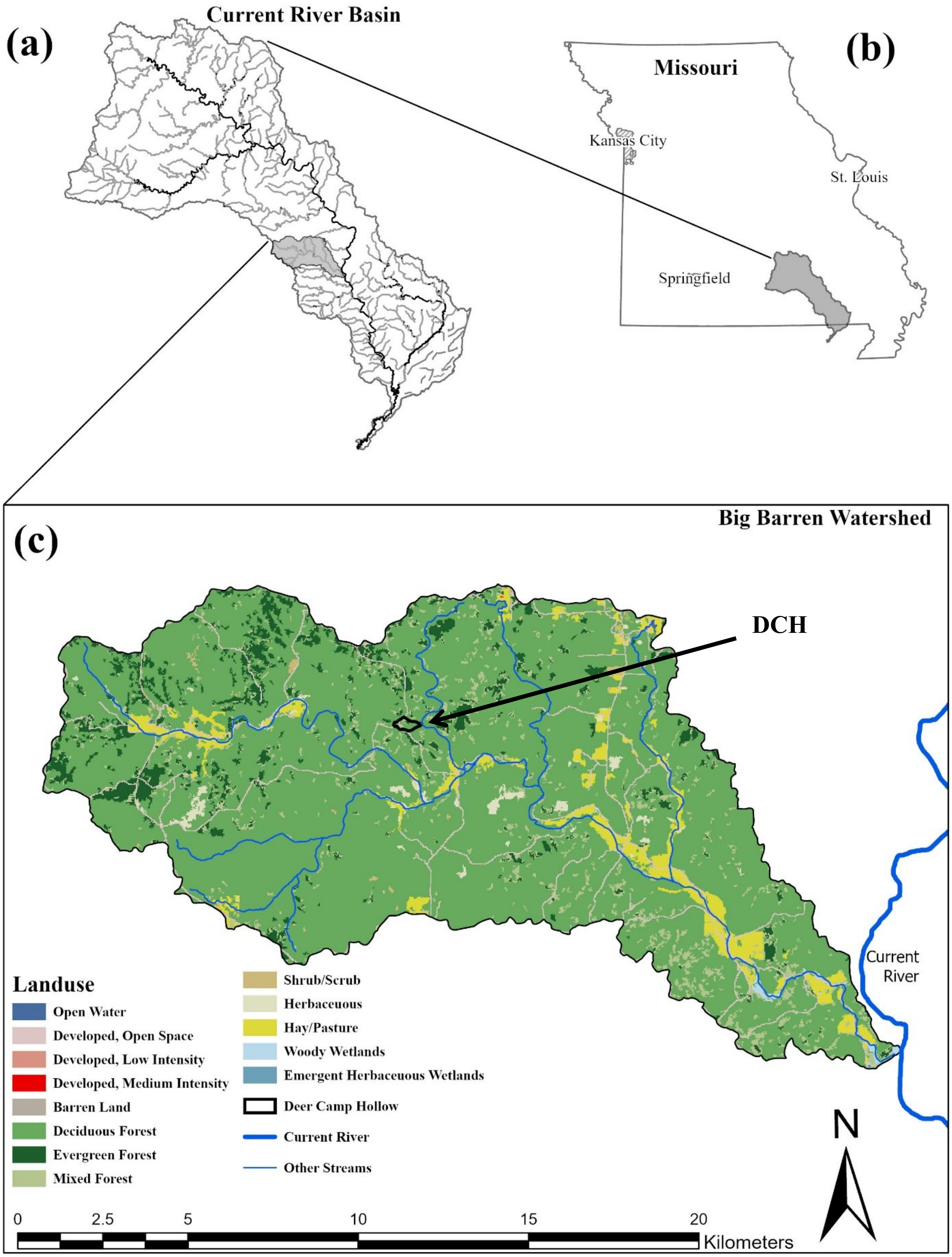


Fig. 4. Region location of DCH, including land use/land cover in the Big Barren Creek Watershed.

CHAPTER TWO: STEP-POOL CHANNEL MORPHOLOGY AND FORCING EFFECTS IN THE OZARK SALEM PLATEAU SUB-REGION, SE MISSOURI

Introduction

Step-pool streams are identified as a specific channel form with a primary function to maximize flow resistance and reduce stream power in high-gradient areas (Abrahams et al., 1995; Montgomery and Buffington, 1997). Step-pool channels contain sequences of longitudinal steps and pools similar to a staircase where the steps are composed of the largest material supplied to the channel (typically cobbles and boulders) which can span the width of the channel perpendicular to flow direction. Pools form immediately below the steps, to provide local sections of tumbling flow that dissipates energy and deposits sediment (Comiti et al., 2009). This natural process limits the erosive potential of the channel and prevents excess sediment from being transported downstream. Step-pool channel processes can control flooding and create healthy aquatic habitat and therefore are of concern in the environmental fields of geomorphology, biology, and engineering (Splinter et al., 2010; Thomas et al., 2000; Wilcox et al., 2011). Step-pool streams typically occur and are most commonly studied in mountainous regions of the western United States. In the modern age of urbanization, mountainous areas are becoming more and more inhabited (Wohl, 2006). Thus, a greater understanding of step-pool morphology has important implications for stream management in mountain areas (Chin and Wohl, 2005).

The size and distribution of step-pool bedforms have been described as a function of maximum energy dissipation within the active channel boundary (Abrahams et al., 1995).Thus, step-pool channels have relatively high slopes (3-6.5%) and roughness coefficients (0.3-0.8) (Montgomery and Buffington, 1997). In general, downstream variations in slope, sediment supply, and size of the available sediment tends to control the channel geometry of step-pool streams (Wooldridge and Hickin, 2002). The largest material available to the channel forms the steps (Chin, 1999; Grant and Mizuyama, 1991) and spacing distance between the steps is dependent on the slope of the channel (Chartrand and Whiting, 2000). Geomorphic variables commonly used to quantify step-pool channel morphology are step-height, wavelength, slope, and sediment size (Nickolotsky and Pavlowsky, 2007). These geomorphic variables can vary in magnitude at the reach-scale due to subtle differences in lithology and vegetation influence (Chin and Wohl, 2005).

Step-pools streams are usually located in relatively narrow valleys and are influenced directly by hillslope processes (Whiting and Bradley, 1993). Hillslope processes often supply large sediment and wood to the channel through mass wasting and diffusive processes, creating forcing factors that can easily span the entire width of the active channel. External forcing factors and types include: (1) bedrock obstacles from channel degradation which can control channel morphology through structural and lithological influences (Nickolotsky and Pavlowsky, 2007); (2) colluvial block input via diffusional hillslope processes, that supply large material to the channel (Gomi et al., 2002); (3) LW supplied from the landscape, forcing steps and pools in reach segments which may not occur normally (Jackson and Sturm, 2002; Marston, 1982; Piégay and Gurnell, 1997); and (4) living trees in the channel which can obstruct flow, forcing pockets of excess deposition or erosion (Opperman et al., 2008). Therefore, regional differences in relief, lithology, soil and sediment characteristics, and vegetation typically affect the form and distribution of channel types and cause differences in geomorphic relationships among regions.

Furthermore, episodic inputs of sediment by landslides and slumps increase sediment loads and obstructs channel flow (Gomi et al., 2002), but large boulders and LW tend to provide the most frequent influences on the morphology of step-pool channels (Wilcox and Wohl, 2006). How these specific forcing factors alter step-pool channel form and geometry is stillpoorly understood, especially in regions other than the western United States (Curran and Wohl, 2003; MacFarlane and Wohl, 2003; Nickolotsky and Pavlowsky, 2007)

Since steep headwater streams are usually located in mountainous areas, studies of these stream types in the U.S. have been primarily limited to the west, with a few exceptions in Alaska and the Appalachian Mountains of the eastern U.S. (Adams and Spotila, 2005; Kraft and Warren, 2003). However, the Ozark Highlands of the south-central United States is an area with an abundance of steep headwater streams, with elevations reaching 780 m with high local relief (50-100 m) in the Boston and St. Francis Mountains, and the Salem Plateau (Gott, 1975). Nickolotsky and Pavlowsky (2007) assessed step-pool channel morphology in the Boston Mountains of northwest Arkansas, where they compared step-pool measurement protocols and channel reach morphology. Other studies have been performed in eastern Oklahoma that assessed the variation of channel morphology among ecoregions (Ozark Highlands and the Boston and Ouachita Mountains) (Splinter, 2013; Splinter et al., 2011, 2010). Lastly, Shepherd et al. (2010) performed a study in headwater catchments of the Illinois River Watershed in the Ozark Highlands of northwest Arkansas, which concluded that increased urbanization increased bed slope and channel cross-sectional area. None of these previous studies have addressed the Missouri portion of the Ozark Highlands, which encompasses largest percentage of the area (~75%) (Fig. 5). The objectives of this study are to: (1) complete a geomorphic assessment of step-pool channels within the Deer Camp Hollow (DCH) (0.2 km^2) watershed of MTNF and (2) evaluate the influence of forcing factors on step-pool morphology, in the Mark Twain National Forest (MTNF) in the Salem Plateau physiographic subregion of the Ozark Highlands.

Study Area

Deer Camp Hollow (DCH) is a second-order stream in the headwaters of the Big Barren Creek watershed in the Eleven Point District of Mark Twain National Forest of Southeastern Missouri (Fig. 4). It drains 0.2 km^2 (20 Ha) of the Current River Hills land type association, which contains moderately steep hillsides with narrow and broad sinuous valleys (Kabrick et al., 2000). The main channel is about 865 m in length, with a basin slope of 8.5% flowing from a peak divide elevation of 283 masl to 198 masl at its confluence with Fools Catch Creek (9.9 km^2), a major tributary of Big Barren Creek (190.6 km^2) (Fig. 4). Big Barren Creek flows into the Current River below Van Buren, Missouri. Portions of the Current River were declared sections of the Ozark National Scenic Riverways in 1974 in an attempt to preserve streams, springs, caves, and wildlife, as well as establish recreational areas in Missouri (Barks, 1982).

Geology and Soil. The Salem Plateau physiographic region of the Ozark Highlands is known for its karst topography represented by extremely weathered and widespread soluble carbonate rocks (primarily dolomite and limestone) with interbedded sandstone members (Gott, 1975). The Roubidoux formation primarily comprises the bedrock geology in the upper and middle reaches of the watershed (93%), with a small portion of the Gasconade formation outcropping in the lower reaches (Fig. 6). The Roubidoux is from 150-200 ft (46-61 m) thick, whereas the Gasconade is from 300-400 ft (91-121 m) thick (Gott, 1975). Both formations consist of sandstone and cherty dolomites of Ordovician age (Kabrick et al., 2000). The Limestone and dolomite members of the Roubidoux formation are known for their relatively rapid denudation rates compared to the sandstone bedrock, often exposing large sandstone blocks from the middle of the formation at the surface (Gott, 1975; Overstreet et al., 2003; Repetski et al., 1998) (Fig. 7). The outcropping of this sandstone unit at the surface has caused forcing of the channel form in the middle of the watershed, where bedrock and colluvial boulders >1.5 m are frequently formed in the channel (Fig. 8). The resistant sandstone of the Roubidoux formation comprises most of the channel sediment, supplying large clasts capable of forming steps which can range from 0.2 to 1m high, typical of step-pool morphology.

