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Geomorphic Characteristics and Sediment Transport in Natural and Channelized Reaches of Big Barren Creek, Southeast Missouri

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GEOMORPHIC CHARACTERISTICS AND SEDIMENT TRANSPORT IN NATURAL AND CHANNELIZED REACHES OF BIG BARREN CREEK, SOUTHEAST MISSOURI

A Masters Thesis

Presented to

The Graduate College of

Missouri State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Geospatial Sciences in Geography, Geology, and Planning

By

Matthew Steven Thies

May 2017

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ABSTRACT

Channelization, levee construction, and gravel mining are land management practices that are used for flood control. However, they often alter the balance between sediment supply and available sediment transporting power in streams, causing channel instability. Streams can respond to instability through channel incision and sediment aggradation which can degrade riparian habitat, increase flood risks, and cause property damage. These problems have been observed along segments of Big Barren Creek, which drains 190 km^2 of the Missouri Ozarks in Mark Twain National Forest. Field assessment and modeling methods were used to evaluate the spatial distribution of channel instability along the upper 20 kilometers of Big Barren Creek and quantify the changes in channel morphology, hydrology, and sediment transport capacity related to channel modifications. Results show that channelized reaches of Big Barren Creek are generally steeper, up to two times deeper, and can transport up to four times more sediment than nearby natural reaches. High sediment transport capacity given unchanged sediment supply can account for headcuts, bed coarsening, and downstream sediment aggradation that are associated with channelized reaches of Big Barren Creek. These findings identify channelization as the primary contributor to channel instability within Big Barren Creek. Restoration efforts should focus on development plans to mitigate channelization and enhance channel recovery.

KEYWORDS: geomorphology, instability, channelization, sediment transport, Ozarks

This abstract is approved as to form and content

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Dr. Robert Pavlowsky
Chairperson, Advisory Committee
Missouri State University

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CHAPTER 1—INTRODUCTION

The dynamics between human activity and stream response is a fundamental inquiry in the field of fluvial geomorphology (Gilbert, 1917; Lane, 1954; Leopold et al., 1964; Gregory, 2006). Flowing water erodes, transports, and deposits sediment to create the optimal channel morphology and slope for transporting the imposed sediment supply from the watershed (Schumm, 1977; Lane, 1954; Montgomery and Buffington, 1997; Church, 2002; Church, 2006; Friend, 1993). In natural settings, streams maintain a state of dynamic equilibrium by responding to changes in hydrology and sediment supply through erosion and deposition (Mackin, 1948). However, human land management can cause abrupt changes in hydrology, channel morphology, and sediment supply that overwhelm the ability of a stream to adapt to change, causing stream channel instability (Wolman, 1967; Jacobson, 1995; Gregory, 2006). Stream channel instability can cause incision, bank erosion, and increased sediment loads while degrading riparian ecosystems (Groffman et al., 2003; Jacobson, 1995). In the United States, more than $1 billion is spent annually to manage streams that are affected by channel instability (Bernhardt et al., 2005).

Humans are often drawn to settle on river floodplains, landforms that provide flat-lying land and fertile soil for agriculture (Petroski, 2006). However, these areas are often prone to flooding, which can cause property damage and the loss of life (Hooke, 1986). Channelization, levee construction, and gravel mining are used to contain high flows, reduce the frequency of overbank flows, and mitigate flood risk on floodplains (Petroski, 2006). Channelization and levee construction lower the channel bed elevation, creating a

wider deeper channels that is typically straight and free of instream wood and vegetation (Figure 1) (Hooke, 1986; Simon and Rinaldi, 2006). Instream gravel mining maintains large channel dimensions through the removal of sediment from the channel bed that can also be used as a construction aggregate (Kondolf, 1994).

Channelization and Channel Instability

Channelized reaches are often prevented from interacting with the adjacent floodplain, concentrating flow energy that would normally be dispersed by the floodplain (Wohl, 2014). Channel modifications can also reduce hydraulic roughness and change the

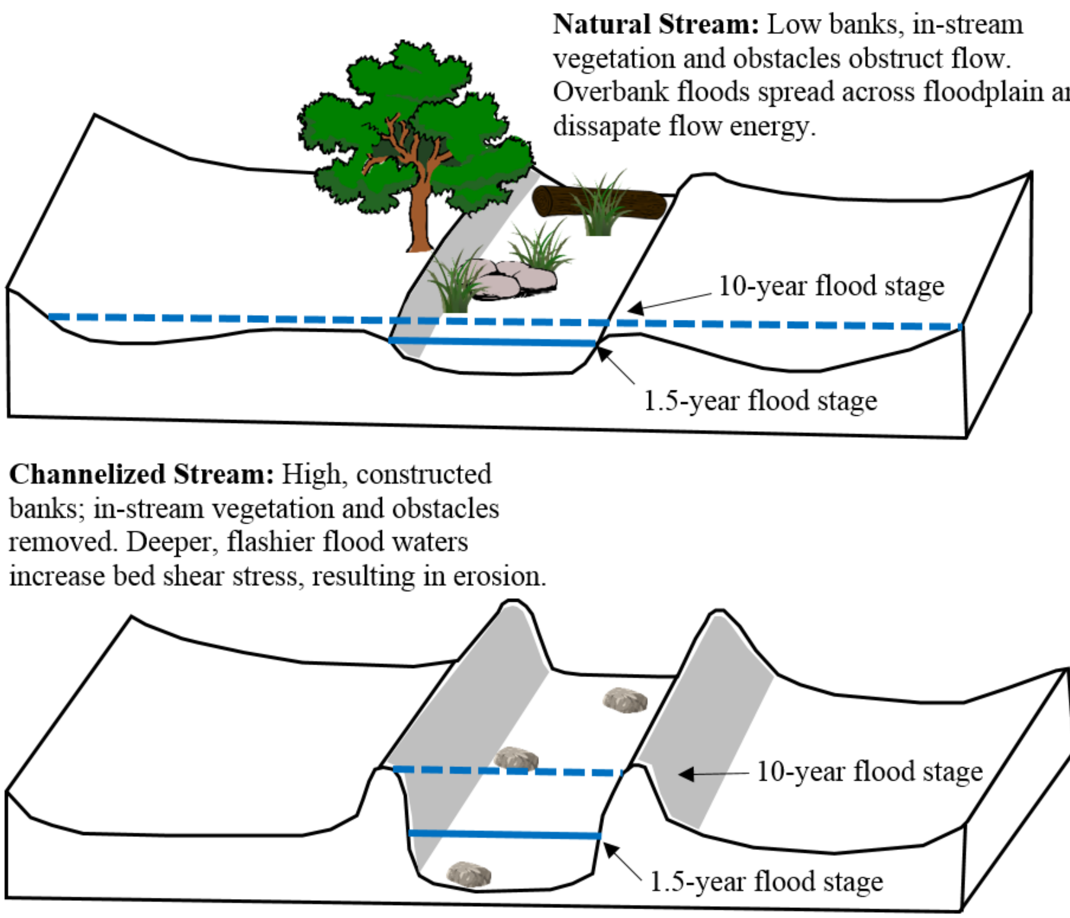

Figure 1. Conceptual diagram of natural and channelized stream channels.

amount of sediment that is available for transport (Kondolf, 1997). These changes can create an imbalance between the sediment transport capacity of a channel and the amount of sediment that is available for transport, causing stream channel instability (Simon and Rinaldi, 2006). Sediment transport capacity is a measure of the maximum amount of sediment that can be transport by a channel, and provides insight into the amount of energy that is available to transport sediment (Wilcock et al., 2009). Channel instability has upstream and downstream effects in a watershed, including incision, headcuts, bank erosion, sediment aggradation, and bed armoring.

Channel Incision. Incision is a fundamental indicator of channel instability (Simon and Rinaldi, 2006). Channel modification and maintenance typically increases channel slope or creates abrupt changes in the bed elevation, which increases the amount of energy that is available to exceed the bed resistance and incise the channel bed (Simon and Rinaldi, 2006; Surian and Rinaldi, 2003; Ortega et al., 2014; Rinaldi et al., 2005; Martín-Vide et al., 2010; Landemaine et al., 2015). Incision can cause channel deepening through the formation of headcuts or widening through bank erosion. Headcuts are erosional features that migrate upstream, incising into the undisturbed channel bed (Brush and Wolman, 1960). As the channel deepens, the banks can over-steepen and erode, causing the channel to widen (Simon and Rinaldi, 2006). As a result, incision caused by channel modification can affect unmodified upstream channel reaches through headcut migration and associated incision (Simon and Rinaldi, 2006).

Sediment Aggradation. Incision increases the sediment load of channelized streams. Changes in channel geometry from channelization reduce the ability of the channelized reach to transport sediment during low flows, resulting in sediment

aggradation downstream of unstable reaches (Rhoads, 1990). Over time, aggraded sediment can be reworked by the modified channel to form bars and inset floodplains as the channel adjusts to change (Landwehr and Rhoads, 2003). Sediment aggradation gradually reduces the channel bed slope, reducing the rate of upstream incision (Brush and Wolman, 1960). Sediment aggradation also fills in the channel area, reducing the discharge capacity of the channel which can increase the frequency of overbank floods (Slater, 2016). Gravel mining can be used to remove aggraded sediment from the channel bed, maintaining large channel dimensions that prevent overbank flooding. However, gravel mining often prolongs channel instability by reducing the amount of available sediment that can be used by the channel to adjust to instability (Rinaldi et al., 2005; Chin et al., 2014).

Sediment Connectivity. Channelization affects the linkage, or connectivity, of sediment movement through a drainage network (Hooke, 2003). Modified channels can transport volumes of sediment during high flows that cannot be transported by natural reaches downstream, causing sediment deposition (Constantine et al., 2003; Brierley et al., 2006; Fryirs, 2013). During high flows, fine-grained material can be winnowed out of the modified channel bed and deposited downstream, forming a coarse, armored channel bed upstream and a fine-grained, aggraded bed in downstream unmodified segments with a reduced sediment transport capacity (Dietrich et al., 1989; Parker and Klingeman, 1982; Venditti et al., 2010). These changes can affect bed mobility and aquatic habitat quality (Rinaldi et al., 2005; Vendetti et al., 2010). Sediment pulses and bed coarsening have been observed downstream of channelized streams that are maintained by gravel mining (Kondolf, 1997; Rinaldi et al., 2005; Frings et al., 2009).

Historical Channel Instability in the Missouri Ozarks

Stream channel instability has been studied in the Ozark Plateau physiographic province, which includes portions of Missouri, Arkansas, Kansas, and Oklahoma. The Ozarks have a history of natural channel instability that is preserved in Holocene alluvial deposits (Jacobson, 2004). However, historical land use practices associated with agriculture, mining, and timber production have accelerated the delivery of water and sediment to Ozark streams, causing channel instability (Martin and Pavlowsky, 2011). When understood in a historical and physiographic context, the measurement of overbank deposits, channel planform, gravel bars, and bed material can be used to assess the magnitude of stream channel instability (Montgomery and MacDonald, 2002).

Over the past century, long-time residents of the Ozarks have observed changes in the landscape, specifically large volumes of gravel that have accumulated in streams, reducing the size of the channel and causing streams to migrate laterally through bank erosion (Jacobson, 1995; Jacobson and Primm, 1997). These observations have been supported by studies of large Ozark rivers (Jacobson, 1995; Jacobson and Gran, 1999; Owen et al., 2011; Martin and Pavlowsky, 2011). Widespread, low-intensity landscape disturbance from logging and agriculture has caused headwater streams to incise into gravel-rich Quaternary deposits, forming large gravel waves that are routed through drainage networks and accumulate in larger rivers (Jacobson and Gran, 1999). While current land use practices do not contribute to gravel waves that are observed on large Ozark rivers, gravel waves reduce channel dimensions which can cause channel instability, degrade aquatic habit, and increase flood risks (Jacobson and Gran, 1999). Upland land disturbance associated with historical mining, agriculture, and logging has

also increased historical overbank sedimentation rates (Owen et al., 2011) and caused changes in channel planform (Martin and Pavlowsky, 2011) in large Ozark rivers. The greatest amount of disturbance is typically observed at the confluence of tributaries and larger rivers (Jacobson, 1995; Jacobson and Gran, 1999; Martin and Pavlowsky, 2011).

Headwater streams convey upland landscape disturbances to larger rivers through runoff and sediment loading (MacDonald and Coe, 2007). Therefore, it is important to understand the geomorphic processes in headwater streams that contribute to downstream channel instability. Shepherd et al. (2011) assessed the geomorphic characteristics of Ozark headwater streams in northwest Arkansas that were located in forest, agricultural, and urban settings. The authors found that bankfull cross-sectional areas of urban and agricultural streams were up to 60% larger than that of forested streams, contributing to a 90% increase in shear stress and a 120% increase in unit stream power. The authors suggest that increased channel dimensions, shear stress, and stream power from land use changes sediment connectivity in urban streams, causing bed coarsening and incision.

While there have been many studies on the effects of landscape disturbance on channel instability in larger Ozark rivers, fewer have focused on the headwater streams that supply sediment to larger rivers (Jacobson, 1995; Jacobson and Gran, 1999). Shepherd et al. (2011) provide insight into the potential downstream effects of widespread land use in headwater streams. However, there is a current gap in knowledge of the effects of direct channel modification on Ozark headwater streams, including channelization, levee construction, and gravel mining.