The upland areas of DCH consist of the Captina silt loam (22.7 %) and Clarksville very gravelly silt loam (76.4%) (Fig. 6). Both are classified as ultisols with fragipan formed in clayey residuum with varying amounts of chert fragments and sand percentages (Gott, 1975; Kabrick et al., 2000). The Captina silt loam occurs in the uppermost part of the watershed on flatter uplands and shoulder slopes, consisting of a thin loess layer over residuum weathered cherty limestone. The Clarksville very gravelly silt loam is on narrow ridges and hillslopes and is formed in deep somewhat excessively drained alluvium and colluvium over residuum weathered from cherty limestone. The Tilk-Secesh complex (0.9%) occurs on alluvium and alluvial forms deposited at the mouth of DCH where it meets with Fools Catch Creek., which is well-drained and composed of gravelly alluvium, with rounded to sub-angular gravel and cobbles of sandstone and chert (Fig. 6).

Climate and Hydrology. Southeast Missouri receives 112 cm (44 in) of mean annual precipitation and is considered a humid temperature climate with a mean yearly temperature of 14.4^{o} C (58^{o} F) (Adamski et al., 1995). The hydrologic complexity of the region is due to dense subsurface flow networks within the fractured karstic bedrock and frequent springs. This generates runoff events that are more prevalent during winter and late spring, including flashy flood events which occur in ephemeral or perennial stream systems (Kabrick et al., 2000). DCH itself is an ephemeral stream, which is typically dry for a majority of the year. However, significant storm events have been observed to cause significant flood events within the watershed.

Land Use. The region was short-leaf pine dominated before the historical logging era of the late 1800s to early 1900s, which persisted until the early 1920s (Kabrick et al., 2000). Logging in the area started by clearing nearly all of the pine followed by oak, throughout the entire region (Jacobson and Primm, 1997). Evidence of historical logging in the DCH includes an old tram bed that crosses the lower 200 meters of the watershed. Mark Twain National Forest was created in 1976. However, the land was purchased by the U.S. government in 1939 due to the increasing concern of the barren and often abandoned forest lands remaining after the exploitation of logging ended (Halpern, 2012). Current forest management practices in DCH do not include prescribed burning but do include local timber stand improvements by removing lower quality trees to increase timber growth. DCH is currently comprised of mixed oak-pine forests (>99% canopy coverage).

Methods

For this study, reaches were classified in the field as cascade, step-pool, or pool-riffle channels and sub-reach sites were selected for a more in-depth channel morphology assessment. Overall, the methods can be split into three major constituents: field data collection, geospatial data analysis, and data processing. Field data collection was completed using surveying tools, gravelometers, and human judgment (Chartrand and Whiting, 2000; Chin, 1999; Zimmermann and Church, 2001). Geospatial methods included the analysis of light detection and ranging

(LiDAR)-derived digital elevation models (DEM's), and GIS software (ArcPro 2.3) used to accurately map the watershed (Vianello et al., 2009; James and Hunt, 2010; Tompalski et al., 2017).

Stream Classification. Initial rapid assessment classification of stream type was performed to assess the entire watershed for potential study reaches following that of Montgomery and Buffington (1997) which uses distinct bedforms types to classify reach segments (Fig. 2). The field assessment also included channel type, number of channel threads, channel width/depth/substrate, and forcing types, if present. This assessment was performed in 10-meter intervals, starting 5 meters from where the main stem crosses the road. For the small tributary, the assessment started 125 meters upstream of the confluence and also assessed channel characteristics every 10 meters. From this data set, ten reaches were selected to perform a more in-depth channel assessment. Reaches were selected based on a central valley location, with little contact with valley margins and limit the influence of local discharge and sediment inputs from nearby hollows or hill-slides on channel form (Fig. 6).

Channel Geometry and Step Surveys. A cross-section and longitudinal profile were surveyed at each reach using an auto level and stadia rod to assess channel width, depth, and step-pool geometry. Cross-sectional surveys extend across the valley floor between margins and included active channel, floodplain and lower terraces. The primary points of the longitudinal surveys focused on the highest point of the crest on each step and the lowest point of each pool. On relatively longer sections of glides or riffles, additional locations were surveyed in the thalweg. An average of 35 points, with a range of 24 to 46 points, were collected at each of the longitudinal profiles with an average length of 28.8 m ranging from 19.9 m to 33.0 m. The average length of the ten cross-sections across the valley including the channel was 9.3 m (7.0 m – 14.5 m) with an average of 12 survey points collected, ranging from 10 to 16 points.

The methodology from Chartrand and Whiting (2000) was used to assess step height, wavelength, and height/length ratios (H/L) (Fig. 3). Step height was calculated using the vertical distance between the step crest and the deepest point of the downstream pool and step wavelength was calculated using the horizontal distance from step crest to the downstream crest. A step characteristic survey recorded additional step-pool geometry such as forcing type, step form, and step/pool width. Step characteristics were averaged by reach to assess specific step-pool morphology.

Pebble Counts. Two different pebble count procedures were used as modified from Wolman's (1954) method of pebble sampling of coarse river bed material. First, a step-size pebble count which recorded the b-axis of the five largest clasts in each step was performed. Clasts were visually selected, measured with a folding ruler, and averaged to estimate the D_{90} of the reaches particle size (Chin, 1999; Chin and Wohl, 2005; Nickolotsky and Pavlowsky, 2007). When selecting the five largest clasts, workers ignored bedrock and large colluvial boulders (clearly immobile blocks), which were considered forcing features similar to that of Nickolotsky and Pavlowsky (2007). Bedrock was considered as any large immobile clasts or exposed rock material (~>0.5 m in diameter) with a majority of their material buried under the channel surface.

Second, a reach-size pebble count was performed to determine the sediment size distribution in each of the ten reaches using a gravelometer with graduated sieve sizes or folding ruler when clasts were embedded in the channel or more massive than 180 mm. Survey specifics were dependent on reach length. Reaches were separated by transects every 3 meters ranging from 10 to 13 transects per reach. At each transect, three pebbles were selected using the blindtouch method within one-third segments of the channel bed (Wolman, 1954) and particle size was recorded using a gravelometer. One pebble was selected within each of three cells across the channel from the left, middle, and right "thirds" of the channel. At each reach, a minimum of 30 samples was collected to calculate the grain size distribution of the channel. Also, at each transect the largest max clast size was recorded and averaged to obtain the average maximum clast for reach. Bedrock and fines were both included in this pebble count and used to calculate percent bedrock and fines for each reach. Selecting max clast size is subjective, so both pebble counts were performed by the same workers to limit sampling errors, maintain sampling consistency, and reduce variation in maximum clast selection (Bunte et al., 2009).

Geospatial Data Collection. ArcGIS Pro 2.3 was used for creating maps, delineating the watershed, and calculating watershed-scale variables for this study. A Trimble Geo7x GPS was used to collect points at 10-meter intervals for the rapid geomorphic assessment, location of reach channel surveys, and creating map layers. The U.S. forest service provided LiDAR data with 0.5 m resolution in order to delineate the watershed, assess watershed and reach-scale geomorphology, and create map features. Geologic data was obtained from the Missouri Spatial Data Information Service (MSDIS), where the Wilderness and Handy quadrangle was mapped in 2003 at 1:24,000 scale (Harrison and McDowell, 2003). Soil data was obtained in 2014 from the Web Soil Survey (WSS) created by the Natural Resource Conservation Services (NRCS), also at 1:24,000 scale.

Results and Discussion

Reach characteristics. Ten reaches were sampled with the number of channel types as follows: cascade/step-pool (3), step-pool (4), step-pool/pool-riffle (2), and pool-riffle (1) (Table

1). The characteristics of the channel system reflect those normally associated with step-pool channels, with an average spacing/width ratio of 1.1, high slopes between 4.2 and 17.9%, and exposed bedrock in the bed up to 80% (Table 1). Reach 4 had no bedrock and exhibited relatively shallow slope and low step-pool geometry values, as well as, reaches 9 and 10 (48 and 6% bedrock, respectively) where DCH grades into the valley floor of Fools Catch Creek (Fig. 9). Reach 5 has the steepest bed slope, is the only reach sampled on a tributary, and displays the only sign of relatively recent slope failure in the form of a slump in fine colluvium (Fig. 10). Reach 10 had the lowest slope being located on an alluvial fan where DCH flows into Fools Catch Creek. A total of 263 m of channel length was surveyed on the main stem and 26 m on the tributary, accounting for approximately 43% of the total stream length between reach 1 and reach 10. Reach elevations ranged from 262 masl at Reach 1 to 204 masl at Reach 10, drainage areas range from 2.74 to 17.35 hectares, and D_{90} ranged from 155 to 210 mm with a mean of 185 mm (Table 1).

Step morphology. A total of 121 step-pool sequences were measured within the nine step-pool reaches. Similar to other studies performed on mountain streams, reach-scale variables were averaged to evaluate geomorphologic relationships (Chin, 1999; Curran and Wohl, 2003; Duckson and Duckson, 1995; Montgomery and Buffington, 1997; Nickolotsky and Pavlowsky, 2007). Step characteristics range from 0.16 to 0.42 m for step-height, 1.12 to 3.24 m for step spacing, and 0.94 to 1.86 m for step width (Table 2). Step-height and width are greatest in the upper segment of the watershed which is most influenced by colluvial substrate and input (Reaches 1-3 and 5) and locally towards the middle segment of the watershed where large boulders and bedrock influence are present, and slopes are relatively high (Reaches 6-8). This can be explained by significant positive relationships between slope and step-height (R^2=0.51, p=0.03) and slope and pool-depth (R^2=0.54, p=0.02) (Fig. 11). Step-spacing ranges from 1.21 m to 3.24 m, with a mean of 2.23 m and spacing/width ratios range from 0.8 to 2.0 channel widths, with an average of 1.1 m (Table 2). Both step-spacing (R^2=0.32, p=0.11) and spacing/width ratios (R^2=0.30, p=0.13) display a moderately weak negative relationship with slope (Fig. 11). These step-spacing variables tend to display an inverse relationship with slope, with the largest values located in Reach 4.

The geomorphic relationships observed in DCH are typical of step-pool streams and indicative of how channel morphology adjusts to maximize flow resistance (Abrahams et al., 1995; Nickolotsky and Pavlowsky, 2007). Significant positive relationships occur between step-height and the D_{90} from the five largest step clast (R^2=0.58, p=0.02), and average max clast and step height (R^2=0.44, p=0.05) which follows the theory that steps are formed using the largest mobile clast in the channel (Chin, 1989). All comparisons of geomorphic variables in DCH with those in Bowers Hollow in Northwest Arkansas show similar trends in their relationships (Fig. 11). All of the relationships described in Fig. 11 trend in the same direction with similar slopes as Bowers Hollow, despite both having varying degrees of local bedrock influence on step characteristics.

Forcing relationships. Forcing factors have a significant influence on morphologic relationships for step-pool channels in DCH. Percent bedrock on the channel bed was calculated from pebble count data and shows significant positive relationships with average maximum clast size (R^2=0.73, $p<0.01$) and step-height (R^2=0.63, p=0.01) (Fig. 12). Percent bedrock in the channel also displays a significant positive relationship with slope (R^2=0.40, p=0.05). However, bedrock percentages are poorly related to D_{90} (R^2=0.22, p=0.20), step-spacing ($R^2<0.01$, p=0.93), and spacing/width ratios which has a negative relationship (R^2=0.19, p=0.24) (Fig. 12). Of the

122 steps assessed, 89 (72.9%) displayed some form of forcing. Of the 89 steps that displayed forcing, 13 (14.6%) displayed more than one type of forcing, 87 had bedrock, six with LW, six trees, and one colluvial boulder (Table 3). Table 4 displays reach average means of forced and unforced morphology. All forcing types were analyzed together for a reach due to the high frequency of steps indicating bedrock forcing.

Mean values of unforced and forced steps increased from 1.87 m to 2.25 m for step-spacing, 0.19 m to 0.36 m for step-height, 1.26 m to 1.46 m for step-width, 0.17 m to 0.19 m for average step clast, 0.12 to 0.18 for H/L ratios, and 1.28 to 1.65 for Spacing/width (Table 4, A). Assuming equal variance and normal distribution, an independent test of two means of all step variables separated by unforced and forced morphology showed that mean step-height and H/L ratios are significantly different ($p<0.01$) and both step-width and spacing/w ratios are moderately significant ($p=0.054$ and $p=0.062$) (Table 4**,** B). To further validate the results from the independent test of two means, downstream variability between unforced and forced steps was assessed. Where both unforced and forced step-height and H/L ratios indicate poor relationships in the downstream direction, along with step-spacing, -density, -width, average max clast, and spacing/w ratios (Fig. 13). The poor relationships between step characteristics with distance downstream oppose Abrahams et al., (1995) and Wilcox and Wohl (2006), two flume studies which reported step-pool geometry typically adjusts to maximize flow resistance with distance downstream. This relationship supports the conclusion that forcing factors can significantly increase step height and H/L ratios in forested mountain drainage basins (Montgomery et al., 1995).

Conclusions

This study evaluated the step-pool morphology of a small headwater stream in the Ozark Highlands of Missouri. The Ozark Highlands is an area of high local relief and slope in the south-central U.S. that has had very few studies of steep headwater stream morphology (Nickolotsky and Pavlowsky, 2007; Shepherd et al., 2010; Splinter et al., 2010). Therefore, improving our knowledge of step-pool stream morphology in this region was a major goal of this study. Furthermore, the effects of different forcing factors on channel form were assessed including bedrock control, colluvial blocks, large wood, and living trees. Bedrock forcing created abrupt changes in channel morphology and greatly affected step-pool characteristics and geomorphic relationships. In this study, the primary source of bedrock control affecting reach-scale channel morphology was outcropping of resistant sandstone on the valley floor in the middle of the watershed.

In general, morphologic relationships in this study show similar trends to that of Bowers Hollow in northwest Arkansas where relationships of step-height with slope (R^2=0.51, p=0.03) and D_{90} (R^2=0.58, p=0.02) display significant positive relationships (Nickolotsky and Pavlowsky, 2007) (Fig. 11). Step-pool morphology occurs along >80% of the total stream length with mean characteristics as follows: a slope of 11.5%, step height of 0.32 m, step width of 1.44 m, D_{90} of 185 mm, mean step spacing of 2.23 m, and 1.1 for the spacing/width ratio. Bedrock influence on the bed is highly correlated with average max clast (R^2=0.72, p<0.01) and step-height (R^2=0.63, p=0.01) (Fig. 12). The independent test of two means for 122 steps indicates that both step-height and H/L ratios show significantly higher values in reaches with frequent forcing by bedrock obstruction and to a lesser degree large wood and trees.

Overall, step-pool and cascade channels in DCH reflect similar geomorphic relationships as found in the Boston Mountains in the southwestern Ozark Highlands. However, the difference in process-form relationships among sub-regions may be related to the frequency and type of forcing involved which can cause local variations in form in step-pool channels. In addition, this knowledge of how forcing factors can affect step-pool channel geometry may be helpful for a variety of disciplines related to stream restoration. Geologic forcing may control the flashy nature of streamflow in the Ozark Highlands to enable stable step-pool channels to form. Adding random and over-sized bedrock control features to engineered channels may help improve the structural integrity of steep constructed channels. Future work may include: (1) further studies of the geography of step-pool forms in different bedrock and relief settings in Mark Twain National Forest, to better understand the effect of variations in local relief and geologic influence; (2) systematic studies of how sediment type and rock substraight affect step-pool characteristics; and (3) the mobility and function of large bed material in step-pool channels including runoff event frequency and channel hydraulics. The ease of access to a variety of step-pool stream systems in MTNF for assessments offers opportunities to improve our understanding of step-pool geomorphology in general.

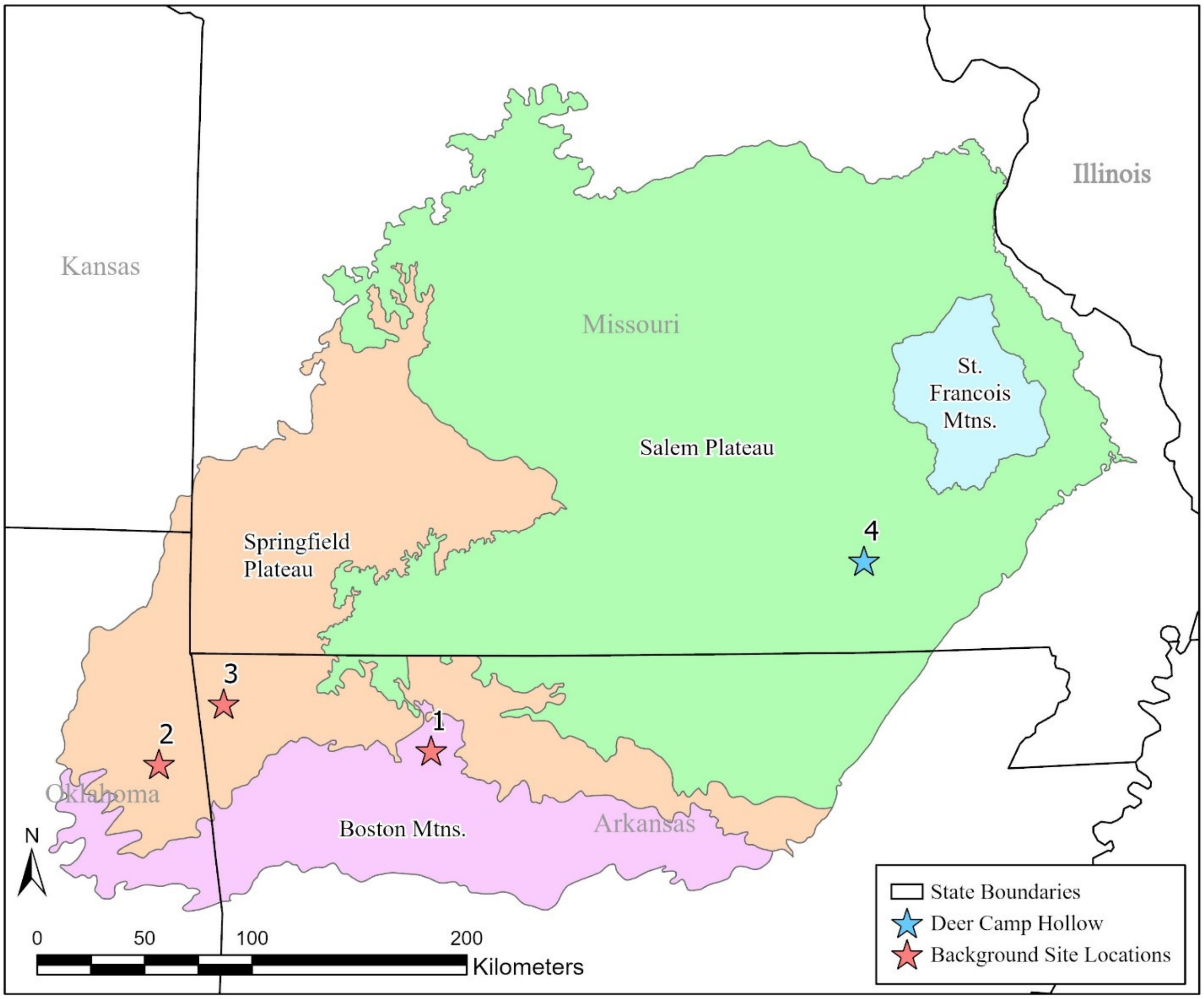


Fig. 5. Four different sub-regions of the Ozark Highlands. Study locations labeled as follows; (1) Nickolotsky and Pavlowsky (2007), (2) Splinter, 2013; Splinter et al., 2011, 2010), (3) Shepherd et al., (2010), and lastly (4) Deer Camp Hollow

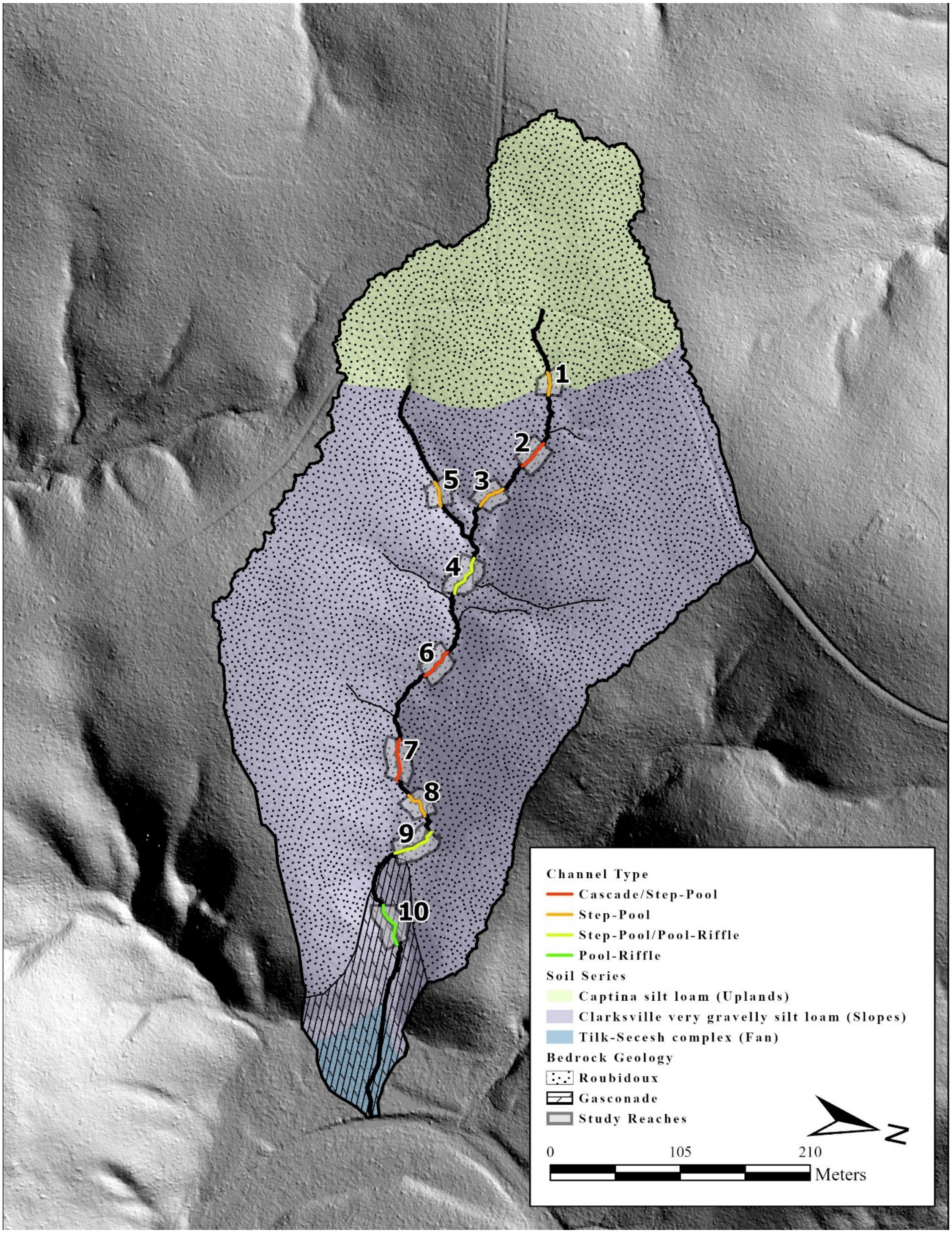
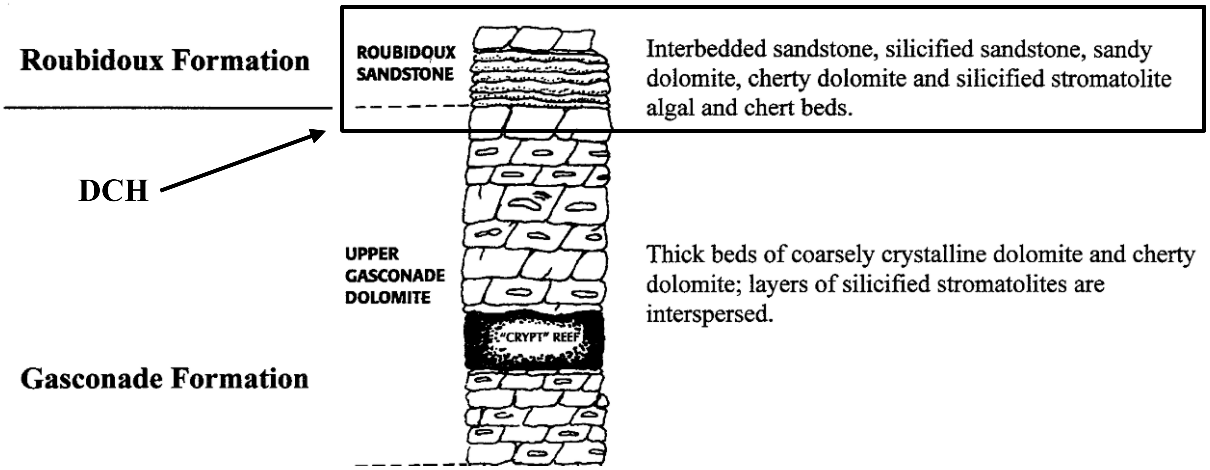