Land Management in Big Barren Creek

Big Barren Creek is a 40 kilometer-long headwater stream within Carter, Ripley, and Oregon counties in the Missouri Ozarks (Figure 2). Locations on Big Barren Creek will be referred to by river kilometer (R-km), with R-km 0.0 at the confluence of Big Barren Creek and the Current River. As part of the Eleven Point Ranger District, the U.S. Forest Service has managed 78% of the watershed since 1935, after the United States government purchased 3.3 million acres of land that was named Mark Twain National Forest in 1939 (United States Forest Service, n.d. a). Since 2012, the U.S. Forest Service

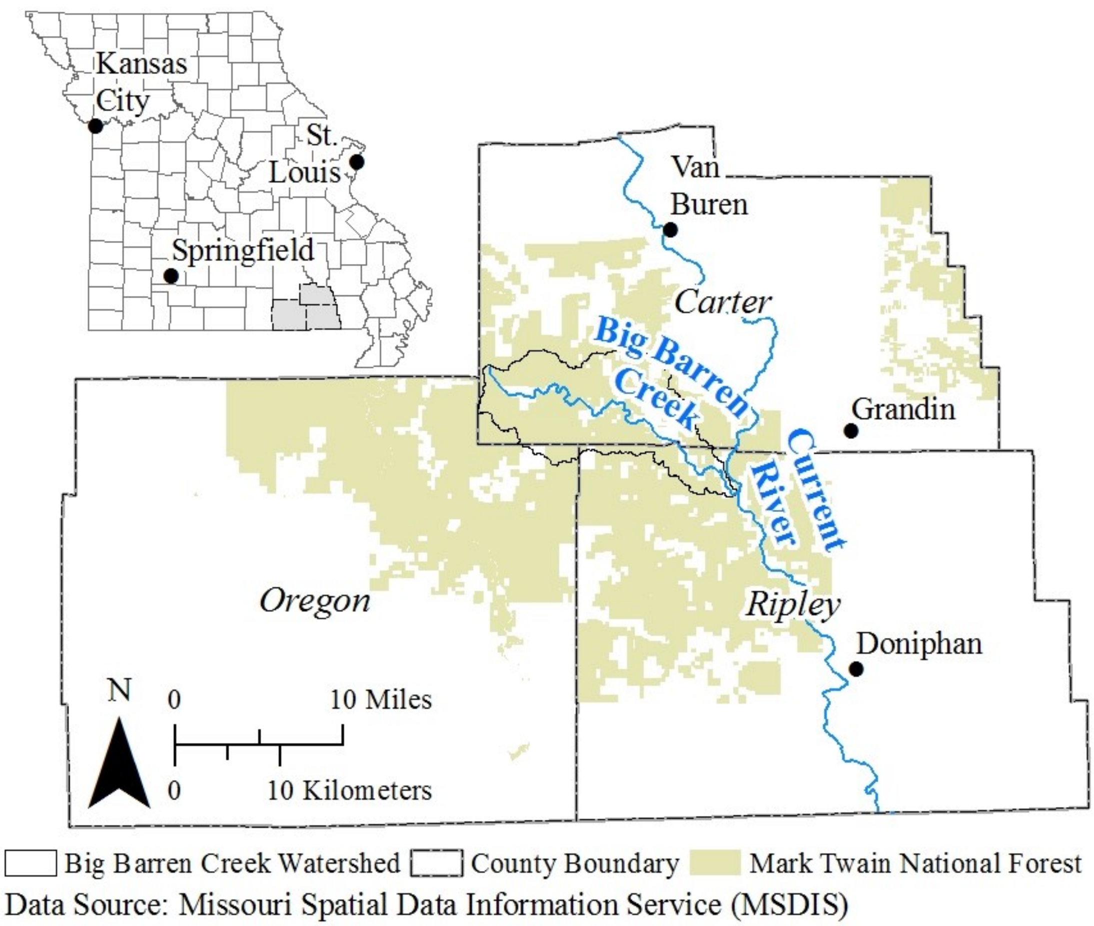

Figure 2. Regional location of Big Barren Creek.

has used prescribed burning and tree planting to restore the Shortleaf pine population that was extensively harvested during the timber boom period from 1880 to 1920 (Cunningham, 2007; United States Forest Service, n.d. b).

Humans have directly modified Ozark streams since early settlement in the 1800s (Jacobson and Primm, 1997). Residents report that riparian forests were left mostly intact, but that some vegetation and instream wood were removed to maintain a “clean” channel (Jacobson and Primm, 1997). Channelization and gravel mining efforts increased in the 1930s and 1940s when large machinery became more accessible (Jacobson and Primm, 1997). Since then, residents have removed gravel from the channel for use as a road aggregate and pushed gravel up on to the channel banks to prevent flooding inadjacent fields (Jacobson and Primm, 1997). Some privately-managed reaches of Big Barren Creek are channelized and maintained by gravel mining that is regulated by The Missouri Department of Natural Resources (2003) (Figure 3). Evidence of channelmodification appears in the earliest available aerial photographs of Big Barren Creek from 1939 (Bradley, 2017).

Recently, landowners have observed an increase in flooding, erosion, and gravel deposition in the Big Barren Creek watershed (OEWRI, 2016). The current perception among landowners is that prescribed burning increases runoff rates that cause upland incision at headcuts, flooding, and sediment deposition along the main stem of Big Barren Creek. Landowners currently remove sediment from the bed of channelized reaches following sediment aggradation (Figure 4). Prescribed burning has been linked to temporary increases in runoff and erosion in forested environments (Cawson et al., 2012).

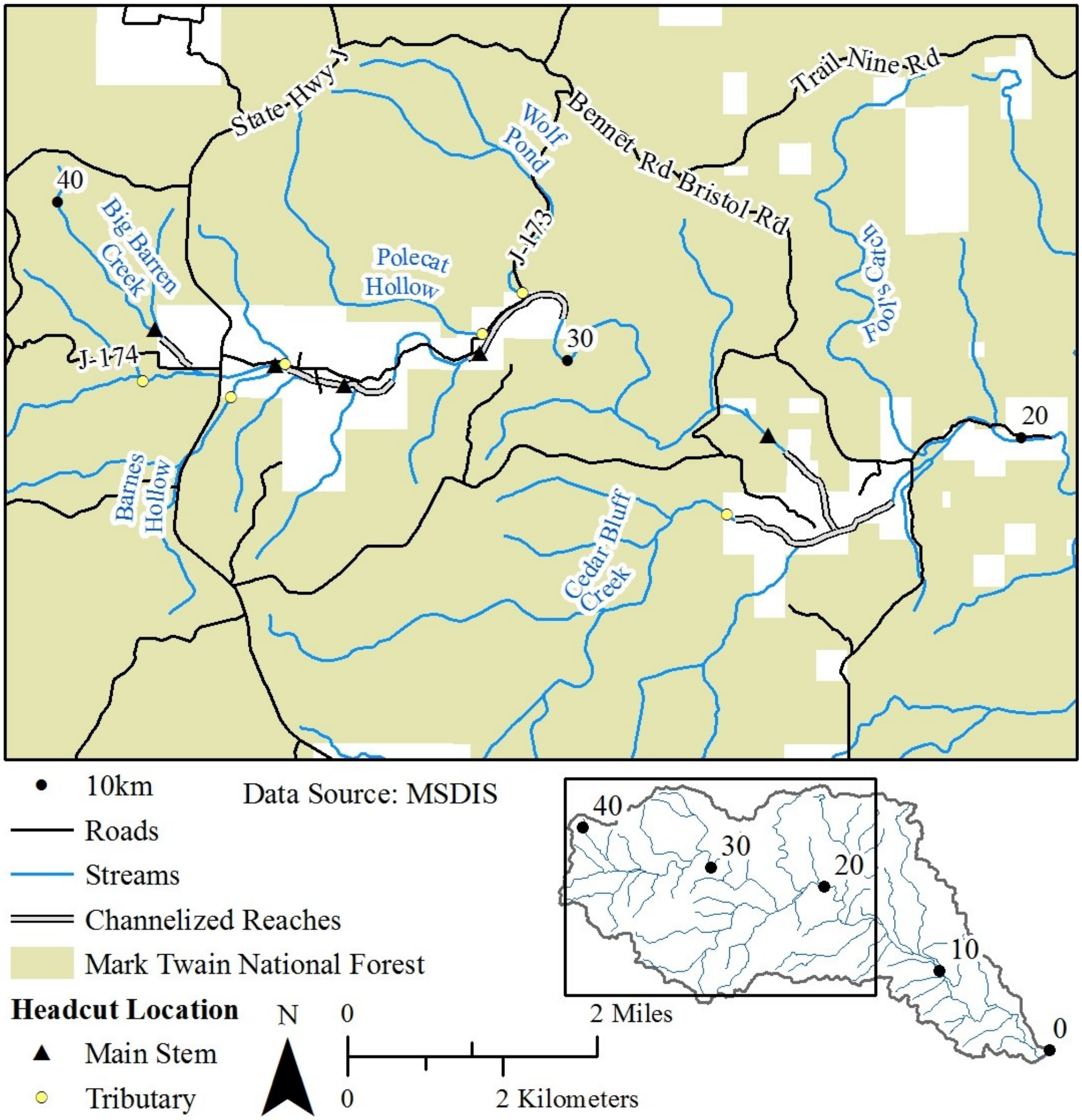

Figure 3. Location of channelized reaches of Big Barren Creek.

However, the hydrologic effects of prescribed burning have not been studied extensively in the Missouri Ozarks. Additionally, current flood patterns may be linked to increased annual rainfall in the past decade (Pavlowsky et al., 2016). Furthermore, the effects of channelization and gravel mining on channel stability have not been studied at Big

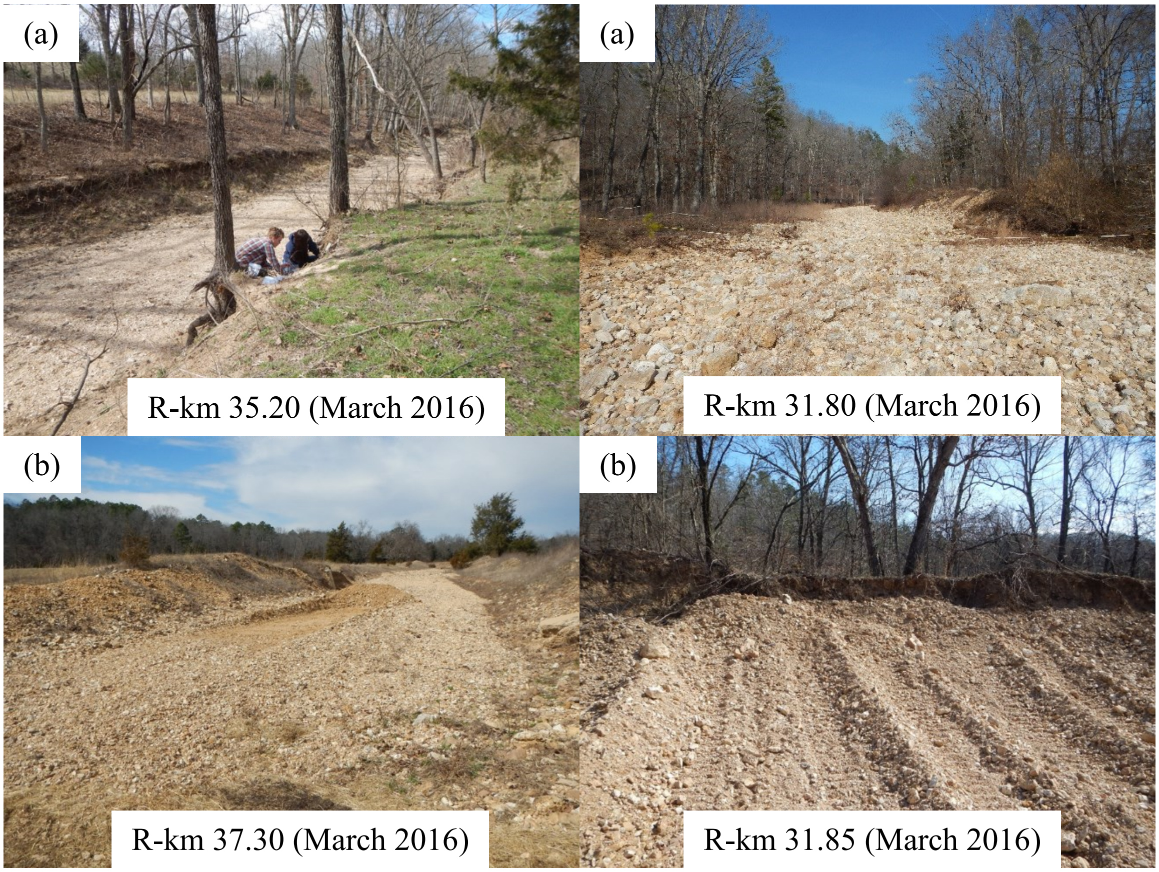

Figure 4. Examples of channelization (a) and maintenance by gravel mining (b).

Barren Creek. These activities have been linked to channel instability elsewhere (Simon and Rinaldi, 2006; Kondolf, 1997).

Purpose and Objectives

The Ozarks have a history of stream channel instability that is associated with land use changes from logging and agriculture (Jacobson and Primm, 1997). Landowners have observed increased flooding in the Big Barren Creek watershed, resulting incision at headcuts in tributaries and along the main stem of Big Barren Creek that introduces sand and gravel into the drainage network. While Pavlowsky et al. (2016) observed an increase

in annual rainfall in the past decade that may contribute to increased flooding, other potential drivers of channel instability in Big Barren Creek have not been evaluated.

The purpose of this study is to evaluate the effects of direct channel modifications on geomorphic and hydraulic processes in Big Barren Creek, and how they may contribute to channel instability. Previous studies suggest that drainage network extension through upland incision introduced large amounts of gravel into larger Ozark rivers from landscape disturbance in the previous century (Jacobson, 1995; Jacobson and Gran, 1999). However, few studies have addressed the role of direct channel modification on headwater channel instability that affects larger rivers in the Ozarks (Shepherd et al., 2011).