Fig. 6. Soils, geology and reach classification distribution



Interbedded sandstone, silicified sandstone, sandy dolomite, cherty dolomite and silicified stromatolite algal and chert beds.

Thick beds of coarsely crystalline dolomite and cherty dolomite; layers of silicified stromatolites are interspersed.

Fig. 7. Regional geologic column. Modified from Kabrick et al., (2000)

Fig. 8. Large colluvial boulders in Reach 7

Table 1. Geomorphic characteristics of the sample reaches

Reach #	Channel Type		Length (m)	Ad (ha)*	Elevation (masl)	Slope (%)	Vw (m)*	w (m)*	d (m)*	Vw/w (m/m)*
1	Step-Pool	-	20	2.74	262	11.5	8.5	1.6	0.20	5.5
2	Cascade/Step-Pool	-	32	4.29	252	16.6	8.3	1.7	0.19	4.9
3	Step-Pool	-	25	4.98	243	14.5	6.0	2.6	0.18	2.3
4	Pool-Riffle/Step-Pool	-	31	6.89	236	4.9	9.7	1.6	0.22	5.9
5	Step-Pool (Trib)	-	26	2.54	245	17.9	5.0	2.8	0.27	1.8
6	Step-Pool/Cascade	-	30	11.54	231	10.3	6.0	1.4	0.25	4.2
7	Step-Pool/Cascade	-	32	12.85	219	16.7	12.0	2.3	0.40	5.1
8	Step-Pool	-	29	13.38	213	11.7	9.3	2.9	0.28	3.3
9	Step-Pool/Pool-Riffle	-	30	15.02	209	7.1	7.3	3.1	0.18	2.4
10	Pool-Riffle	-	33	17.35	204	4.2	11.5	4.5	0.3	2.6

* Ad = Drainage area, Vw = Valley width, w = channel width, d = average channel depth, and Vw/w = Confinement ratio

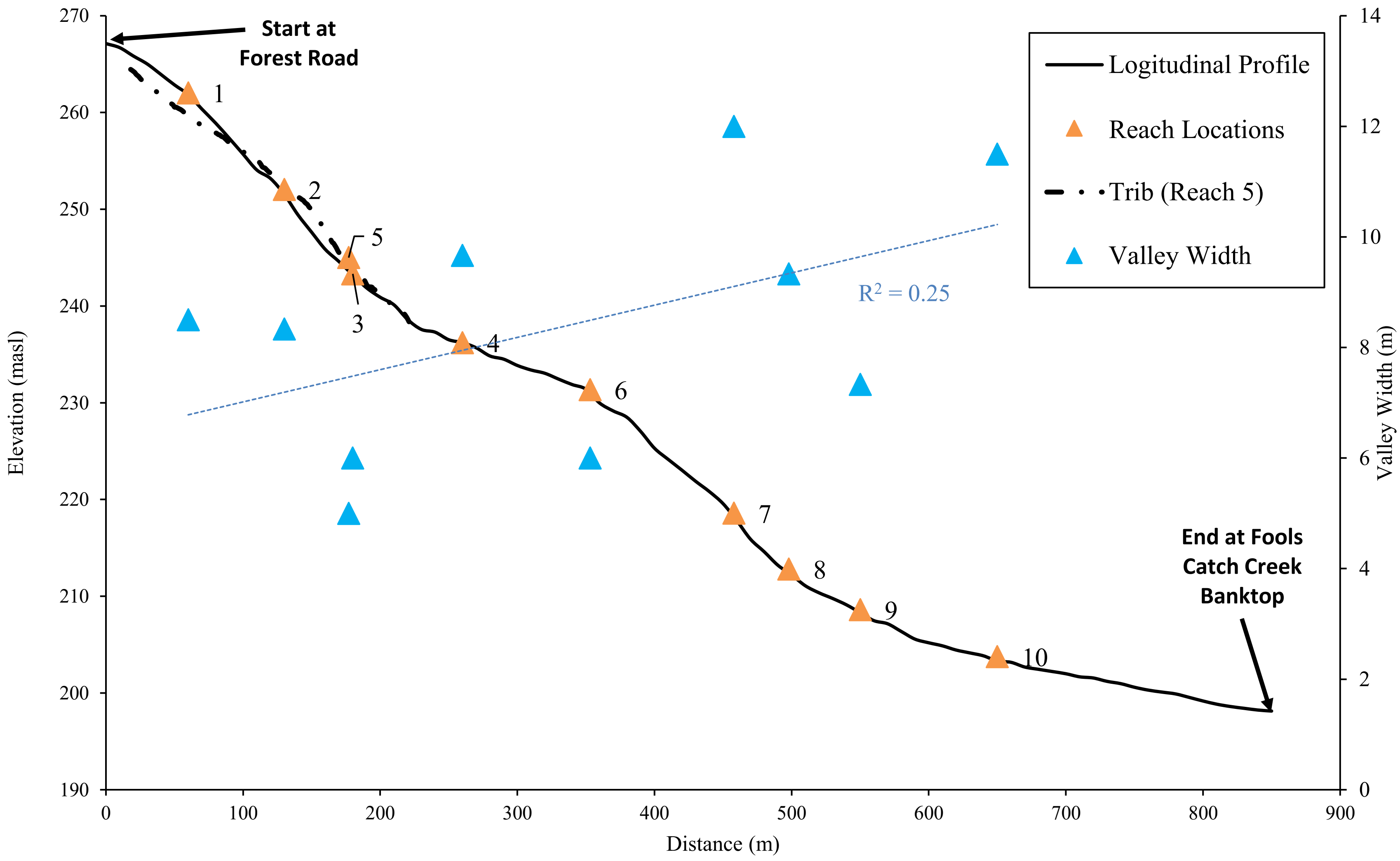


Fig. 9. Channel bed and valley width of Deer Camp Hollow.

Fig. 10. Old slope failure scar in Reach 5 of DCH. This was the only example of a mass wasting event observed in this study

Table 2. Reach bedform and substrate characteristics

	Bedform and Substrate				Step Morphology				
Reach #	D_{50} (mm)	D_{90} (mm)	Avg. Max Clast (mm)	Percent Bedrock (%)	Step Number (#)	Step Density (#/length)	Step Height (m)	Step Spacing (m)	Spacing /width ratio
1	22.6	159	222	0	17	0.85	0.16	1.21	0.8
2	16	178	638	36	16	0.50	0.35	2.07	1.2
3	16	188	490	48	11	0.43	0.4	2.28	0.9
4	32	187	280	0	10	0.32	0.22	3.24	2
5	13.5	206	418	45	12	0.47	0.39	1.98	0.7
6	45	155	727	42	17	0.57	0.27	1.79	1.2
7	90	210	959	80	15	0.47	0.42	2.16	0.9
8	32	209	634	39	14	0.48	0.39	2.15	0.8
9	45	173	441	48	10	0.33	0.26	3.21	1
10	64	-	248	6	-	-	-	-	-
Average	37.61	185	506	35	13.56	0.49	0.32	2.2	1.1

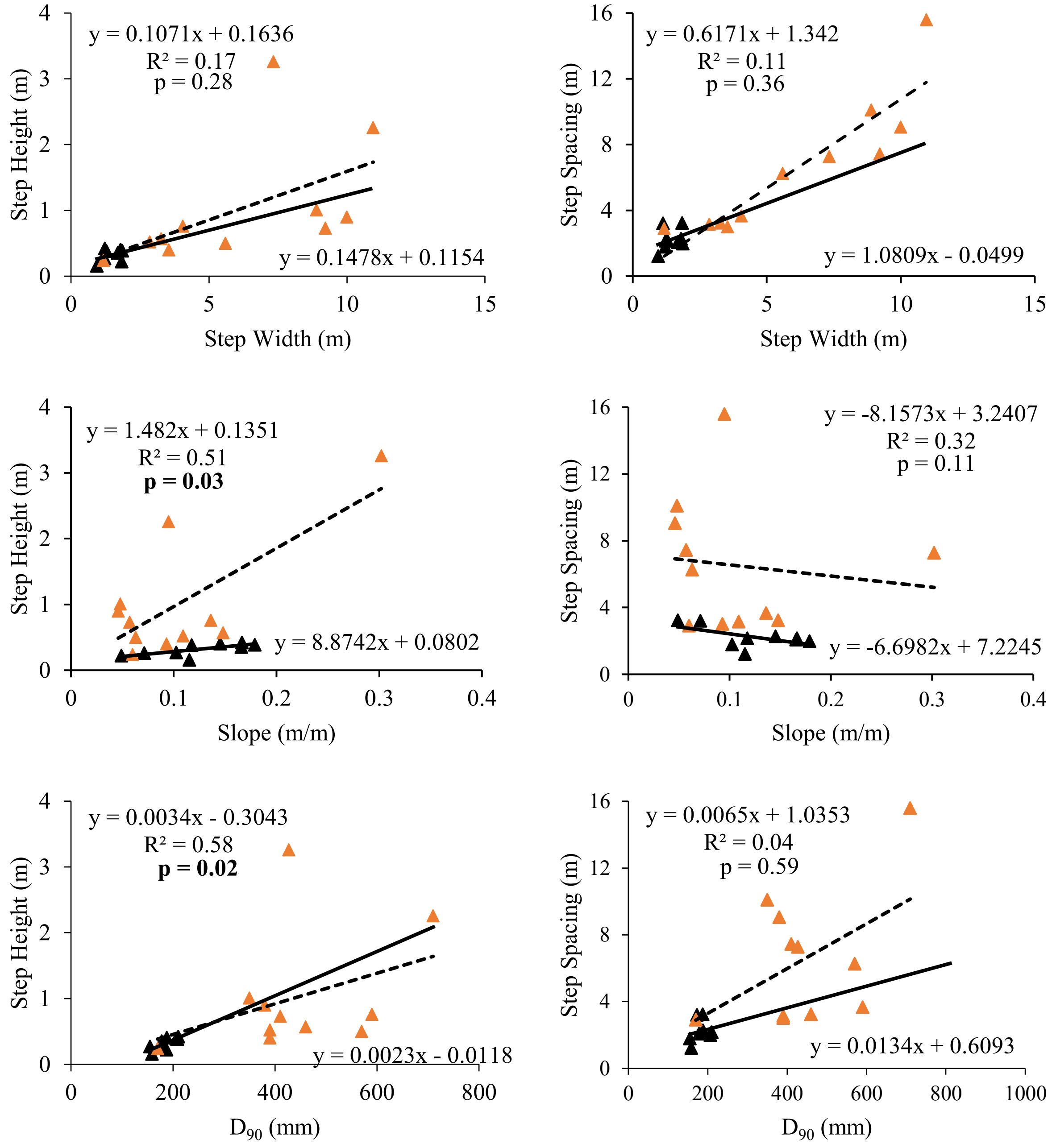


Fig. 11. DCH and Bowers Hollow Comparison. (Black squares and solid regression lines/equations with respective R^2 and p values are associated with DCH. The dotted line and orange triangles represent the step-pool geometry from Bowers Hollow) (Nickolotsky and Pavlowsky, 2007).