This study will evaluate the geomorphic, hydrologic, and hydraulic differences between reaches of Big Barren Creek with differing land management practices. The objectives of this study are to (1) characterize the channel morphology and sediment characteristics of channelized reaches and "natural" reaches that have not been channelized; (2) quantify differences in hydrology and hydraulics between natural and channelized reaches; and (3) use sediment transport modeling to understand the differences in geomorphic processes between natural and channelized reaches that contribute to channel instability. The guiding hypothesis of this project is that natural and channelized segments will have different geomorphic and sediment transport properties that may contribute to the observed incision and sediment aggradation in Big Barren Creek.

Benefits of Study

This study will contribute to an existing body of knowledge on fluvial geomorphology in the Ozarks. Historical channel instability in the Ozarks has been linked to headwater channel incision from landscape disturbance (Jacobson, 1995; Jacobson and Gran, 1999). Shepherd et al. (2011) identified geomorphic differences in forested, agricultural, and urban Ozark streams that could potentially cause channel instability. This study will evaluate direct channel modification as a driver of channel instability in the Ozarks. The findings could be used to understand the processes that have caused previous channel instability in the Ozarks.

The results of this study can also be used to understand the current channel instability problem in Big Barren Creek. Direct channel modification can cause upstream incision and downstream sediment aggradation, affecting multiple stakeholders in a watershed. Understanding the geomorphic and hydraulic processes that are changed by channel modification is important for predicting the adjustment of the channel over time, and identifying actions that can be taken to reduce the effects of stream channel instability (Latapie et al., 2014). Ultimately, this study could help managers understand the cause-effect relationships resulting from direct channel modification at Big Barren Creek, and assist in identifying areas to focus channel restoration practices.

CHAPTER 2—STUDY AREA

Big Barren Creek is a tributary of the Current River that drains 190 km^2 of the Salem Plateau of the Ozark Highlands physiographic province. The Salem Plateau is characterized by dissected Paleozoic sedimentary strata (Fenneman, 1928). Tributaries of the Current River are low-gradient, shallow pool-riffle streams with gravel beds (Panfil and Jacobson, 2001). Drainage basin morphology and an extensive karst network are primarily controls on channel morphology in the Current River basin, with minor influences from land use (Panfil and Jacobson, 2001).

Geology and Soils

Big Barren Creek is underlain by Lower Ordovician-age strata, including the Gasconade Dolomite, Roubidoux Formation, and Jefferson City Dolomite (Weary et al., 2014) (Figure 5). The Gasconade Dolomite and Jefferson City Dolomite are composed of dolomite with minor sandstone and chert. The Roubidoux Formation is composed of sandstone, with minor chert and dolomite (Weary et al., 2014). The Wilderness-Handy Fault Zone, a group of Northeast-trending faults, runs through the middle and lower portions of the Big Barren Creek watershed, forming steep bedrock bluffs (Weary et al., 2014).

Soils in the Salem Plateau are typically classified as alfisols or ultisols that are formed by the weathering of chert-rich bedrock (USDA, NRCS, 2006). Some areas are capped by a layer of nutrient-rich glacial loess (Jacobson, 2004). There are seven alluvial soil series in the Big Barren Creek watershed (USDA NRCS Soil Map Unit Symbol

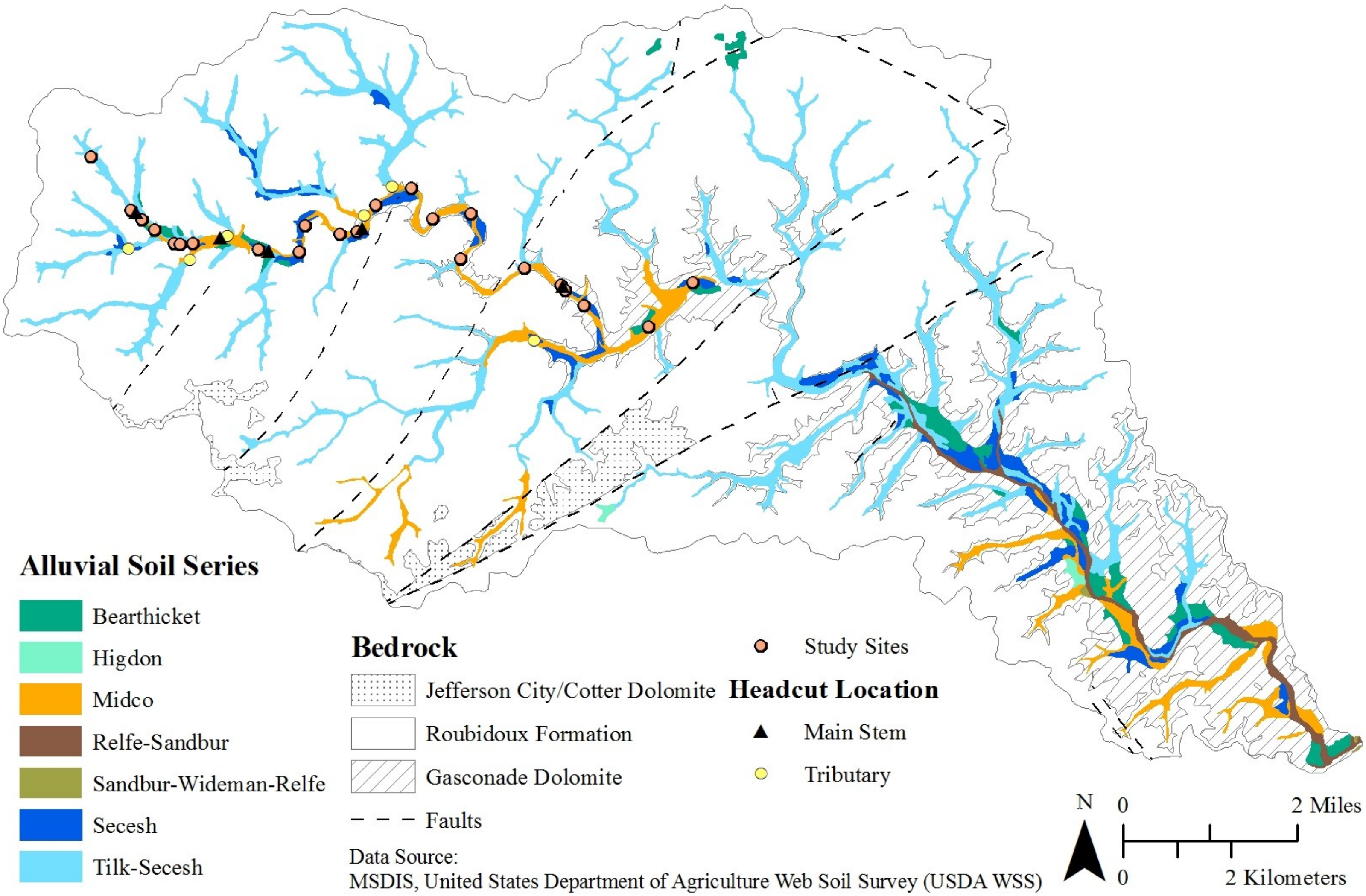

Figure 5. Bedrock geology and alluvial soils of the Big Barren Creek watershed.

74625-76999) that are located in the valley bottom of upland tributaries and the main stem of Big Barren Creek (Figure 5). Although alluvial soils make up about 12% of all soils in the watershed, they contain high amounts of sand and gravel that are quickly delivered to the drainage network through incision (Jacobson, 2004). An overview of the alluvial soil series in the Big Barren Creek watershed and the sedimentology of each soil series are presented in Tables 1 and 2, respectively.

The Midco, Secesh, and Tilk-Secesh soil series underlay most of the streams in the Big Barren Creek water. The Midco very gravelly loam contains up to 70% sand, while the Secesh series and the Tilk-Secesh complex and contain up to 30% and 60% sand (USDA NRCS Web Soil Survey). The Secesh series contains up to 75% gravel-size rock fragments, while the Midco series and Tilk-Secesh complex contain up to 90%

Table 1. Alluvial soil series in the Big Barren Creek watershed (USDA NRCS Official Soil Series Descriptions)

Series Name	Area (km^2)	% of Alluvial Soils	% of All Soils
Bearthicket silt loam	2.1	9.1	1.1
Higdon silt loam	0.2	0.7	0.1
Midco very gravelly loam	4.8	20.5	2.5
Relfe-Sandbur complex[1]	1.4	6.2	0.8
Sandbur-Wideman-Relfe complex[1]	0.1	0.3	0.04
Secesh silt loam	2.8	11.8	1.5
Tilk-Secesh complex[1]	12	51.3	6.3

[1]Complexes include multiple, dissimilar soil series that occur in a repeating pattern

Table 2. Big Barren Creek alluvial soil sedimentology (USDA NRCS Official Soil Series Descriptions)

				Overbank Unit			Coarse Unit	
Series Name	Land-form[1]	Slope (%)	Parent Material	Depth (m)	Texture	% Rock Fragments	Texture	% Rock Fragments
Bearthicket	Tr, Fp	0-3	Silty alluvium	0.51	Silt loam - Silty clay loam	0-5	Silt loam - Sandy clay loam	0-80
Higdon	Tr, Ft	0-9	Silty colluvium, alluvium	0.58	Silt loam - Silty clay loam	0-3	Loam - Silty clay loam	0-40
Midco	Fp	1-4	Alluvium	0.20	Gravelly loam	35	Very - Extremely gravelly sandy loam	30-80
Relfe	Fp	0-3	Sandy and gravelly alluvium	0.15	Very gravelly sandy loam	50	Very - Extremely gravelly loamy coarse sand	65-90
Sandbur	Fp	0-3	Loamy alluvium	0.48	Fine sandy loam - Loamy fine sand	0	Loamy fine sand - Fine sand	0-5
Secesh	Fp, Tr, Ft	0-8	Loamy alluvium, Cherty residuum	0.48	Silty clay loam - Loam	5-25	Gravelly silty clay loam - Extremely gravelly sandy clay loam	25-75
Tilk	Fp, Af, Tr	0-5	Loamy and sandy alluvium with rock fragments	0.20	Loam - Coarse sandy loam	25-75	Silt loam - Loamy coarse sand	35-90
Wideman	Fp	0-5	Sandy alluvium	0.30	Fine sand	0	Loamy sand - Fine sand	0-85

[1]Tr = Terrace; Fp = Floodplain; Ft = Footslope; Af = Alluvial Fan

gravel-size rock fragments (USDA NRCS Official Soil Series Descriptions). The high percentage of sand and gravel in these soil series can account for the coarse sediment supply that enters the drainage network through incision.

Climate and Hydrology

The Ozark Plateau has a temperate climate with a mean annual temperature of 15° C (Adamski et al., 1995). Annual high temperatures occur in July and annual low temperatures occur in January (Adamski et al., 1995). Precipitation patterns are influenced by moist air masses that originate in the Gulf of Mexico in the spring (Adamski et al., 1995). The southern region of the Ozark Plateau receives 120 cm of rainfall annually (Adamski et al., 1995). In the past decade, annual rainfall and the frequency of extreme rainfall events (> 7.6 cm/day) have increased in the Big Barren Creek watershed (Pavlowsky et al., 2016).

Carbonate rock dissolution has formed an extensive karst aquifer system in the Ozark Plateaus. Abundant karst drainage causes headwater streams to typically be dry, except during flash flood events that oversaturate soils and initiate overland flow (Jacobson, 2004). The Big Barren Creek watershed lies above the Lower Ozark aquifer member of the Ozark Plateaus aquifer system. Interbedded sandstone layers in the Roubidoux Formation store groundwater within the Lower Ozark aquifer (Westerman et al., 2016; Orndorff et al., 2001). The Lower Ozark aquifer has one of the highest densities of springs in the United States, playing an important role in the human development in the Ozarks (Vineyard and Feder, 1974).

Land Use

The Ozarks were originally inhabited by hunter-gatherer societies (Jacobson and Primm, 1997). Widespread settlement began in the early 1800s after the United States acquired the Ozarks during the Louisiana Purchase (Jacobson and Primm, 1997). Settlers cleared valley bottoms for grazing, row crop production, and minor timber production (Jacobson and Primm, 1997). A population influx occurred during the timber boom period, which began in the 1880s and lasted until the onset of the Great Depression in the 1920s (Jacobson and Primm, 1997). At the peak of the timber boom period, lumber from up to 0.3 km^2 of forest was processed daily at Grandin Mill in Grandin, MO (Cunningham, 2007). The population of the Ozarks declined after the timber boom period, and the remaining residents used the land for subsidence agriculture (Jacobson and Primm, 1997).

The Ozarks are currently dominated by mixed oak, hickory, and shortleaf pine forest and grassland. The landscape is used for logging, recreation, and agriculture (USDA, NRCS, 2006). The land within the Big Barren Creek watershed is classified mostly as deciduous forest (75.6%), with minor evergreen forest (9.5%), mixed forest (6.8%), and farmland (4.2%) (Table 3; Figure 6). The US Forest service manages 78 percent of the property in the Big Barren Creek watershed, while the rest is privately managed. The road network is made up of unpaved forest roads and two state highways.

Table 3. National Land Cover Database (NLCD, 2011) land use classification

Land Use Class	Percent of Watershed
Open Water	0.03
Developed	2.1
Deciduous Forest	75.6
Evergreen Forest	9.5
Mixed Forest	6.8
Shrubland	0.5
Grassland/Herbaceous	0.7
Planted/Cultivated	4.2
Wetlands	0.5

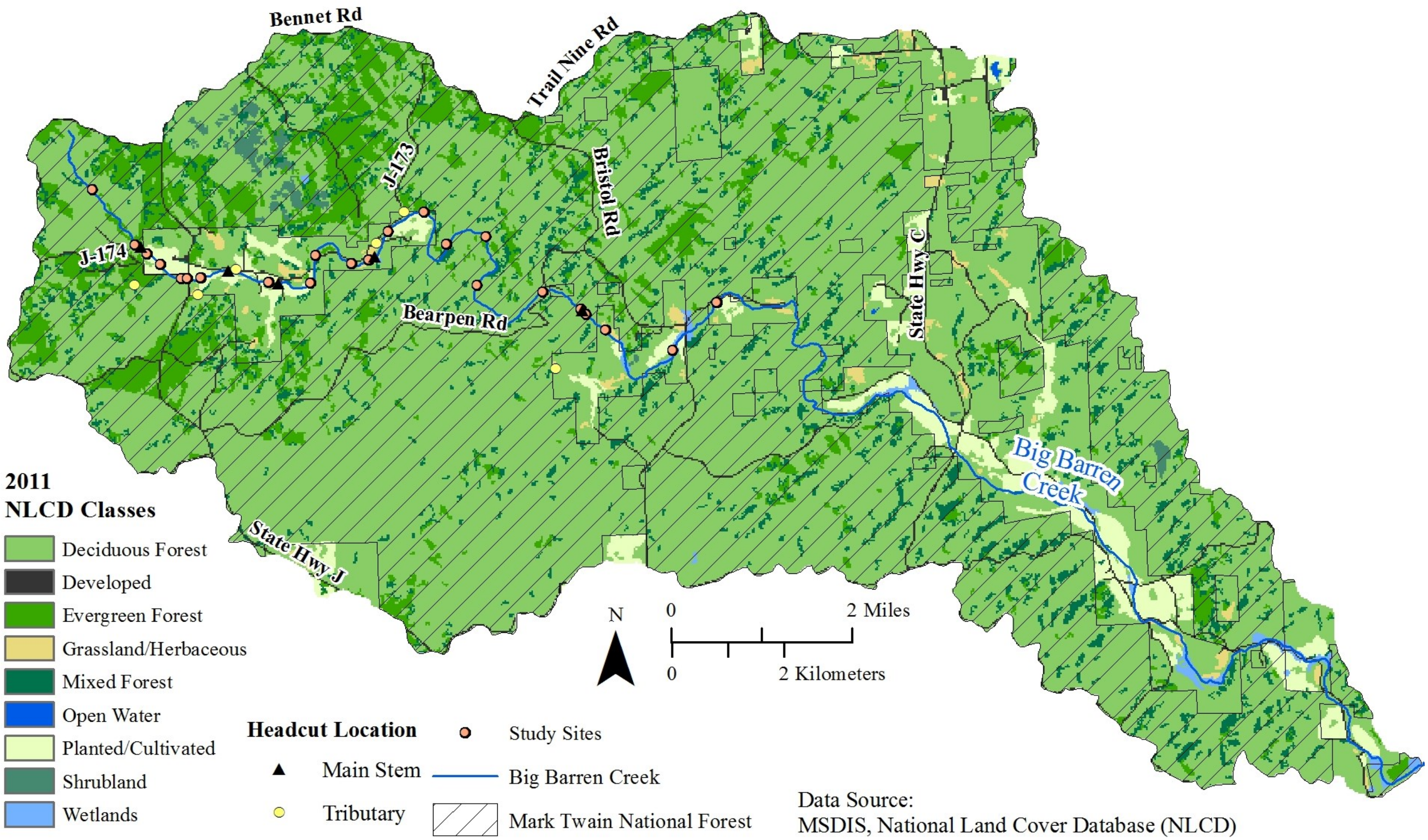

Figure 6. Land use classification for the Big Barren Creek watershed.

CHAPTER 3—METHODS

Field methods were used to characterize the overall channel morphology and substrate of the upper 20 kilometers of Big Barren Creek. From this study, three pairs of natural and channelized reaches were selected for additional geomorphic analysis and sediment transport modeling to understand differences in boundary conditions and geomorphic processes that may contribute to channel instability. Field, laboratory, and computational methods were used to collect and prepare input data for sediment transport modeling.

Model Site Selection and Description

A geomorphic assessment was conducted to characterize the downstream trends in channel geometry and sediment properties of Big Barren Creek. Twenty three study sites were selected along the upper 20 kilometers of Big Barren Creek that reflect changes in drainage area and land use (Figure 7). A longitudinal profile, cross-section, pebble count, and large woody debris (LWD) inventory were collected at each site. The longitudinal profile spanned three riffle-pool sequences, or six channel widths if notable bed topography was absent. The channel cross-section was surveyed at the middle riffle crest along the longitudinal profile. Channel geometry was surveyed with an auto-level and stadia rod following methods described by Harrelson et al. (1994). Five bed particles were blindly-selected and measured with a gravelometer at seven transects along the longitudinal profile using the Wolman (1954) pebble count method. If LWD was present at a study site, the length and diameter was measured with a stadia rod or tape measure.

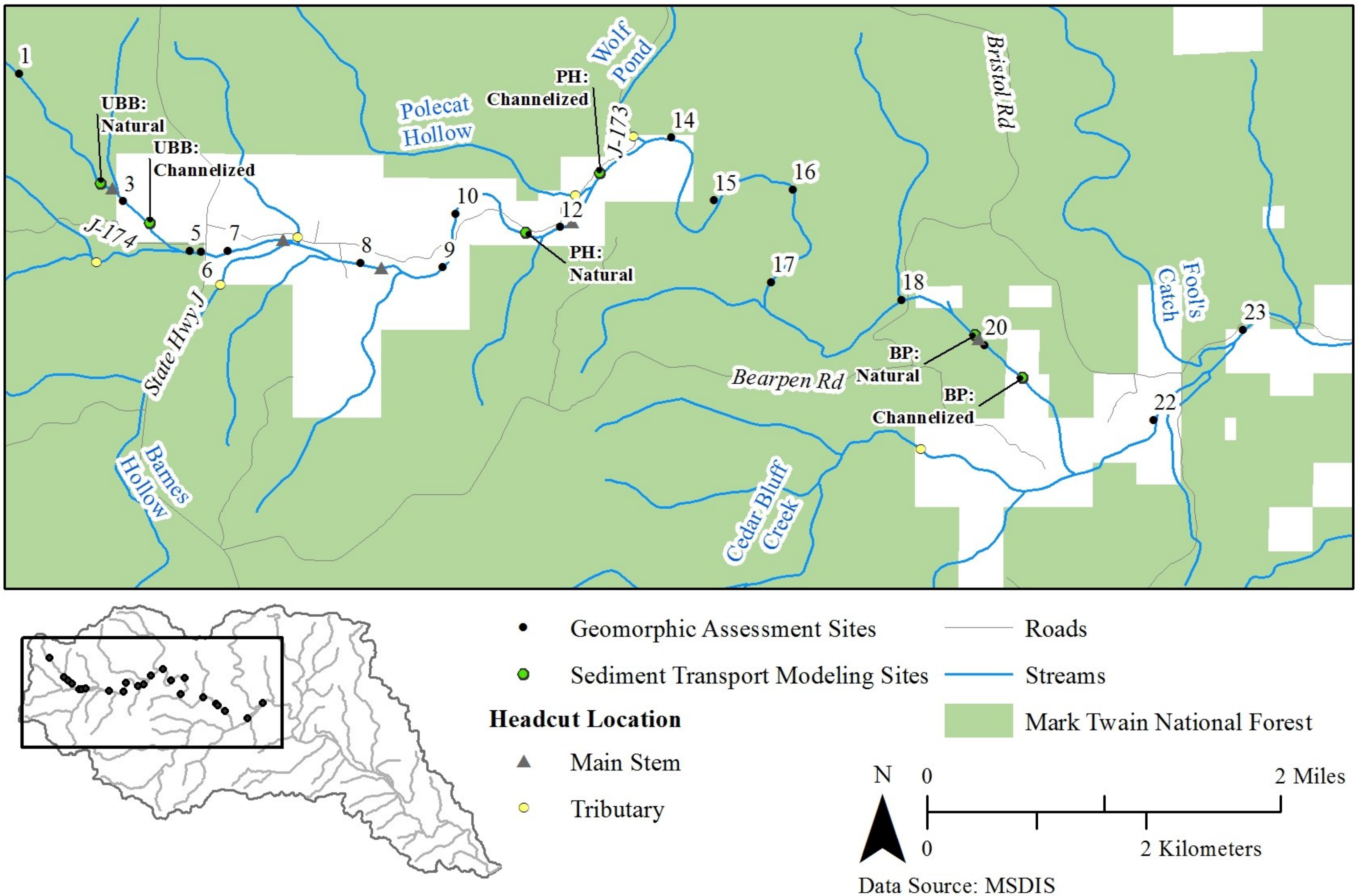

Figure 7. Map of study sites used in this project.

During the geomorphic assessment, potential indicators of channel instability were found along the main stem of Big Barren Creek. Headcuts were found upstream of channelized reaches and fine-grained sediment pulses were found downstream of headcuts (Figure 8). Headcuts indicate vertical incision that increases the sediment supply in the channel. Fine-grained sediment pulses indicate sediment aggradation in response to increased sediment supply from incision. The close proximity of headcuts and fine-grained sediment pulses to channelized reaches suggests that these features may be linked to abrupt changes in land management. To test this hypothesis, three pairs of natural and channelized reaches were selected for additional geomorphic analyses and sediment transport modeling to compare differences in channel geometry, hydraulics, and hydrology that lead to differences in the maximum sediment transport capacity that can cause instability. The following three sites were selected for sediment transport modeling:

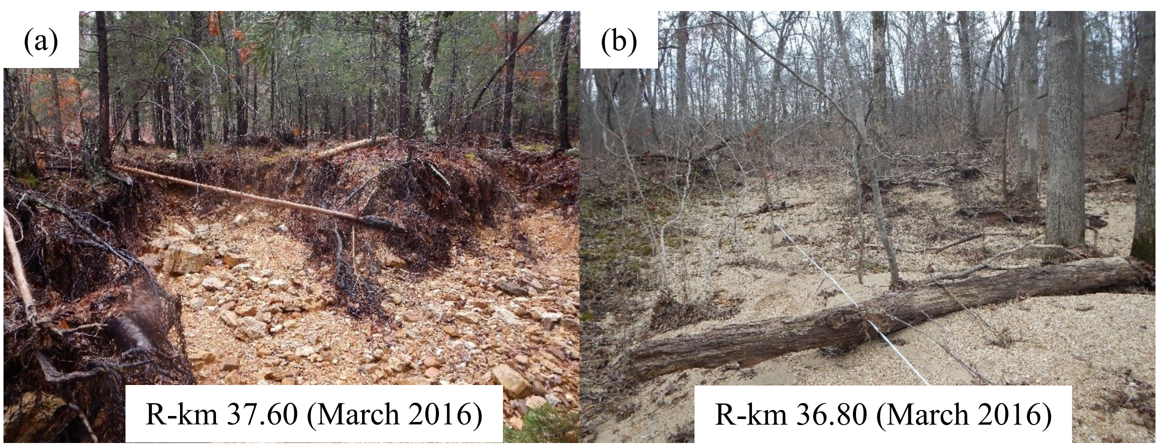

Figure 8. Examples of channel incision (a) and sediment aggradation (b) that were observed during the geomorphic assessment of Big Barren Creek.

The Upper Big Barren (UBB) model site is located upstream of State Highway J between R-km 37.94 and 36.68 (Table 4). The natural reach is managed by the US Forest Service and the channelized reach is privately managed. A 1-meter tall headcut has incised into the Tilk-Seceh complex and Midco very gravelly loam between the two reaches, supplying sand and gravel to the drainage network. The channelized reach is maintained by gravel mining. An aggraded reach is located downstream of the channelized reach, extending to State Highway J.

The Polecat Hollow (PH) model site is located along County Road J-174 between R-km 32.90 and 29.70. The natural reach is located upstream of the confluence of Polecat Hollow and Big Barren Creek, and is covered with a layer of fine-grained sand and gravel. The channelized reach is located below the confluence of Polecat Hollow and Big Barren Creek and is maintained by gravel mining. Both reaches are located on private property. While there are no headcuts on the main stem of Big Barren Creek at this model site, headcuts at Wolf Pond and Polecat Hollow have incised into the Tilk-Secesh complex and Midco very gravelly loam, suppling sand and gravel to the channelized reach. An aggraded reach is located downstream of the channelized reach, extending to R-km 29.70.

Table 4. Longitudinal extent of channel types at model reaches (R-km)

Site	Natural	Incised	Channelized	Aggraded
Upper Big Barren (UBB)	37.94 - 37.85	37.85 - 37.65	37.65 - 37.02	37.02 - 36.68
Polecat Hollow (PH)	32.90 - 32.77	32.77 - 32.10	32.10 - 30.65	30.65 - 29.70
Bearpen Road (BP)	24.99 - 24.90	24.90 - 24.65	24.65 - 23.13	N/A

The Bearpen Road (BP) model site is downstream of County Road J-176, locally known as Bearpen Road, between R-km 24.99 and 23.13. The natural reach is managed by the US Forest Service and the channelized reach is privately managed. The channelized reach extends below the confluence of Cedar Bluff Creek and Big Barren Creek. A 2-meter headcut has incised into the Midco very gravelly loam between the natural and channelized reaches, supplying sand and gravel to the channelized reach. Sediment aggradation was not as easily identifiable at this site, suggesting that fine-grained sediment has a greater mobility that in upstream reaches of Big Barren Creek. This most likely occurs because groundwater enters Big Barren Creek at springs near the confluence of Cedar Bluff Creek, providing more frequent flows that are capable of mobilizing fine-grained sediment.

Bedload Transport Processes and Modeling

Changes in channel dimensions, slope, and substrate from channelization can increase the amount of energy in a channel that is available to transport sediment (Simon and Rinaldi, 2006). Instability can occur if the channel has the capacity to move more sediment than it is being supplied (Simon and Rinaldi, 2006). In this study, sediment transport modeling was used to estimate the maximum transport capacity of natural and channelized reaches. Understanding the differences in sediment transport between natural and channelized reaches of Big Barren Creek will provide insight into the downstream effects of abrupt changes in land management (Wilcock, 2001).