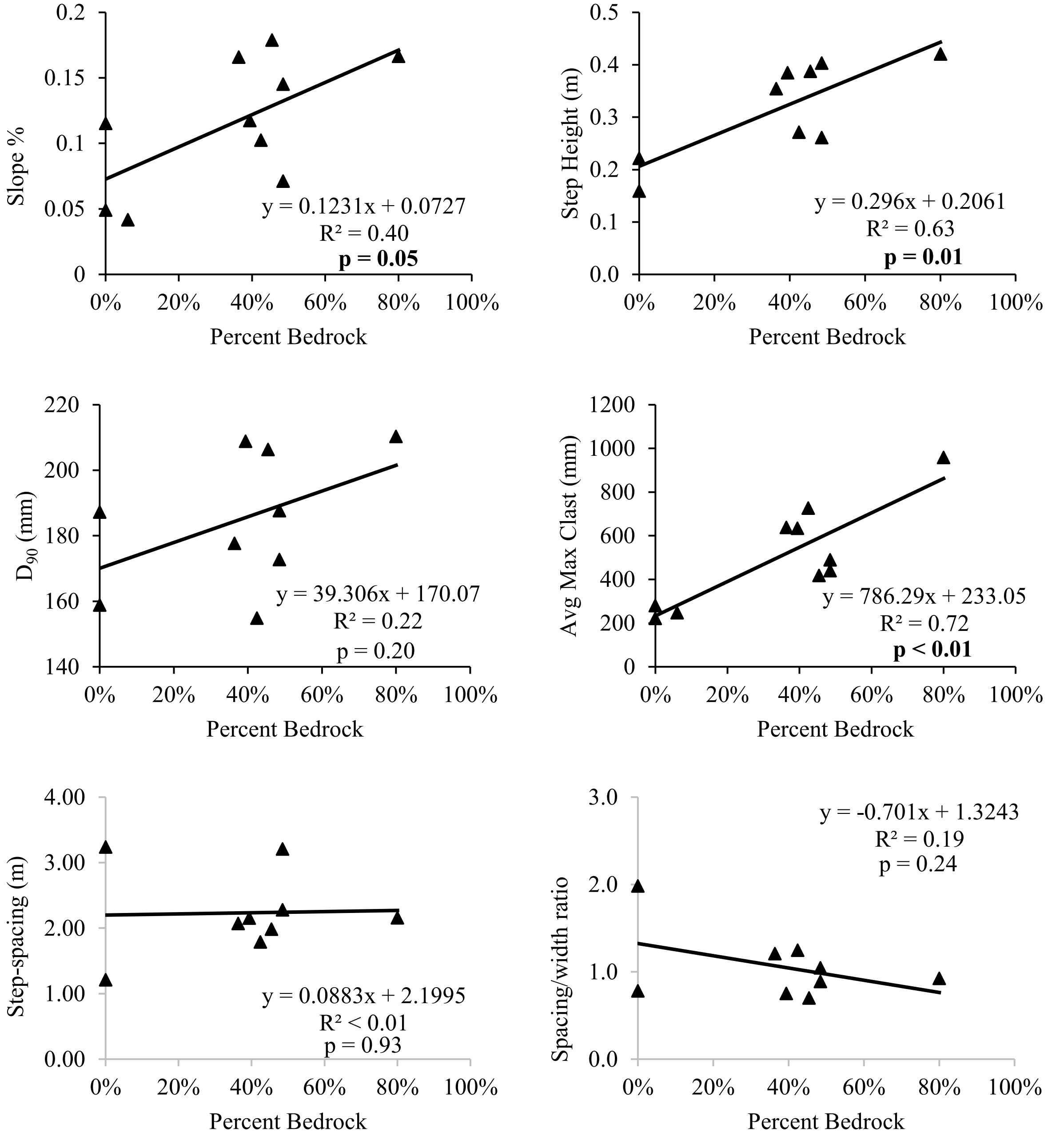


Fig. 12. Linear relationships of bedrock influence on channel morphology

Table 3. Forcing characteristics. Step Forcing Characteristics (Percent of Total)

Reach #	Channel Type	Number of Steps	Number of Forced Steps (% of Total Steps)	Steps w/ Bedrock Forcing (% Forced Steps)	Steps w/ LW Forcing (% Forced Steps)	Steps w/ Tree Forcing (% Forced Steps)	Steps w/ Colluvial Boulder Forcing (% Forced Steps)
1	Step-Pool	17	1 (6)	-	-	1 (6)	-
2	Cascade/Step-Pool	16	16 (100)	16 (100)	-	1 (6)	-
3	Step-Pool	11	11 (100)	11 (100)	3 (27)	1 (9)	-
4	Pool-Riffle/Step-Pool	10	4 (40)	4 (40)	2 (20)	-	-
5	Step-Pool	12	6 (50)	5 (42)	-	2 (17)	1 (8)
6	Step-Pool/Cascade	17	14 (87.5)	14 (87.5)	-	-	-
7	Step-Pool/Cascade	15	15 (100)	15 (100)	-	-	-
8	Step-Pool	14	14 (100)	14 (100)	-	-	-
9	Step-Pool/Pool-Riffle	10	8 (80)	8 (80)	1 (10)	1 (10)	-
	Total	122	89 (73)	87 (98)	6 (7)	6 (7)	1 (1)

Table 4. (A) Reach averages for unforced vs. forced step characteristics, (B) Results of Independent Mean sample test for unforced and forced step characteristics

Unforced vs. Forced Step Charachteristics by Reach												
	Step Spacing		Height		Step Width		Avg Max Clast		H/L Ratio		Spacing/w	
Reach #	Unforced	Forced	Unforced	Forced	Unforced	Forced	Unforced	Forced	Unforced	Forced	Unforced	Forced
1	1.14	2.30	0.15	0.34	0.94	1.00	0.16	0.21	0.13	0.15	1.38	1.91
2		2.07		0.35		1.69		0.18		0.20		1.55
3		2.30		0.40		1.80		0.19		0.19		1.36
4	3.23	3.27	0.15	0.32	1.48	2.38	0.18	0.19	0.06	0.09	0.63	1.34
5	1.98	2.38	0.41	0.37	1.88	1.83	0.22	0.19	0.20	0.15	1.55	1.16
6	1.80	1.78	0.11	0.31	1.37	1.19	0.16	0.15	0.08	0.19	1.49	1.47
7		2.16		0.42		1.23		0.21		0.20		1.70
8		2.15		0.39		1.29		0.21		0.21		1.71
9	2.95	3.29	0.15	0.29	1.20	1.11	0.17	0.17	0.05	0.11	1.43	2.80
Total	1.87	2.25	0.19	0.36	1.26	1.46	0.17	0.19	0.12	0.18	1.28	1.65

(B)	Independent Samples Test				
Levene's Test for Equality of Variances			t-test for Equality of Means		
	F	Sig.	t	df	Sig. (2-tailed)
Step-Spacing	0.115	0.735	-1.597	112	0.113
Height	3.701	0.057	-4.772	120	0.000
Width	0.615	0.435	-1.947	119	0.054
Avg. Max Clast	0.04	0.841	-1.622	114	0.108
H/L Ratio	3.246	0.074	-3.159	112	0.002
Spacing/w	2.161	0.144	-1.886	118	0.062

*Signifies significance <0.1

**Signifies significance <0.05

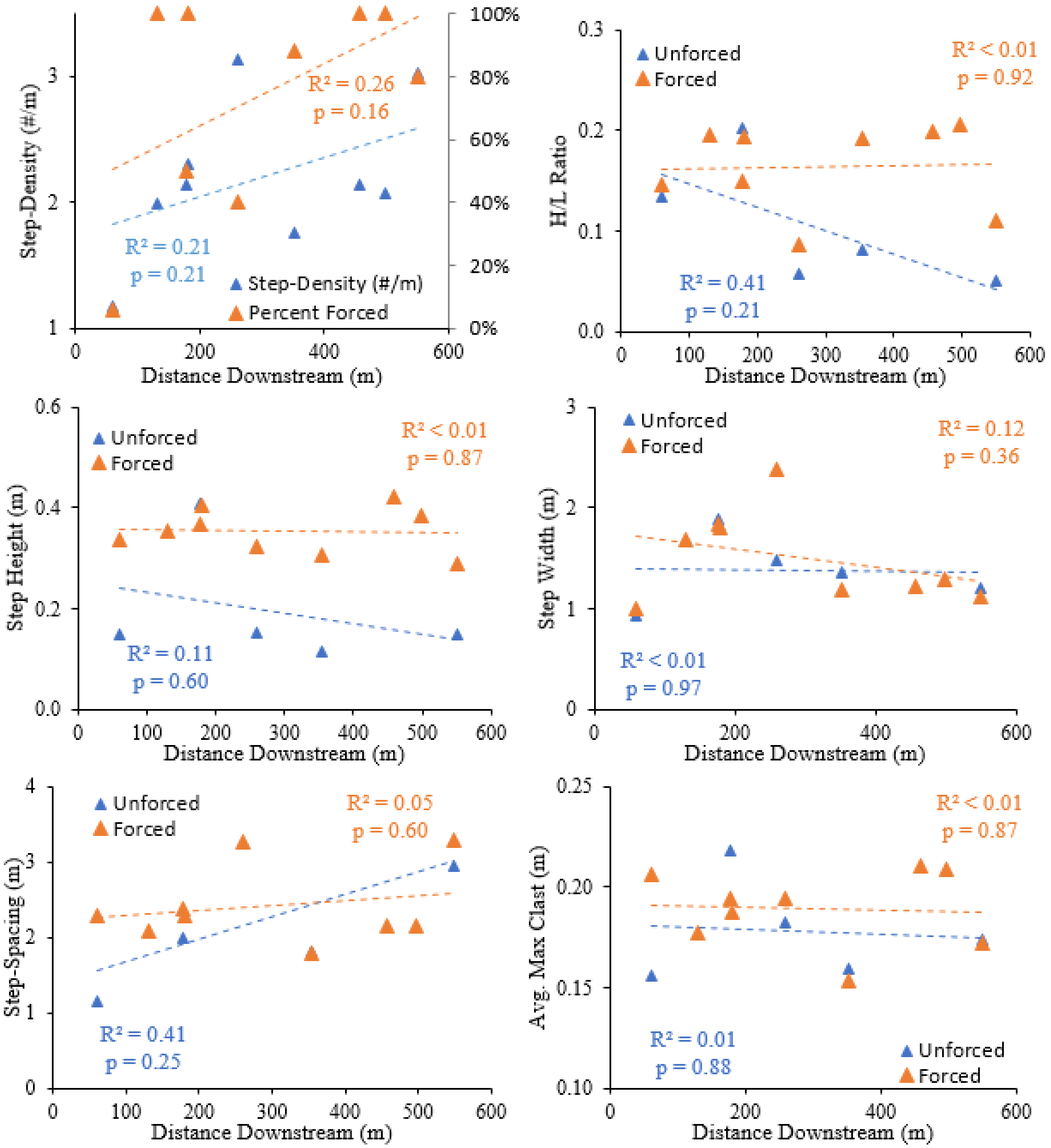


Fig. 13. Step-variation by forcing with distance downstream. (Blue represents unforced, and orange represents forced steps. Except for in the top left chart, where blue represents reach average step-spacing on the primary vertical axis and orange represents reach percent of forced steps on the secondary vertical axis.)