The bedload of a stream is defined as the coarse sediment that is not typically suspended in the water column (Church, 2006). Bedload moves by rolling, sliding, or

bouncing along the channel bed during high flows (Church, 2006). Because the bedload is infrequently mobilized, it acts as the "engine" of fluvial geomorphology by regulating channel geometry and slope (Montgomery and Buffington, 1997; Church, 2006; Wilcock et al., 2009; Pfeiffer et al., 2017).

Bedload transport is controlled by shear stress; the frictional force that acts parallel to the channel bed. The amount of available shear stress in a channel at a given water depth is expressed by the following equation (Baker and Ritter, 1975):

$$\tau = \rho\, g\, R\, S$$

where τ is the available shear stress (N/m^2), ρ is the density of the fluid in the channel (kg/m^3), g is the acceleration due to gravity (m/s^2), R is the hydraulic radius (m), and S is the channel slope (m/m). Particle movement begins when the available shear stress exceeds the frictional resistance of the channel bed, referred to as critical shear stress. The following equation is used to calculate critical shear stress:

$$\tau_c = \tau^*(\rho_s - \rho_w)\, g\, D$$

where τ_c is the critical shear stress (N/m^2), τ^* is a dimensionless Shields number for sediment with a grain size of D (m), ρ_s is the sediment density (kg/m^3), ρ_w is the fluid density (kg/m^3), and g is the acceleration due to gravity (m/s^2) (Buffington and Montgomery, 1997). The first dimensionless Shields numbers were derived by Shields (1936) using homogeneous sediment in a flume. Subsequent studies have shown that flow turbulence, drag, grain protrusion, and grain packing influence the Shields number in heterogeneous sediment, resulting in a wide range of Shields numbers for natural stream channels (Buffington and Montgomery, 1997).

Bedload transport rates are commonly expressed as a function of the discharge of water that flows through the channel (Wilcock et al., 2009). Discharge (m^3/s) is the product of the cross-sectional flow area (m^2) and the flow velocity (m/s) at a given depth. The average flow velocity in metric units is calculated with the Manning equation:

$$v = \frac{R^{\frac{2}{3}} S^{\frac{1}{2}}}{n}$$

where v is velocity (m/s), R is the hydraulic radius (m), S is the channel slope (m/m), and n is Manning's n; a dimensionless hydraulic roughness coefficient that quantifies the amount of flow resistance that is offered by the boundary conditions of the channel. While the Manning equation does not account for non-uniform flow, differences in velocity in the water column, and local acceleration and deceleration from obstacles and backwatering, the equation is commonly used to characterize the average flow velocity of natural channels (Ferguson, 2010). A variety of empirical and visual methods are used to estimate Manning's n values for natural channels (Barnes, 1967; Limerinos, 1970; Pizzuto et al., 2000; Arcement and Schneider, 1989; Phillips and Tadayon, 2006).

Bedload Assessment for Gravel-bed Streams (BAGS) Modeling

The BAGS model is an Excel-based sediment transport model that was developed by the US Forest Service (Wilcock et al., 2009). It was previously used by Owen et al. (2012) to predict the optimal timing of in-channel dredging of lead-contaminated sediment in the Missouri Ozarks. The model estimates sediment transport rates (kg/s) and sediment transport stage between a minimum and maximum discharge. The transport stage is a dimensionless ratio of the available shear stress to the critical shear stress at a

given discharge (Pitlick et al., 2009). Significant sediment transport occurs as the transport stage approaches and exceeds a value of one (Church, 2006).

Six different calibrated and uncalibrated sediment transport equations can be used in the BAGS model. All equations are based on the concepts of available shear stress and critical shear stress that vary with discharge (Pitlick et al., 2009). The Wilcock-Crowe (2003) surface-based equation (WC) and the Parker-Klingeman (1982) sub-surface-based equation (PK) were used for this project. Both equations are uncalibrated and use complex operators to produce sediment transport rates for multiple size fractions of the grain size distribution (Pitlick et al., 2009). The WC and PK equations were chosen because they model sediment transport for the entire grain size distribution and do not require empirical bedload data to operate.

The BAGS model requires a channel cross-section, slope estimate, surface or sub-surface grain size distribution, and hydraulic roughness estimate to operate. Minimum and maximum discharge values are required to produce a rating curve. The following methods were used to collect the channel morphology, grain size, and hydrologic data to operate the model.

Channel Morphology. An auto-level and stadia rod were used to survey the cross-sectional area and longitudinal profile of each model reach following standard methods (Harrelson et al., 1994). The longitudinal profile of the UBB channelized reach was surveyed with a Topcon total station. Longitudinal profiles included three riffle-pool sequences or 12 active channel widths if bedforms were not easily identifiable. One channel cross-section was surveyed at the riffle crest at the center of the longitudinal profile, and extended to the elevation of the high terrace in the natural reaches or the

maximum levee height in the channelized reaches. The elevation of bankfull indicators and flood debris deposits were included in channel cross-sections.

Grain Size. Field and laboratory methods were used to produce grain size distributions of the surface and sub-surface sediment at each model site. A pebble count method was used to determine grain size distribution of a number of measured particles, and volumetric sampling was used to determine the grain size distribution of the weight of a sub-surface sediment sample. Comparing the surface and sub-surface sediment provided insight into the degree of armoring in each model reach (Bunte and Abt, 2001). Although different methods were used to characterize the surface and sub-surface grain size distribution, the grain size distributions can be compared without conversion (Kellerhals and Bray, 1971; Rice and Church, 1996).

A Wolman (1954) pebble count technique was used to measure the intermediate axis of 30 blindly-chosen particles from the bed surface with a gravelometer along eight transects with a spacing of one active channel width. Particles that could not be measured with the gravelometer were classified as sand (0.063 mm), fines (2 mm), or soil. Soil was considered to be non-mobile, cohesive sediment and was not included in the grain size distribution for the BAGS model.

Sub-surface sediment was collected from a pit that was dug to a depth of at least twice the diameter of the largest mobile clast on the channel bed (Bunte and Abt, 2001). Two to three bedload pits were dug in each sub-reach to account for heterogeneity in the sub-surface sediment distribution. The sediment was passed through the following sieves and weighed in the field with a hanging scale: 63 mm, 45 mm, 25.4 mm, and 16 mm. A portion of the <16 mm fraction was returned to the laboratory, dried in an oven at 60˚ C,

and passed through the following sieves: 8 mm, 4 mm, 2 mm, and 1 mm. Laser diffraction was used to determine the proportion of sand, silt, and clay in a 0.2-gram portion of the <1 mm fraction of each sub-surface sample (OEWRI, 2008). The mass of the size fractions from field sieving, lab sieving, and laser diffraction methods were combined to produce a cumulative frequency distribution of grain size to the total mass of each sub-surface sample.

The BAGS model assumes that all sediment has a uniform density of 2.65 g/cm³ (Pitlick et al., 2009). The density of particles in the three modified sub-reach bed load pits was measured by water displacement using a beaker and digital scale. Particles were divided by lithology into chert and non-chert and into the following size categories: 8-16 mm, 16-32 mm, and 32-45 mm. Chert samples had a mean density of 2.33 g/cm³ with a 10.09 % coefficient of variation, while the non-chert samples had a mean density of 2.26 g/cm³ with a 13.59 % coefficient of variation (Figure 9). In both cases, the modeled

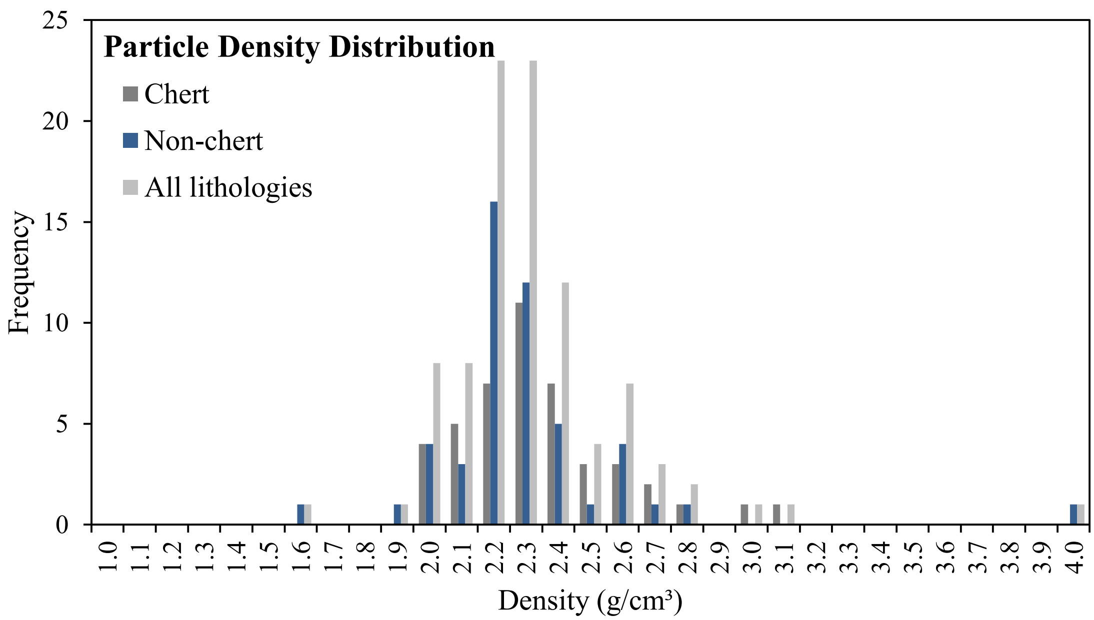

Figure 9. Particle density distribution of model site sub-surface sediment.

sediment in Big Barren Creek has a lower density than what is assumed by the BAGS model. Because sediment density contributes to the critical shear stress of the bed sediment, it is possible that the BAGS model could under-predict sediment transport rates for the degree of variation in the channel cross section, n_3 accounts for the effect of obstructions on flow resistance, n_4 accounts for the amount of vegetation in the channel, and m accounts for the degree of meandering in the channel (Arcement and Schneider, 1989).All values are dimensionless, and the selection guides that were used to estimate the base n and adjustment factors are presented in Appendix A.

Measurements of the position and diameter of trees within 20-meter cells centered at the cross-sections of natural reaches were used to calculate the percentage of flow obstruction from vegetation. Additionally, the following equation was used to calculate the vegetation density of each natural reach (Petryk and Bosmajian, 1975):

$$\text{Vegetation density} = \frac{\sum A_i}{AL}$$

where $\sum A_i$ is the total frontal area of vegetation blocking the flow through the reach (m^2), A is the cross-sectional flow area (m^2), and L is the length of the channel reach (m) (Petryk and Bosmajian, 1975).

Flood Frequency. Flood frequency estimates provide insight into the timing of bedload-transporting discharge events. Least-squares regression equations published by the US Geological Survey were used to estimate the 2-, 5-, 10-, 25-, 50-, and 100-year flood discharge for each model site, using drainage basin area (mi^2) and slope (ft/mi) (Alexander and Wilson, 1995). Basin slope is measured between two points that are at 10 and 85 percent of the distance from the mouth of the channel. The equations were derived from hydrologic data from basins in rural Missouri between 0.33 and 29,700 km^2 in size

and have an average standard error between 30 and 40 percent (Alexander and Wilson, 1995). The drainage basin area and slope at each model site were calculated in ArcMap (version 10.2.2) using a delineated Big Barren Creek drainage network from a USGS 10-meter Digital Elevation Model.

Discharge Capacity. Calculated flood discharges were simulated in channel cross-sections using Intelisolve (2006) Hydraflow Express software. This analysis was used to estimate the bankfull stage in the natural reaches to measure channel geometry, model flow recurrence intervals at model reaches, and select the minimum and maximum discharge values for the BAGS model operation. This process was based on the assumption that the 2-year flood discharge is roughly equivalent to the bankfull discharge at which the channel is filled to immediately before spilling out onto the floodplain (Dury, 1961; Wilkerson, 2008). The calculated 2-year flood discharges were confirmed to be similar to the estimated bankfull discharge at the natural model sites. The discharge capacity for channelized and incised segments of Big Barren Creek was defined as the maximum volume of water that can be contained by the incised channel or modified channel dimensions. From this analysis, the BAGS model was operated between one fifth of the 2-year flood discharge and the 100-year flood discharge at each model site.

CHAPTER 4—RESULTS AND DISCUSSION

Downstream Trends in Channel Morphology

Channel width, depth, and cross-sectional area of all 23 sites were measured in Hyraflow Express at the estimated bankfull stage in natural reaches. At incised and channelized reaches that are non-alluvial, these dimensions were measured at the maximum channel capacity (Florsheim et al., 2013). These dimensions, along with channel slope and median grain size, were plotted against the drainage area at each site (Figure 10). A sequence of four distinct channel types was observed during the geomorphic assessment that was supported by non-linear overall trends in channel geometry, slope, and substrate. Photos of various sites are presented in Appendix B. Channel assessment sites were classified as natural, channelized, incised, or aggraded based on the channel geometry and sediment that was present at the site (Table 5; Figure 11; Appendix C). Natural reaches of Big Barren Creek are wide and shallow, with mixed gravel-cobble beds that are stabilized by trees and vegetation. Channelized reaches have a similar width but are deeper, free of instream vegetation, bounded by artificial levees, and have loose, armored gravel-cobble beds. Incised reaches have headcuts, steep slopes, and small width-depth ratios and are located upstream of channelized reaches. Aggraded reaches are located downstream of channelized reaches and have a natural channel morphology that is blanketed by a layer of sand and fine gravel (Appendix B).

The reoccurring pattern of incised and aggraded reaches near channelized reaches suggested that channelization may be linked to incision and sediment aggradation on the main stem of Big Barren Creek (Figure 12). Other studies have shown that channelization

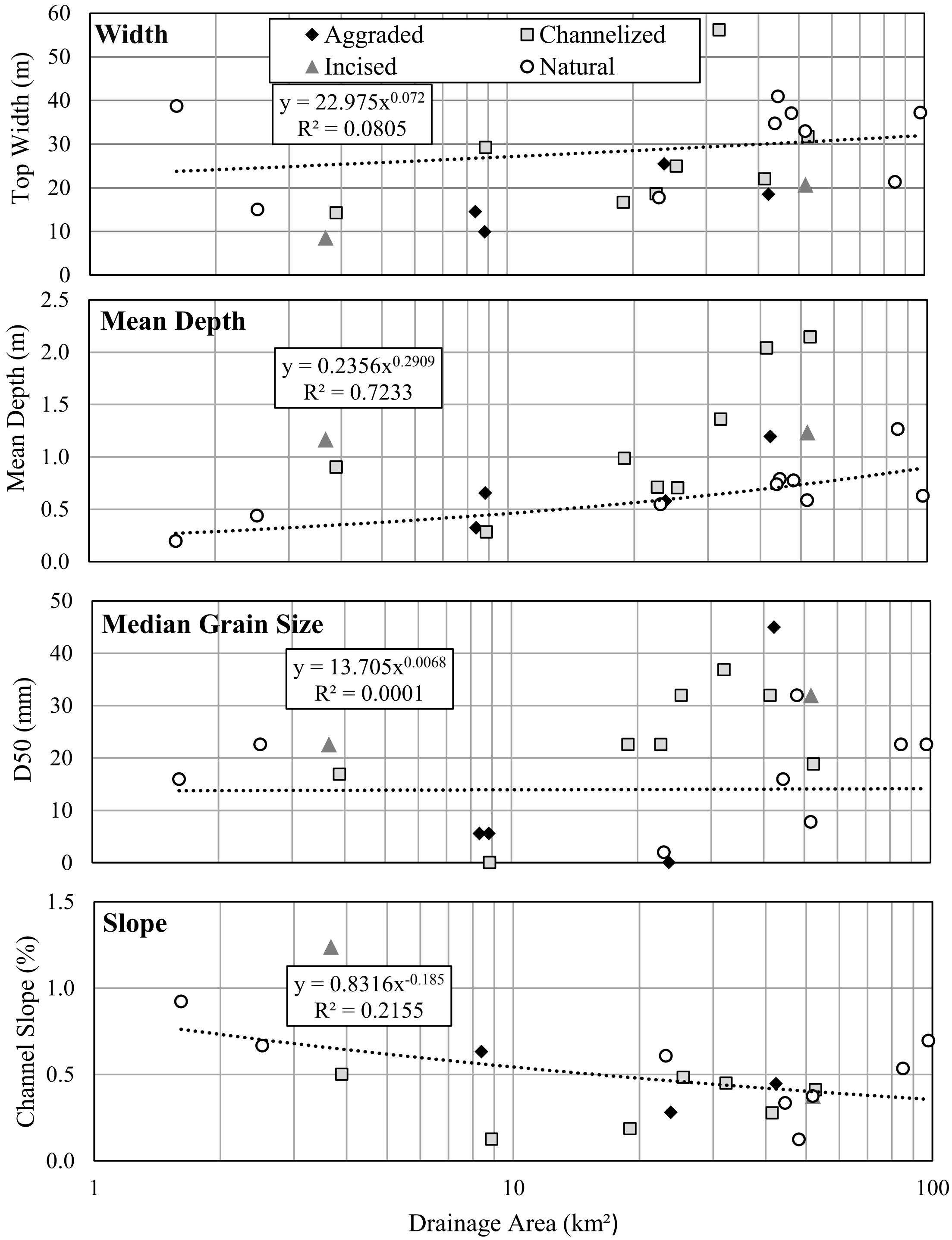

Figure 10. Downstream trends in channel geometry, substrate, and slope in the upper 20 kilometers of Big Barren Creek. Note: trend line fitted to natural sites.

Table 5. Mean values of channel morphology characteristics for different channel types

Channel Type	Sites (n)	Width (m)	Mean depth (m)	Max depth (m)	CS Area (m^2)	W/D Ratio	D50 (mm)	Slope (%)	LWD Volume (m^3)
Natural	9	30.7	0.7	1.3	20.1	60	17.7	0.53	0.2
Aggraded	4	17.1	0.7	1.3	12	29.9	14.1	0.45	0.7
Incised	2	14.7	1.2	2	17.8	12.1	27.3	0.81	0
Channelized	8	26.7	1	1.9	32.3	33	22.7	0.35	0.13

alters channel geometry, substrate, and bed resistance, which can initiate upstream incision and downstream sediment aggradation (Simon and Rinaldi, 2006; Gregory, 2006; Landwehr and Rhoads, 2003). These effects are often attributed to an increase in the available energy to transport sediment, coupled with a decrease in the erosional resistance of the modified channel bed (Simon and Rinaldi, 2006). The downstream progression of channelization-induced disturbance at Big Barren Creek is illustrated in Figure 13.

Figure 11. Channel types of Big Barren Creek.

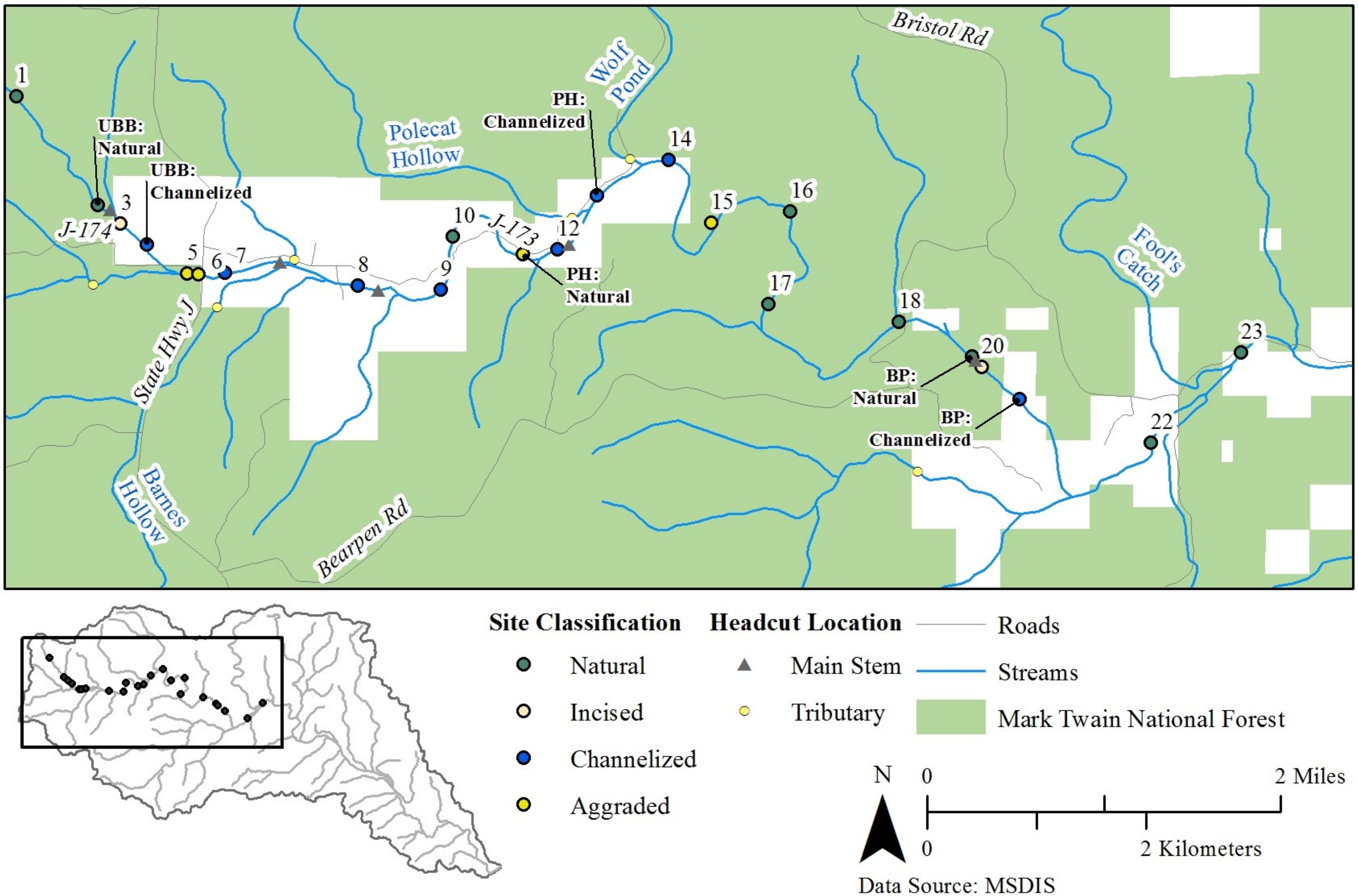

Figure 12. Classified survey sites from the geomorphic assessment.

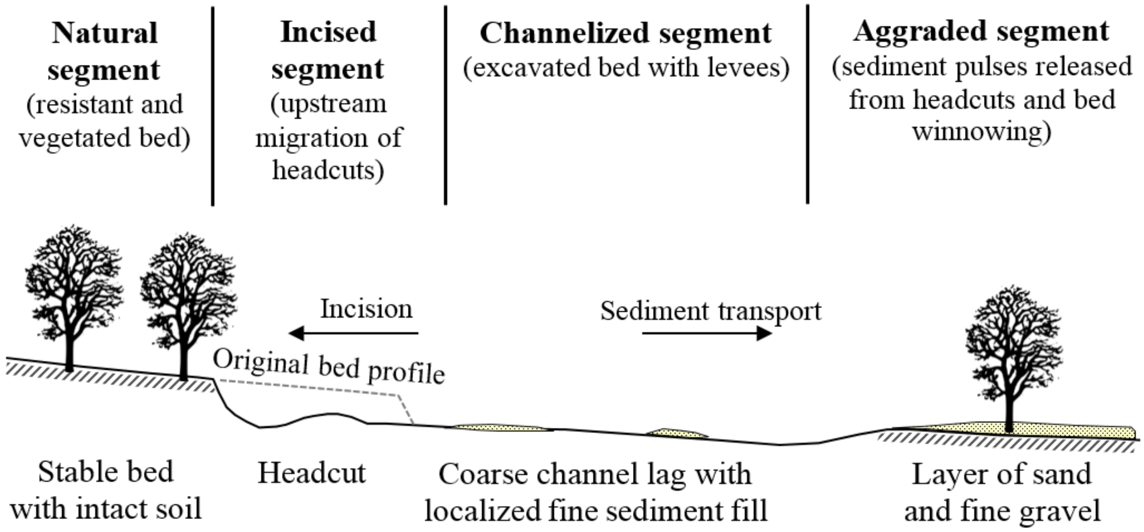

Figure 13. Conceptual diagram of channelization-induced instability on Big Barren Creek.

Geomorphic Characteristics of Model Sites

Upstream incision and downstream sediment aggradation were observed near channelized reaches of Big Barren Creek, suggesting that abrupt changes in land use may initiate channel instability. Three pairs of natural and channelized sites were selected for additional geomorphic analysis and sediment transport modeling to quantify differences in channel morphology, hydraulics, hydrology, and sediment transport that may lead to channel instability (Appendix B). Paired sites are between 500 and 1,000 meters apart and have drainage areas that range within 30% of each other. Natural and channelized sites were selected in close proximity to each other to reflect differences that can be attributed to land use. However, there may be natural drivers of geomorphic differences at the PH site. The natural and channelized reaches are separated by the confluence of Polecat Hollow and Big Barren Creek, which provides 8 km^2 of additional drainage to the channelized reach. This could cause the channel to naturally enlarge to accommodate the

increased discharge that does not flow through the natural reach. Additionally, the channelized reaches receives sediment from a headcut on Polecat Hollow.

Channel Morphology and Hydraulics. Natural and channelized reaches of Big Barren Creek have distinct differences in channel geometry, substrate, and vegetation that influence hydraulic roughness, discharge capacity, and sediment transport processes (Table 6). Natural and channelized reaches have similar channel widths, but channelized channels are deeper, increasing the cross-sectional flow area by up to 130%. With the exception of the Upper Big Barren modeling site, the slopes of channelized reaches are up to 45% steeper than the natural reaches (Appendix D). While these large channel dimensions reduce overbank flooding in channelized reaches of Big Barren Creek, they also increase the amount of excess flow energy that can cause incision and channel instability (Simon and Rinaldi, 2006).

In addition to modifying channel dimensions, channelization actions often remove vegetation and trees that grow in the active channel and the riparian zone (Hooke, 1986). Vegetation and trees can promote channel stability by increasing hydraulic roughness that dissipates flow energy and facilitates sediment deposition (McKenney et al., 1995; Keeton et al., 2017). McKenney et al. (1995) found that tree roots can promote bank stability in Ozark streams if the rooting depth is greater than the bank height; however the effects on bank stability decrease with increasing drainage area. Due to the ephemeral nature of the upper portion of Big Barren Creek, woody vegetation and up to 200 year-old trees grow on the active channel bed of natural reaches. This vegetation forms a root and soil-supported matrix that stabilizes the channel bed of natural reaches. Removing this vegetation during channelization can cause instability by altering the erosional

Table 6. Channel morphology and hydraulics of model sites

	Upper Big Barren		Polecat Hollow		Bearpen Road	
	N[1]	C[1]	N	C	N	C
River kilometer	37.87	37.3	32.82	31.85	24.95	24.35
Drainage area (km^2)	2.52	3.89	23.75	32.17	51.76	52.75
Cross-sectional area[2] (m^2)	6.61	12.87	14.78	76.45	18.52	68.08
Channel width[2] (m)	15.02	14.26	25.49	56.71	31.5	31.73
Maximum depth[2] (m)	0.76	1.4	1.03	2.38	0.91	3.05
Surface D50 (mm)	22.6	16.9	0.063	36.9	7.8	18.5
Sub-surface D50 (mm)	6.8	7.0	3.1	5.7	2.5	11.3
Slope (%)	0.67	0.5	0.28	0.45	0.38	0.41
Vegetation density (per meter)	0.0042	N/A	0.0085	N/A	0.0088	N/A
Hydraulic roughness (dimensionless)	0.065	0.04	0.063	0.045	0.065	0.04

[1]N = Natural; C = Channelized

[2]Dimensions at estimated bankfull stage in natural reaches and top of levees in channelized reaches

resistance of the natural channel bed (Hooke, 1986; Montgomery and Buffington, 1997).