CHAPTER THREE: GEOMORPHIC FRAMEWORK APPLICATION IN STEEP HEADWATER STREAMS, OZARK HIGHLANDS

Introduction

Mountain headwater streams are important to classify since they often make up a majority of an overlying watershed's total stream length (Vianello et al., 2009), occur in numerous locations across the world (Marston, 2008), and are extremely susceptible to anthropogenic disturbance (Wohl, 2006). Stream classification frameworks consist of two primary categories: form-based classification (e.g., Rosgen, 1994) and process-based classification (e.g., Whiting and Bradley, 1993). Form-based classification is a morphological type of classification used to describe the physical traits of a stream or river and is based on how the channel looks and the geomorphic features present. Alternatively, process-based classification accounts for geomorphic processes and their effects on channel form based on the behavior of discharge, erosion, and sediment transport. In recent years, geomorphologists have debated the use and application of different classification systems given concerns about the simplicity of form-based frameworks which can make classification highly subjective and the high cost of labor and data processing involved with process-based frameworks (Juracek and Fitzpatrick, 2003; Roper et al., 2008; Simon et al., 2007). However, most geomorphologists agree that stream classification is an important and useful tool for: (1) describing current channel conditions; (2) evaluating anthropogenic influences; and (3) and predicting future adjustments to channel disturbance (Buffington and Montgomery, 2013).

Geomorphic classification systems have been used to categorize a variety of stream types in different environments. However, understanding stream morphology in small mountain watersheds is often complicated and may require a different approach than used for lowland rivers (Lamb et al., 2017). Compared to lower gradient alluvial rivers, mountain streams are conceptually and physically different in both observed forms and dominant processes (Montgomery and Buffington, 1997; Wohl and Merritt, 2008). Channels with wide floodplains can control their slope by lateral migration to respond to water, sediment, and wood inputs (Montgomery and Macdonald, 2002). However, mountain streams often lack the ability to adjust laterally due to increased valley confinement, episodic colluvial sediment inputs, and frequent bedrock control (Adams and Spotila, 2005). Process domains describe specific locations of the dominant geomorphic processes active in channel and floodplain areas also vary between mountain and lowland rivers (Montgomery, 1999) (Fig. 1). Floodplain rivers are more frequently affected by channel migration and avulsions, exhibit frequent bed mobility, and low discharge variance. Whereas mountain stream morphology is most commonly affected by hillslope processes, including low-frequency mass wasting events such as debris flows and landslides, and diffusive processes such as soil creep, tree throw, and raindrop erosion (Montgomery and Buffington, 1997). High spatial and temporal variability in process domains makes it inherently challenging to classify streams in mountain environments.

In general, mountain streams exhibit relatively steep channel gradients, larger sediment sizes, and flashy hydrology (Bonell, 1998). Geomorphic classifications of mountain streams need to address these limitations: (1) High valley confinement increases a reaches susceptibility to hillslope processes (Whiting and Bradley, 1993); (2) Small channels and features require higher resolution assessment procedures and increased difficulty in establishing flow recurrence intervals and bankfull dimensions (Vianello and D’Agostino, 2007); (3) Relatively small channel widths and discharge allows for reaches to be heavily influenced by additional geomorphic factors such as biologic and geologic forcing (Duckson and Duckson, 2001; Montgomery et al., 1995; Zimmermann and Church, 2001); and (4) Highly variable or flashy flows in small drainages that make it challenging to visualize channel form metrics such as bankfull channel indicators that are often needed by classification systems (Roper et al., 2008).

Studies of mountain stream channels in the U.S. are primarily limited to the mountain west with a few exceptions in Alaska and the Appalachian mountains of the eastern U.S. (Adams and Spotila, 2005; Gomi et al., 2003; Kraft and Warren, 2003). This has led to geomorphic frameworks being explicitly designed for use in streams in the western United States. However, the Ozark Highlands of the south-central United States is an area with an abundance of headwater streams in a mountain terrain with elevations reaching 780 m and with high local relief from 50 to 100 m in the Boston and St. Francis mountains and the Salem Plateau (Gott, 1975). Nickolotsky and Pavlowsky (2007) assessed step-pool channel morphology in the Boston Mountains of northwest Arkansas, where they evaluated step-pool measurement protocols and compared channel morphology to other regions. Splinter (2013) and Splinter et al. (2011, 2010) performed studies in eastern Oklahoma that compared stream channel form among the Ozark Highlands, the Boston Mountains, and the Ouachita Mountains ecoregions. Rohm et al. (1987) concluded that using geomorphic classification by ecoregion is a useful tool in describing aquatic habitat in northwest Arkansas. No studies on mountain streams have been performed in the Missouri portion of the Ozark Highlands despite encompassing the largest percentage of the area coverage (~75%).

This paper uses two different classification systems to classify channels in DCH to evaluate their use for hydro-geomorphic assessments in the Salem Plateau sub-division of the Ozark Highlands. These two classification systems include the Montgomery and Buffington

(1997) classification of channel reach morphology in mountain drainage basins (hence referred to as MON) and the Whiting and Bradley (1993) process-based classification of headwater streams (hence referred to as WHI). The Ozark Highlands is a sub-division of the Salem Plateau physiographic region of the south-central United States, which lacks studies concerning mountain stream morphology. Thus, the results of this stream classification can be used to both understand the processes controlling channel morphology on the Salem Plateuau and to allow geomorphic comparison to mountain streams in other regions

Study Area

Deer Camp Hollow (DCH) is a small headwater stream in the Current River Basin, described as having moderately steep hillsides with narrow and broad sinuous valleys (Kabrick et al., 2000). DCH is a steep headwater stream within the Big Barren Creek watershed that has local relief of about 85 m, with a peak divide elevation of 283 masl and is 198 masl at its confluence with Fools Catch Creek (9.9 km^2) (Fig. 9). DCH is entirely within the Eleven point district of Mark Twain National Forest and is primarily dominated by oak-pine forest (Kabrick et al., 2000). Nine reaches along DCH were selected for this comparison, as well as one reach on a tributary. These reaches range in drainage area from 2.74 ha at reach one to 17.35 ha at reach ten before flowing into Fools Catch Creek. Slopes range from 4.2 to 17.9% and channel widths from 1.4 to 4.5 m (Table 1). An exposed bedrock unit in the middle portion of the watershed indicates a relatively resistant sandstone unit at the surface causing geologic forcing producing local changes in channel morphology. Reaches were selected in a way to try and limit external influence of discharge and sediment supply from nearby hollows or hill-slides, with the main objective to select reaches with a varying range of slopes and bedrock influence (Fig. 6 and Table 1).

Methods

The two different geomorphic classification frameworks each use field-based variables of channel form and substrate conditions to classify channels. Some of these channel variables are included in both frameworks (channel gradient and median grain size), whereas other variables may be used for only one framework (valley-side gradient in WHI and bedform type in MON) (Fig. 14). Overall, a majority of the fieldwork necessary for this study is the same as in Chapter Two, but how it is analyzed and applied varies between classification schemes. Field methods such as the geomorphic assessment, pebble count, and channel surveys are explained more in-depth in the previous chapter, as well as specifics on GIS data retrieval.

Montgomery and Buffington (1997). The MON classification scheme separates mountain stream morphology among alluvial, colluvial, and bedrock channels and then uses channel bedforms, including their planform and profile, to determine specific channel types based empirically on the importance of independent process domains (Fig. 14 and Table 6). In this study, all ten reaches were classified as occupying an alluvial valley with variable bedrock influence (Fig. 2). Slope, relative roughness coefficients, and grain size distribution were also important variables used to evaluate channel type.

Whiting and Bradley (1993). The WHI classification is also a process-based framework used for classifying headwater streams mainly due to the influence of valley confinement and hillslope processes. Variables used in this assessment include channel gradient, median sediment size (D_{50}), valley width and side gradient (Vw and ϴ, respectively), channel width (w), channel depth-slope product (d*slope), and 1 divided by the factor of safety (1/FS), which is equal to 5 tangent(ϴ) (Fig. 15). Both valley and channel width were calculated using the rapid geomorphic assessment described in Chapter 2, where channel data were collected at 10-meter intervals within each reach and averaged to obtain one value. Each reach had three points of assessment except Reach 1, which had two and Reach 10 which was downstream of the endpoint of the rapid geomorphic assessment. Channel gradient and median sediment size values were taken from Table 1 and Table 2, and average channel depth was calculated using bankfull geometry, which is the water level of the channel considered to be when it almost overtops its banks . The valley-side gradient was calculated on the backslope of the valley wall using 0.5 m resolution LiDAR provided by the U.S. Forest Service and ArcGIS Pro 2.3. Three cross-sections which extend up the valley-side were created for each reach and extrapolated to create linear trendlines relevant to each valley-side, then averaged to obtain one valley-side gradient per reach. The valley-side gradient is used to assess slope stability and distinguish stream types in Panel 1 of Fig. 15

Results and Discussion

MON. The ten reaches evaluated by this study were distributed among channel types as follows: cascade/step-pool (3), step-pool (4), step-pool/pool-riffle (2), and pool riffle (1) (Fig. 16 and Table 5). The nine reaches displaying step-pool channel types were analyzed at depth in Chapter Two. Only five reaches were described as a single specific channel type (i.e., step-pool and pool-riffle) within the MON classification framework. The other five were classified as transitional forms between two types with step-pool stream features grading into cascade (higher gradient) and pool-rifle (lower gradient) types.

MON allows for reaches to be a combination of multiple stream types, which can make it challenging to assess the geomorphic processes dominant in the watershed. In our case, the dominant sediment sources for cascade and step-pool streams generally are the same, including fluvial, hillslope and bank failures, and debris flows. However, the streams which exhibit a combination of step-pool and pool-riffle bedforms, do not match the primary locations of sediment storage (sediment storage elements) specified described by Montgomery and Buffington (1997) (Table 6). Step-pool streams deposit sediment in bedforms, whereas pool-riffle streams are subject to both bedform storage and overbank flow deposition. Overall, classifying stream types according to MON is relatively simple, allowing for a quick and easy way of inferring dominant geomorphic processes that control channel geometry. Furthermore, the slope and grain size classes proposed in their research generally fit what was observed within DCH stream types. However, errors of improper classification can occur if background knowledge of fluvial bedforms is lacking.

WHI. Overall, the primary objective of the Whiting and Bradley (1993) classification is to distinguish headwater streams by dominant processes and bed substrate characteristics as evaluated through a step evaluation of geomorphic relationships or “Panels.” Panel 1 of the WHI framework separates reaches by hillslope stability and channel gradient, where a 1/FS (5 times the tangent of the valley-side gradient) >0.8 is considered to have hillslopes prone to failure, this applies until channel gradients are larger than 0.06 where any 1/FS is considered to be susceptible to debris flows. Channel gradients between 0.06 and 0.17 tend to be depositional environments regardless of their 1/FS, and channel gradients >0.17 tend to be an erosional environment regardless of their 1/FS. In this study, nine reaches observed a 1/FS > 0.8, where reach 1 has a 1/FS of 0.24, but has a slope >0.06. Reach 7 was the only reach to have a channel gradient >0.17, and reaches 4 and 10 were the only two reaches to observe channel slopes <0.06. Panel 1 of the WHI classification derived three distinct channel types for the 10 sample reaches; seven DD, one DE, and Reaches 4 and 10 were further differentiated in Panel 2.

Further classification in Panel 2 is based on valley width (Vw) on the y-axis and channel width (w) on the x-axis. This panel differentiates streams with valley widths that are narrower than the sum of its channel width plus: 25 m (AD), 25 m to 50 m (MD), 50 m to 100 m (OD), or >100 m (SD). AD stream classes are assumed to have a 100% probability of accumulating debris flow material, 50 to 100% for MD, 10 to 50% OD, and 0% for SD stream classes. Both Reaches 4 and 10 were classified as AD, meaning that their channels have a 100% probability of accumulating material from debris flows and other hillslope processes.

Panel 2 stream types are further differentiated in panel three, which separates the stream classes by sediment domains from 0-5, dependent on competency to transport given median grain size, with 0 being mostly immovable material except under extreme discharges to 5 which is sediment finer than sand that moves primarily in suspension. Of those three different stream classes, six were classified as DD3, one as DE3, one as DD1, and two as AD2 (Fig. 16 and Table 5).

For the WHI classification, the seven streams delineated as a DD type stream are stated to be susceptible to hillslope processes, yet have a channel gradient gentle enough to deposit debris flows and other mass wasting sediment in the channel. Reach 7 classified as DD1 exhibits a boulder debris chute where bed material is only transported during extreme discharge events. Reaches 1-3, 6, 8, and 9 are classified as an aggrading gravely debris chute with an unarmored mobile bed composed of fine gravel to cobble (DD3). Whereas Reach 5 is classified as a DE stream, it is expected to be eroded by debris flows due to its steeper channel gradient (Table 5).

Reach 5 is described as a scoured boulder debris chute (DE3), also with an unarmored mobile bed composed of fine gravel to cobble (Table 7). A narrow valley width is also associated with DD and DE streams. Reaches 4 and 10 are classified as an AD2 channel where adjacent hillslopes are prone to debris flows, valleys are narrow, and the channel is a gravelly and shallow, with an armored bed composed of fine gravel to cobble (Table 7).

In DCH, a headwater stream classification system that accounts for hillslope processes appears suited for this watershed. Accounting for hillslope processes adds more confidence in the classification. However, it is essential to understand that this classification framework was designed for areas in the Pacific Northwest where local relief is high enough for debris flows to be more prevalent. Taking this into consideration, some of the claims within the WHI classification for mobile and/or aggrading bed sediment seems unlikely in DCH. The considerably small drainage areas of the step-pool channels evaluated for this study do not appear to be affected by over-supply of coarse or fine sediment. Channel bed profiles seem to be stable with cobble and boulder steps showing little recent movement. However, this classification scheme seems describe downstream trends in zones of relative deposition and erosion seen in the field which are limited by valley width constraints and dominant hillslope processes.

Conclusions

Overall, the MON and WHI frameworks both seem to describe hillslope processes to be the dominant source of sediment within DCH. The MON classification does an adequate job of evaluating channel type and inferring dominant processes, whereas the WHI classification adds support by providing boundaries of different depositional and sediment characteristics. Both the

MON and WHI classification frameworks indicate that steep channel gradients, high valley confinement, and supply of large sediment via hillslope processes are important factors in DCH. MON accurately uses bedforms to explain channel characteristics and governing processes. WHI seems to accurately differentiate depositional and bed environments through quantitative explanation of hillslope and sediment entrainment dynamics. In conclusion, both classification processes can be used in steep headwater streams of the Ozark Highlands, not only to classify stream types but also as an analytical tool to evaluate dominant processes and the influence of valley confinement on planform changes in small headwater catchments.

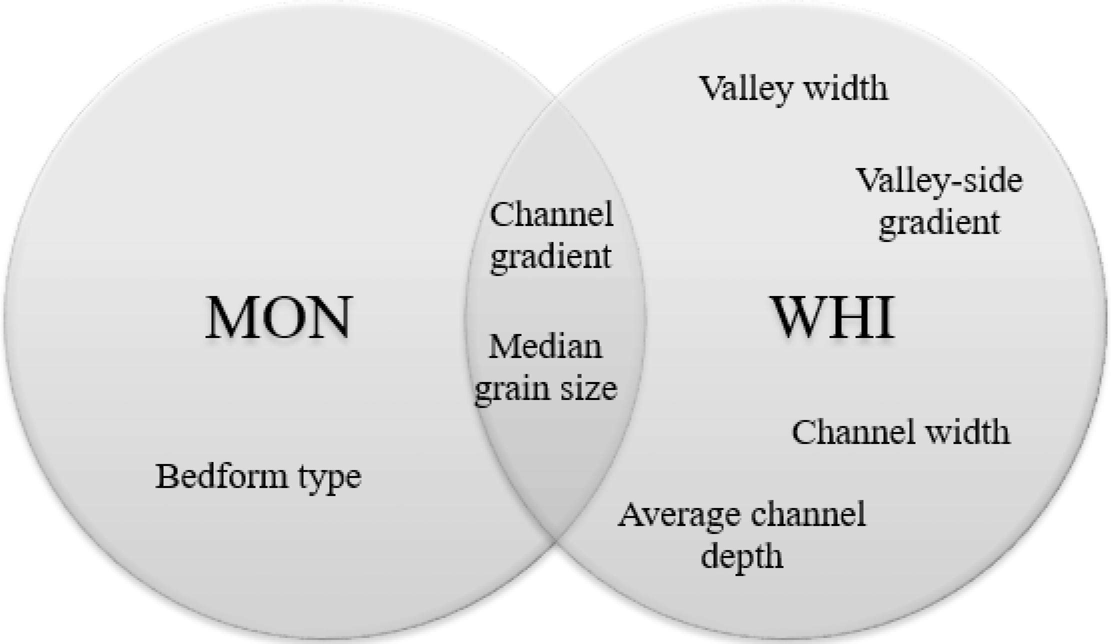


Fig. 14. Parameters shared between stream classification frameworks

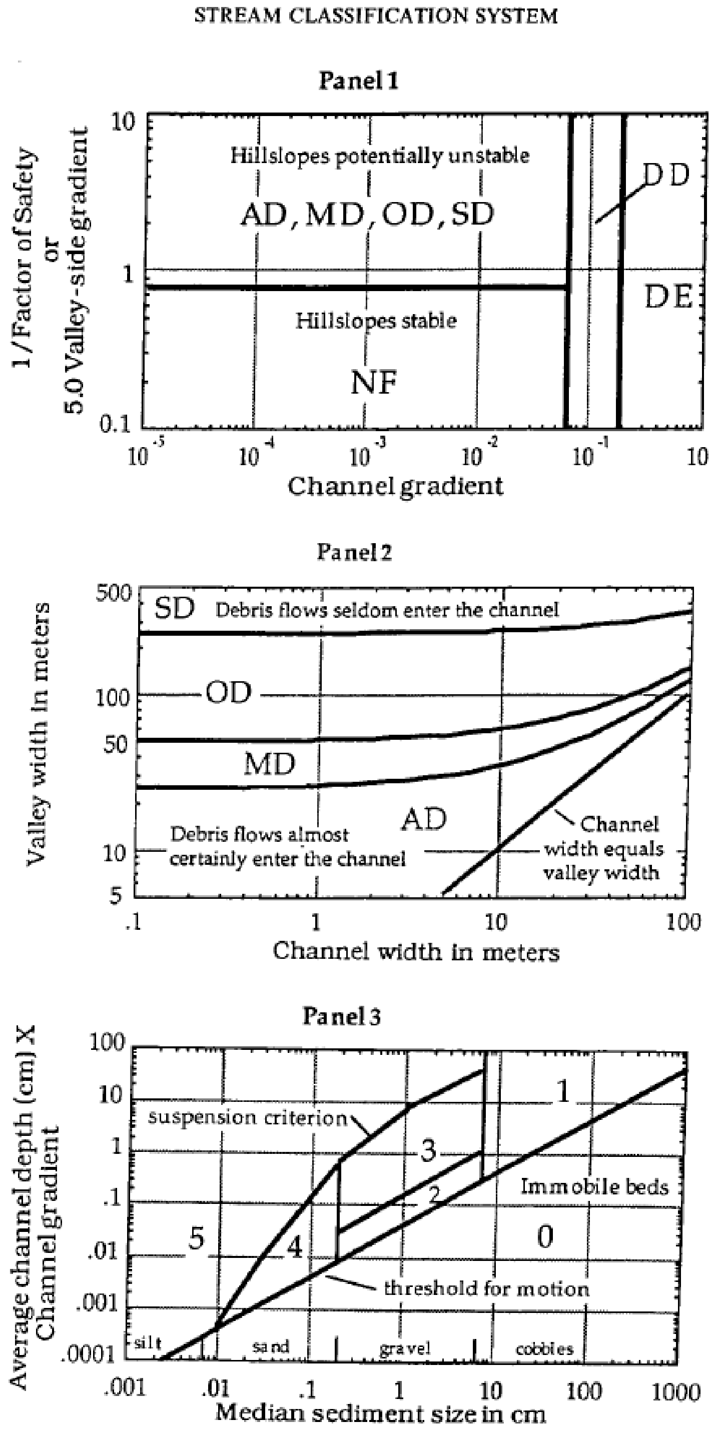


Fig. 15. WHI classification system. Panels 1 and 2 characterize the degree of hillslope interaction with the channel, while panel 3 characterizes the transport of material in the channel. The first two panels assign a two-letter prefix and the third panel assigns a single numeric suffix that together form the stream classification system. Taken from (Whiting and Bradley, 1993)

Table 5. Reach characteristics based on MON and WHI classification frameworks

Reach #	Slope (m/m)	Valley-side Gradient (m/m)	d * Slope	1/FS	Vw (m)	w (m)	D_{50} (cm)	Bedform type	MON	WHI
1	0.12	0.05	1.29	0.24	8.5	1.6	2.3	Steps	Step-Pool	DD3
2	0.17	0.23	1.02	1.15	8.3	1.7	1.6	Steps and Cascades	Cascade/Step-Pool	DD3
3	0.15	0.34	1.79	1.71	6.0	2.6	1.6	Steps	Step-Pool	DD3
4	0.05	0.34	0.23	1.69	9.7	1.6	3.2	Steps and Riffles	Pool-Riffle/Step-Pool	AD2
5	0.18	0.32	1.11	1.58	5.0	2.8	1.4	Steps	Step-Pool	DE3
6	0.10	0.37	0.84	1.86	6.0	1.4	4.5	Steps and Cascades	Step-Pool/Cascade	DD3
7	0.17	0.33	2.73	1.63	12.0	2.3	9.0	Steps and Cascades	Step-Pool/Cascade	DD1
8	0.12	0.29	1.45	1.43	9.3	2.9	3.2	Steps	Step-Pool	DD3
9	0.07	0.29	1.31	1.46	7.3	3.1	4.5	Steps and Riffles	Step-Pool/Pool-Riffle	DD3
10	0.04	0.30	0.75	1.51	11.5	3.5	6.4	Riffles	Pool-Riffle	AD2