Grain Size. Natural and channelized model reaches have different grain size distributions that provide insight into sediment supply and transport processes (Figure 14; Figure 15) (Bunte and Abt, 2001). Natural reaches have a gravel bed with a root-supported mixed soil and gravel sub-surface. Channelized reaches have an armored, gravel-cobble bed surface that overlies loose mixed sand and gravel. With the exception of the Polecat Hollow natural reach, the bed surface sediment is coarser than the sub-

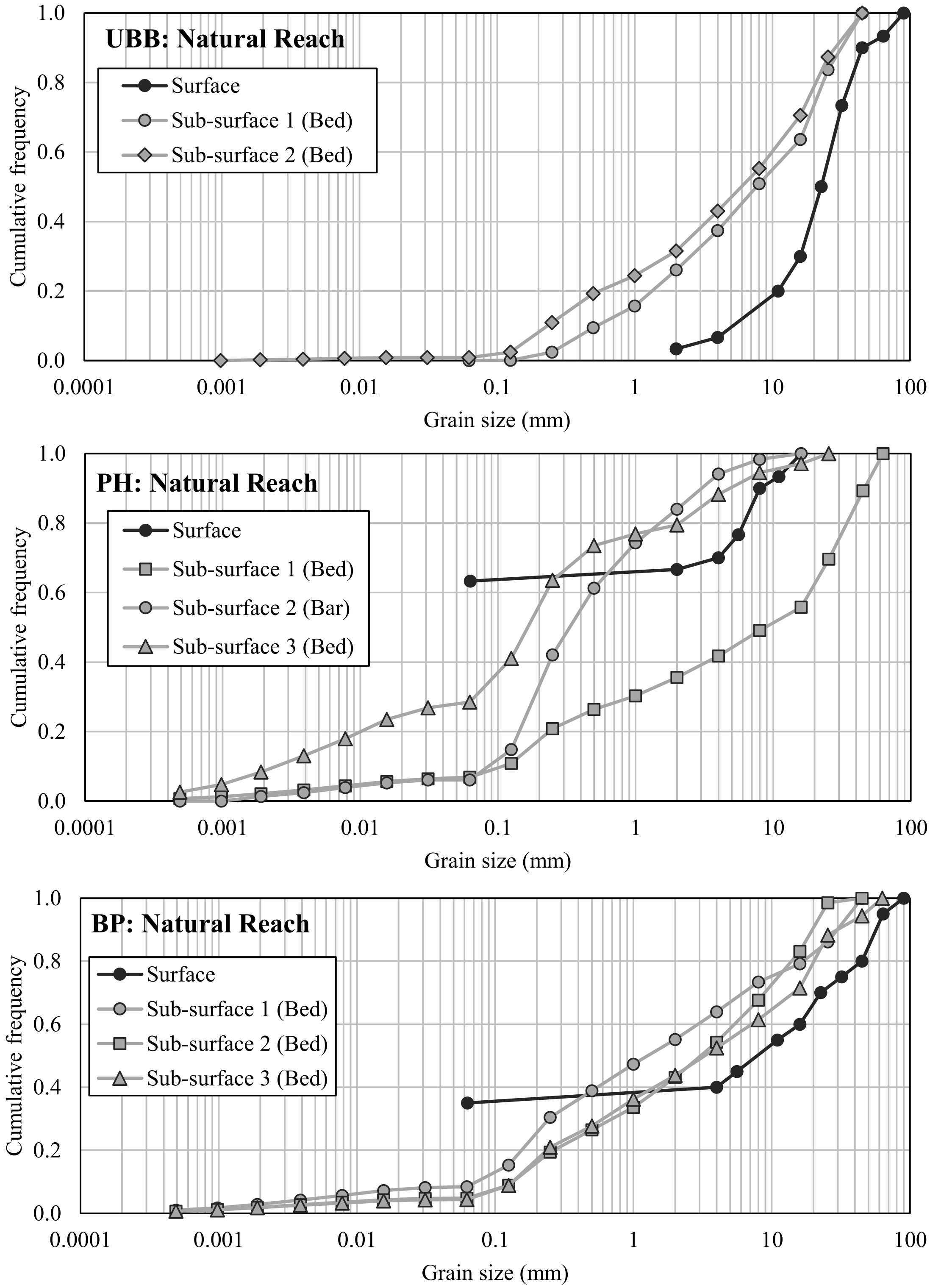

Figure 14. Grain size distributions of the natural reaches at each model site.

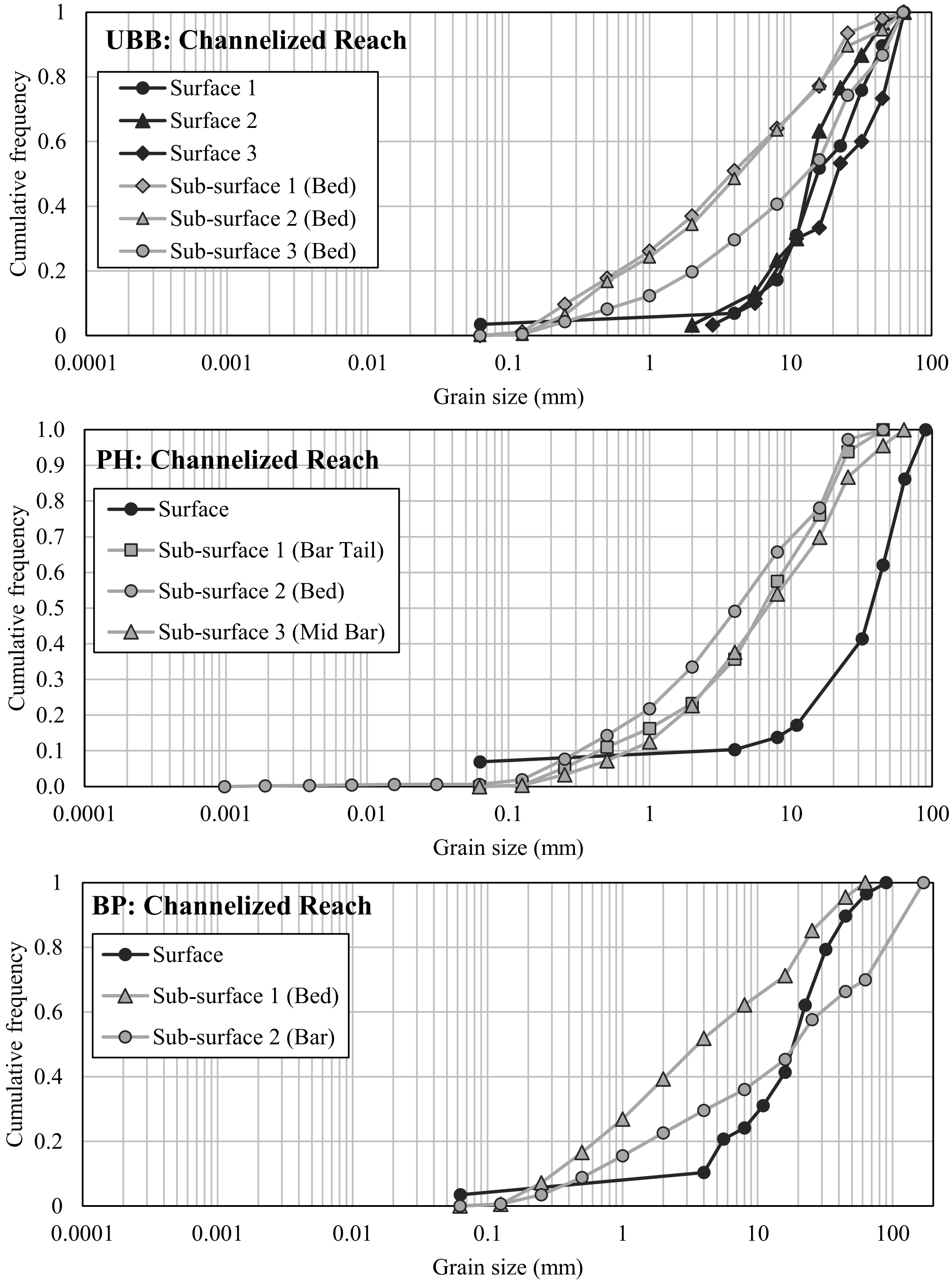

Figure 15. Grain size distributions of the channelized reaches at each model site.

surface sediment at all model reaches (Table 6; Figure 16). At the Polecat Hollow natural reach, a fine-gravel and sand sediment pulse covers the channel bed that was transported downstream from upstream incision. Bed armoring and aggradation have implications for sediment mobility and supply (Bunte and Abt, 2001). Bed armoring occurs when fine-grained sediment is selectively transported and winnowed out of the channel bed (Bunte and Abt, 2001). Fine-grained sediment pulses are indicators of increased sediment loading that overwhelms the transport capacity of the channel (Rhoads, 1990). The thickness and abundance of sediment pulse deposits generally decrease with distance below channelized segments of Big Barren Creek.

Flood Frequency and Discharge Capacity. Channelization is intended to increase the flood conveyance of natural channels by increasing the cross-sectional flow area (Gregory, 2006). However, these changes can concentrate flow energy and cause incision by increasing the sediment transport capacity of a modified channel (Simon and Rinaldi, 2006). The calculated peak flood discharges at different return intervals are presented in Table 7. Natural reaches can contain between 2-year and 10-year flood

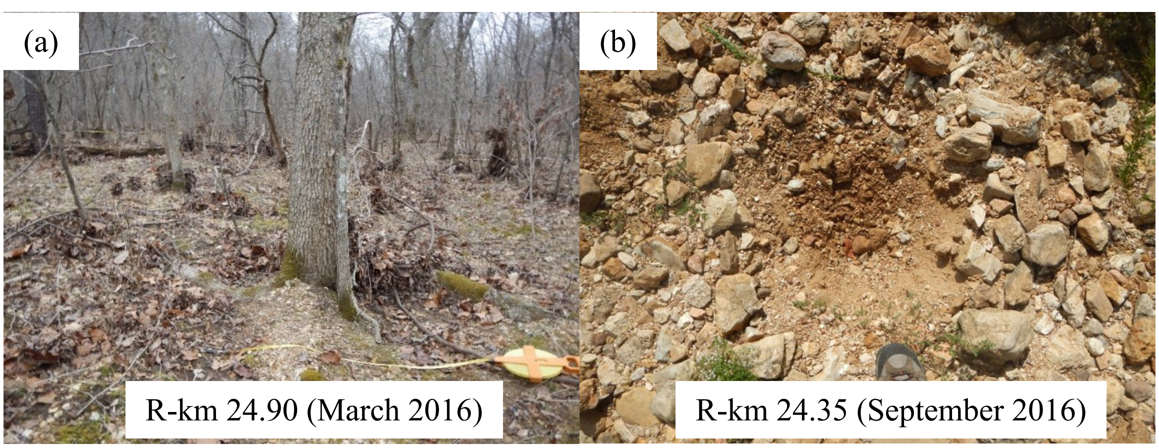

Figure 16. Root-supported natural channel bed (a) and loose, armored channelized bed (b).

events, while channelized reaches can contain between 10-year and 100-year flood events (Figure 17; Figure 18; Figure 19). The greatest differences in peak flood discharges occur between the natural and channelized reaches at the PH model site, where the drainage area increases from the confluence of Polecat Hollow and Big Barren Creek. The abrupt changes in discharge capacity between natural and channelized reaches could potentially cause instability in channelized reaches that is translated upstream and downstream.