Table 6. MON diagnostic features of each channel type. (modified from Montgomery and Buffington, 2007)

	Dune-ripple	Pool-riffle	Plane-bed	Step-pool	Cascade	Bedrock	Colluvial
Typical bed material	Sand	Gravel	Gravel-cobble	Cobble-boulder	Boulder	Rock	Variable
Bedform pattern	Multilayered	Laterally oscillatory	Featureless	Vertically oscillatory	Random	Irregular	Variable
Dominant roughness element	Sinuosity, bedforms (dunes, ripples, bars) grains, bank	Bedforms (bars, pools), grains, sinuosity, banks	Grains, bank	Bedforms (steps, pools), grains, banks	Grains, banks	Boundaries (bed and banks)	Grains
Dominant sediment sources	Fluvial, bank failure	Fluvial, bank failure	Fluvial, bank failure, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Hillslope, debris flows
Sediment storage elements	Overbank, bedforms	Overbank, bedforms	Overbank	Bedforms	Lee and stoss sides of flow obstructions	Pockets	Bed
Typical confinement	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined
Typical pool spacing (channel widths)	5 to 7	5 to 7	None	1 to 4	<1	Variable	Unknown

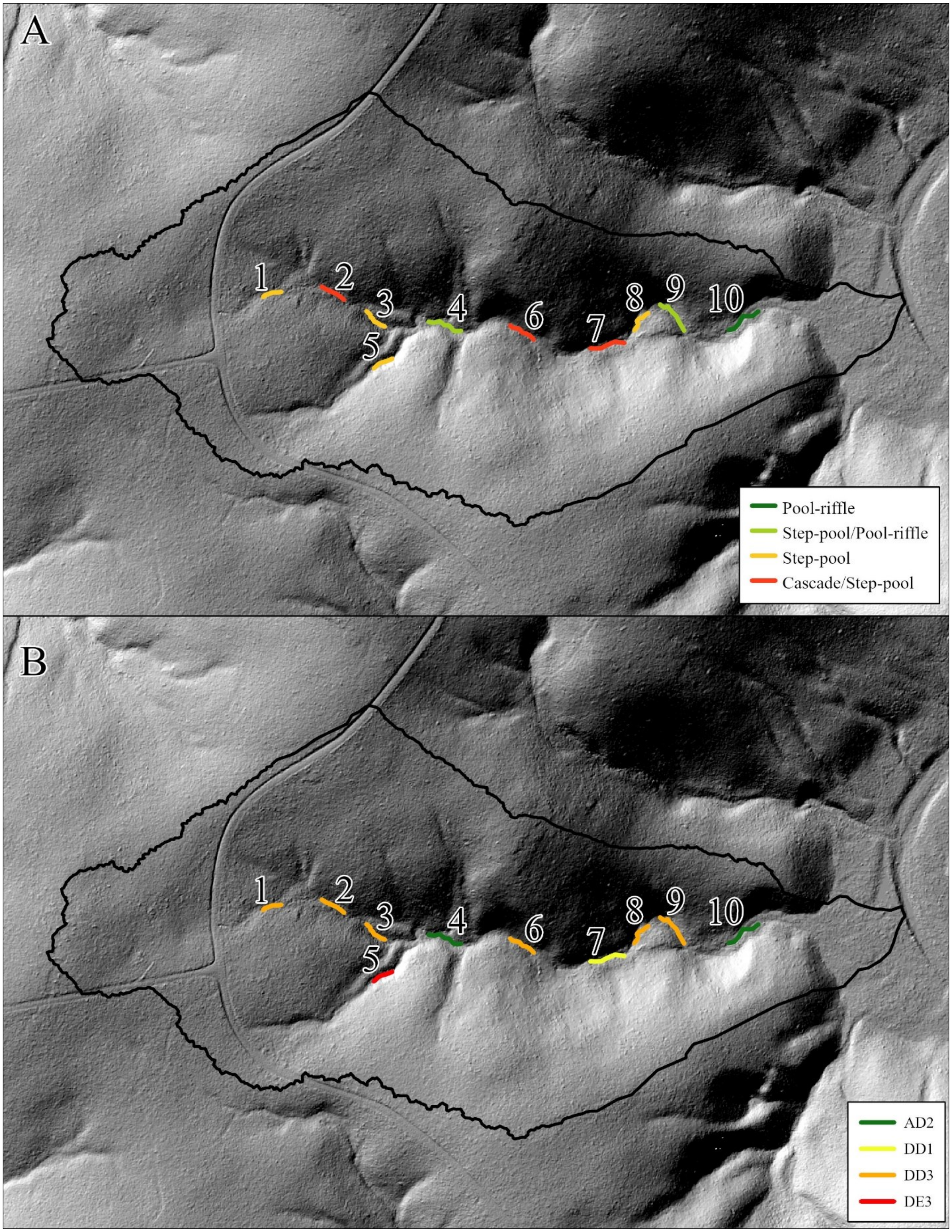


Fig. 16. Geomorphic classification of DCH channels; (A) MON and (B) WHI

Table 7. WHI geometric and hydraulic variables for stream type.(Taken directly from Whiting and Bradley, 1993)

Stream class	Channel/hillslope susceptibility to landslides	Valley aspect	Channel description
DE0	eroding in-channel debris flows	typically narrow	debris chute often on bedrock
DE1		"	scoured bouldery debris chute, w/LOD?
DE2	"	"	scoured bouldery debris chute, w/LOD?
DE3	"	"	****
DE4	"	"	****
DE5	"	"	****
DD0	depositing in-channel debris flows	typically narrow	debris chute
DD1		"	bouldery debris chute w/LOD
DD2	"	"	aggrading gravelly debris chute w/LOD
DD3	"	"	****
DD4	"	"	****
DD5	"	"	****
AD0	adjacent hillslopes prone to failure by debris flows	very narrow; VW–CW < 25 m	ephemeral debris chute
AD1		"	irregular bouldery cascades
AD2	"	"	gravelly shallow channel
AD3	"	"	unarmoured, shallow gravel channel, $T > 3T_{cr}$
AD4	"	"	infilling sandy shallow channel
AD5	"	"	silty multi-strand? shallow channel
MD0	"	narrow; 25 m < VW−CW < 50 m	ephemeral debris chute
MD1	"	"	bouldery cascades
MD2	"	"	locally armoured gravel
MD3	"	"	unarmoured, shallow gravel channel, $T > 3T_{cr}$
MD4	"	"	sandy shallow channel
MD5	"	"	silty shallow channel
OD0	"	moderate; 50 m < VW–CW < 250 m	ephemeral channelway
OD1	"	"	bouldery stepped bed w/fines
OD2	"	"	armoured gravel
OD3	"	"	unarmoured gravel, $T > 3T_{cr}$
OD4	"	"	sandy shallow channel
OD5	"	"	silty channel with flat bottom
SD0	"	wide; VW–CW > 250 m	ephemeral, poorly defined channelway
SD1	"	"	bouldery stepped bed
SD2	"	"	armoured gravel
SD3	"	"	unarmoured gravel, $T > 3T_{cr}$
SD4	"	"	sandy well-formed channel
SD5	"	"	silty channel with pools, bars
NF0	hillslopes stable	variable, often narrow	ephemeral, relict?, coarse? channelway
NF1	"	variable, often narrow	bouldery bars and pools
NF2	"	variable	armoured gravel channel with bars
NF3	"	variable	unarmoured gravel, $T > 3T_{cr}$
NF4	"	commonly wide	sandy stable channel with deep pools
NF5	"	commonly wide	silty channel with deep pools, bars

CW, channel width; VW, valley width; ****, rare, unlikely; T, boundary shear stress; T_{cr}, T at initial motion

CHAPTER FOUR: CONCLUSIONS

This study evaluated the channel morphology of a small headwater stream in the Ozark Highlands of Missouri which has greater than 80% of its total stream length as a step-pool channel. The Ozark Highlands contains areas with locally high relief and channel slope in the south-central U.S. and lacks geomorphic studies of channel form with only a few exceptions (Nickolotsky and Pavlowsky, 2007; Shepherd et al., 2010; Splinter et al., 2010). Therefore, the goal of this study was to contribute a better understanding of step-pool morphology and the applicability of headwater stream classification in DCH. Furthermore, the effects of different channel forcing factors in this headwater catchment were assessed due to exposure of resistant sandstone locally in the middle of the watershed. This resistant sandstone created abrupt changes in channel morphology and greatly affected step-pool characteristics.

Geomorphic classification was performed at all ten of the study reaches to evaluate the application of two different frameworks to describe channel form and process in steep Ozark headwater catchments. The two classification frameworks are Montgomery & Buffington (1997) (MON), and Whiting & Bradley (1993) (WHI). Overall, the MON and WHI frameworks seem to show a significant overlap in the dominant processes active in DCH channels. Both the MON and WHI classification frameworks agree on the importance of steep channel gradients and high valley confinement on the supply of large sediment from hillslope processes and deposition of material within the channel. The MON classification does an adequate job of evaluating channel type and inferring dominant processes, whereas the WHI classification adds support by geomorphic analysis of specific depositional environments and sediment characteristics.

The hypotheses for this study were that step-pool channels will tend to have bed slopes between 3 to 6.5% and step-spacing between 1-4 channel widths. Where step-pool morphology was seen in channels with slopes >4% and up to 18%, and an average spacing/width ratio of 1.1, which was not only in the confines of what was expected but also the same as observed in Bowers Hollow in northwest Arkansas. Secondly, that sediment size and step-spacing will correlate with slope but possibly also be influenced by local bedrock lithology which may affect step-forming clast size. Both step-spacing and sediment size showed a negative relationship with slope and bedrock influence. Finally, that forcing factors such as LW, bedrock boulders, and trees will increase step-spacing and average step-clast size, and decrease channel width, where both step-height and H/L ratios are significantly larger for forced steps, and spacing/width ratios and step-height show moderate significance.

Overall, step-pool and cascade channels in DCH reflect similar geomorphic relationships as found in the Boston Mountains in the southwestern Ozark Highlands. However, differences in process-form relationships among sub-regions may be related to the frequency and type of forcing involved which can cause local variations in step-pool form. Relationships between geomorphic variables and forcing from bedrock influence show a relatively strong correlation (Fig. 10). Where an independent test of two means for the 122 steps assessed in this study indicates that both step-height and H/L ratios show significantly higher values in reaches with frequent forcing by bedrock obstruction and to a lesser degree large wood and trees.

Knowledge of how forcing factors can affect steep headwater channel geometry and classification may contribute to a variety of disciplines related to channel management and stream restoration. Geologic forcing may control the flashy nature of streamflow in the Ozark Highlands to enable stable step-pool channels to form. Adding random and over-sized bedrock control features to engineered channels may help improve the structural integrity of steep constructed channels. Classification systems for headwater streams developed in other regions may be applied in steep headwaters catchments of the Ozark Highlands. Future work may include: (1) studies of the geography of step-pool forms in different bedrock and relief settings in Mark Twain National Forest, to better understand the effect of variations in local relief and geologic influence; (2) systematic studies of how sediment type and rock substraight affect step-pool characteristics; and (3) the mobility and function of large bed material in step-pool channels including runoff event frequency and channel hydraulics. The ease of access to a variety of steep headwater catchments in MTNF for assessments offers opportunities to improve our understanding of their geomorphology in general.

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CHAPTER SIX: APPENDIX A

Appendix A. Reach 1 (Top) displaying a reach with natural steps and Reach 8 (Bottom) displaying forced bedrock steps