Table 7. Peak flood discharge (m^3/s) return intervals (years) at model sites[1]

Return Interval	Upper Big Barren		Polecat Hollow		Bearpen Road	
	Natural	Channelized	Natural	Channelized	Natural	Channelized
Q2	6	8.1	28.4	35.6	47.9	48.2
Q5	10.8	14.7	53.3	67.3	90.4	90.9
Q10	14.8	20.2	73.8	93.6	125.4	126
Q25	20.5	27.9	102.8	130.8	175	175.6
Q50	24.6	33.4	123.9	157.9	210.9	211.6
Q100	28.9	39.3	146.4	186.9	249.3	250

[1]Underlined values indicate maximum flows that are contained by channel dimensions

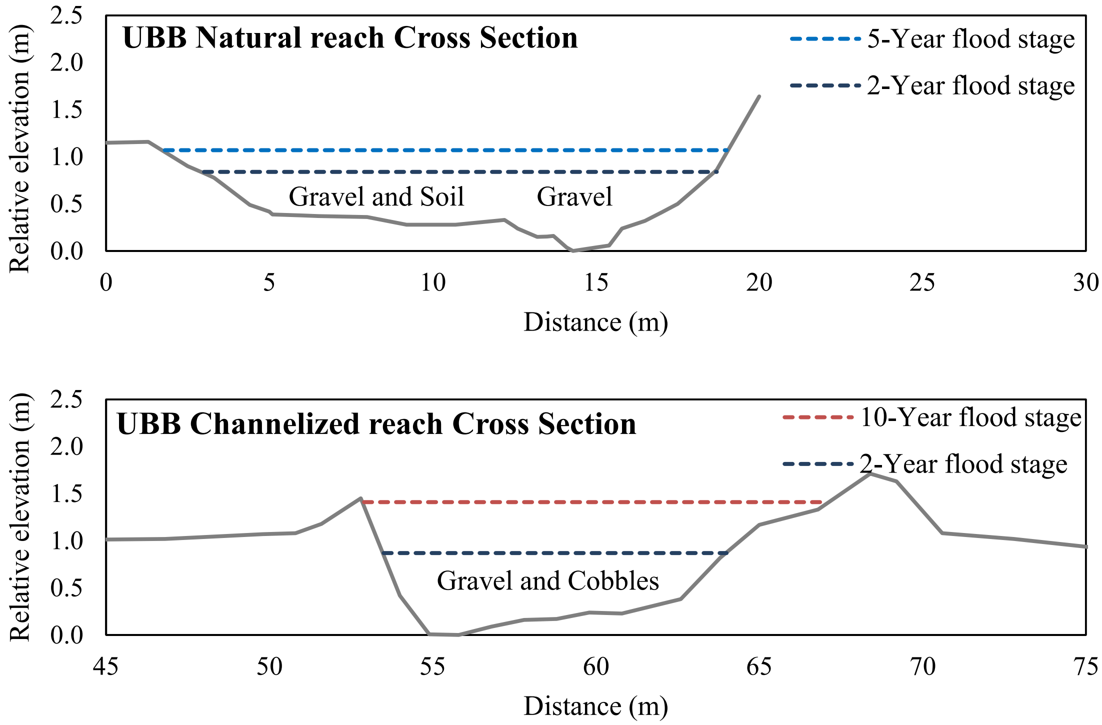

Figure 17. Cross-sectional geometry and discharge capacity of the UBB model reaches.

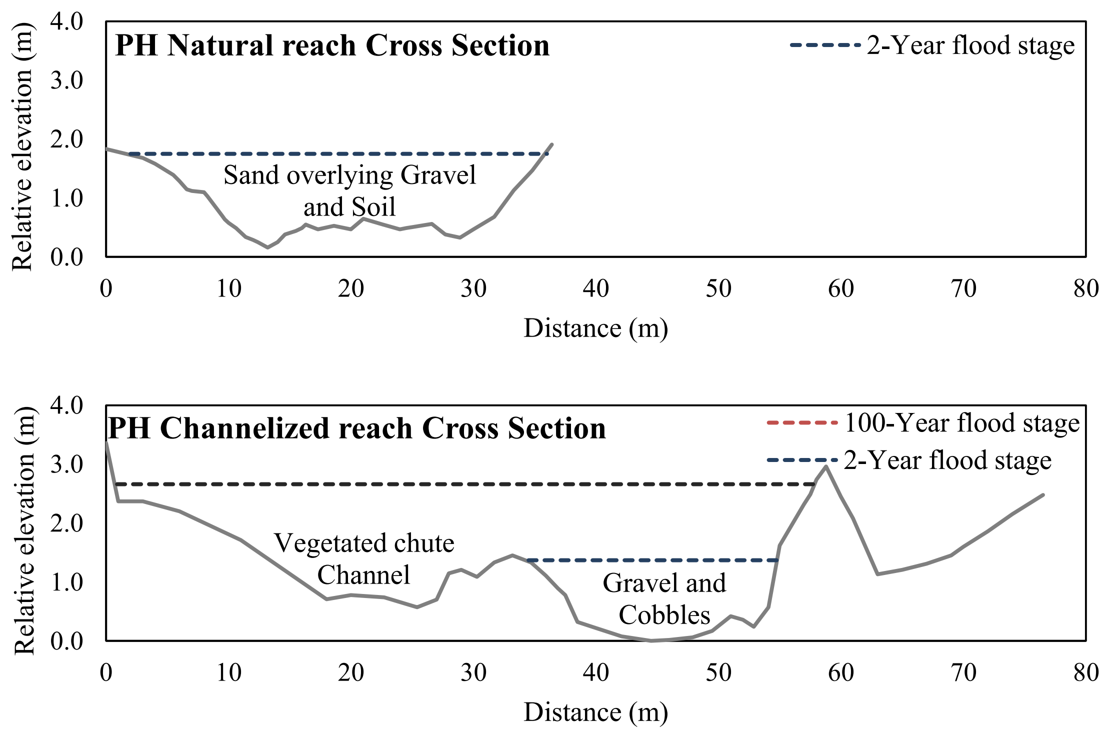

Figure 18. Cross-sectional geometry and discharge capacity of the PH model reaches.

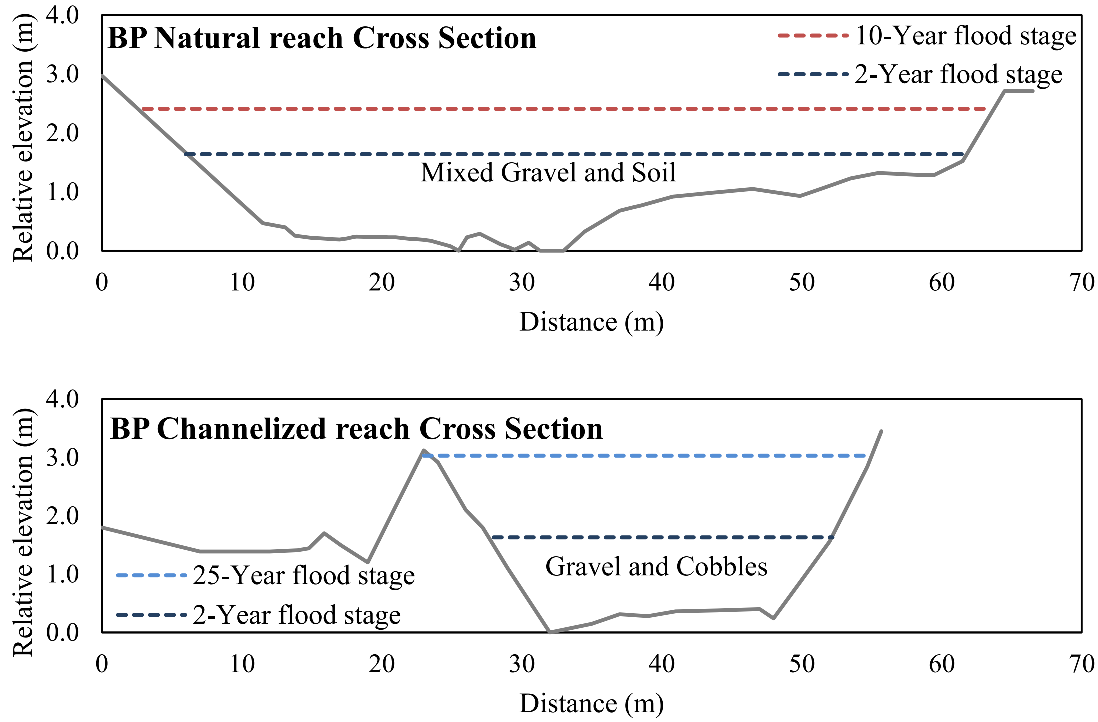

Figure 19. Cross-sectional geometry and discharge capacity of the BP model reaches.

BAGS Modeling Results

The BAGS model provided estimates of sediment transport rates and shear stress for channels with known geometry, hydraulic roughness, and sediment properties (Appendix E). The model was run between one fifth of the 2-year flood discharge and the 100-year discharge at each model reach. Sixth-order polynomial regression methods were used to find the sediment transport rate and the transport stage at the 2-, 5-, 10-, 25-, 50-, and 100-year flood discharge at each model reach for the surface and sub-surface sediment.

Transport Capacity. Sediment transport rates provide an estimate of the maximum transport capacity of a channel (Wilcock et al., 2009). BAGS modeling results indicate that channelized reaches tend to have a greater sediment transport capacity than natural reaches (Figure 20; Appendix F). The greatest differences in sediment transport

capacity are found at the UBB model site, where the channelized reach can transport up to 300 times more surface sediment and up to 6,000 times more sub-surface sediment than the natural reach. These differences decrease with increasing discharge due to the exponential nature of the sediment transport equations (Pitlick et al., 2009). The PH and BP model sites have more moderate differences in surface sediment transport capacity between natural and channelized reaches. At both sites, the channelized reaches can

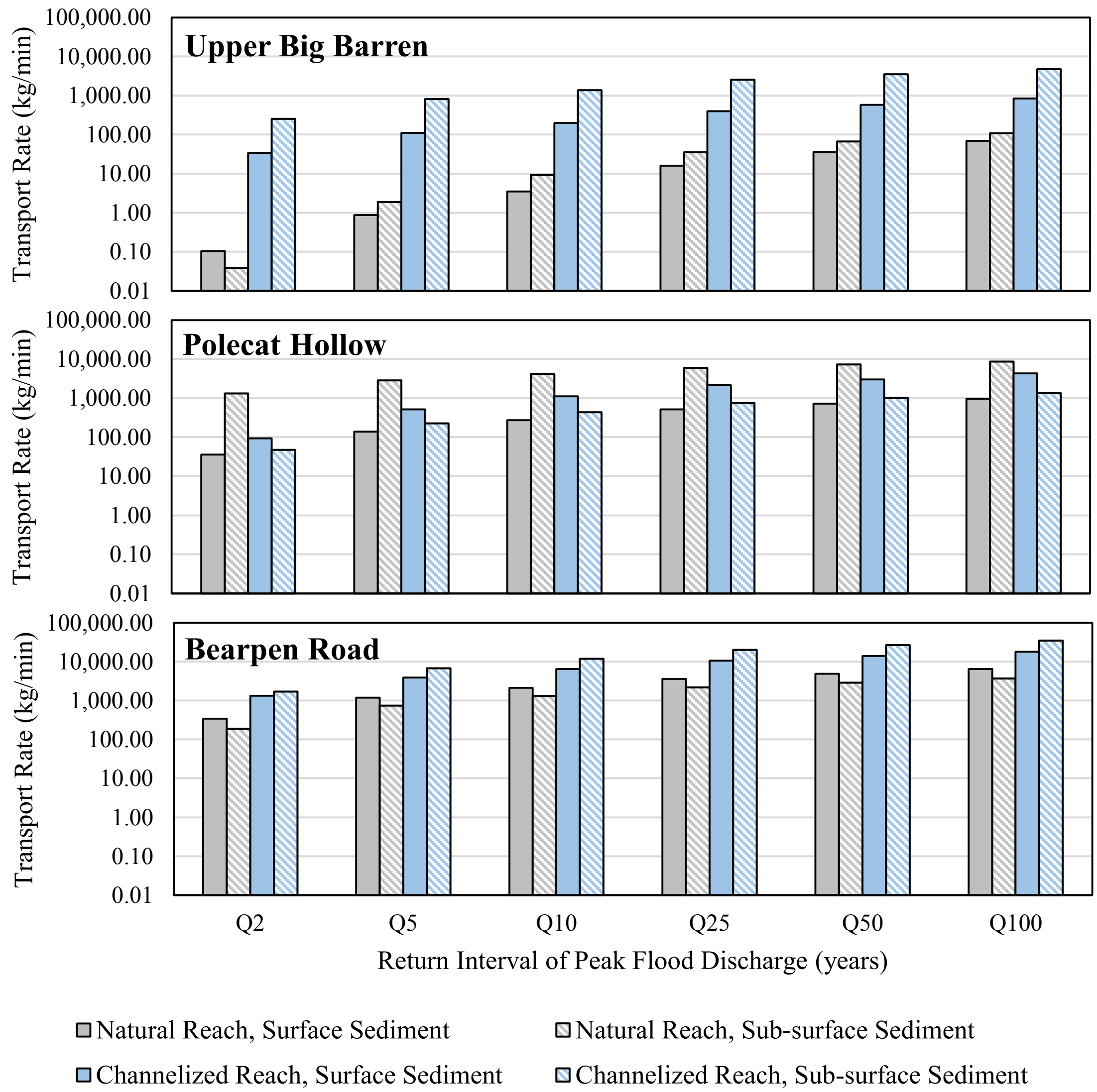

Figure 20. Sediment transport capacity of natural and channelized model reaches.

transport about twice as much surface sediment as the natural reaches. However, the PH natural reach can transport up to 27 times more sub-surface sediment than the channelized reach. This can be attributed to the fine-grained sediment pulse that covers the channel bed and increases bed mobility (Rinaldi et al., 2005).

While the BAGS model output shows that there are large relative differences between the sediment transport capacity of natural and channelized segments of Big Barren Creek, further validation may be required to determine the absolute differences in sediment transport capacity between the model reaches. Actual sediment transport rates are dependent on the available sediment supply, flow discharge, and the boundary conditions of the channel bed that dissipate flow energy (Wilcock et al., 2009). Further work to characterize these influences could refine the model results.

Transport Stage. The transport stage is the ratio of the available shear stress in the channel to the critical shear stress that is required to initiate sediment transport (Pitlick et al., 2009). Sediment transport begins when the transport stage approaches one (Pitlick et al., 2009). Mixed-bedload and suspended load transport occurs when the transport stage exceeds three (Church, 2006). The transport stage-discharge relations for the model reaches have implications for bed mobility and the degree of excess shear stress that may cause incision and bed armoring (Figure 21; Appendix F) (Simon and Rinaldi, 2006; Frings et al., 2009). The results show that the bedload at the UBB natural reach is far less mobile than the other model reaches. A 10-year flood event would be required to mobilize the surface sediment, and a 5-year flood event would be required to mobilize the sub-surface sediment. At all other sites, the surface and sub-surface sediment could be mobilized by a 2-year flood discharge. The transport stage is

consistently greater in the channelized reaches of the UBB and BP model sites than in the respective natural reaches, indicating that there are greater amounts of excess shear stress in the channelized reaches. These findings support other studies that link abrupt changes in shears stress from channelization to channel incision (Simon and Rinaldi, 2006).

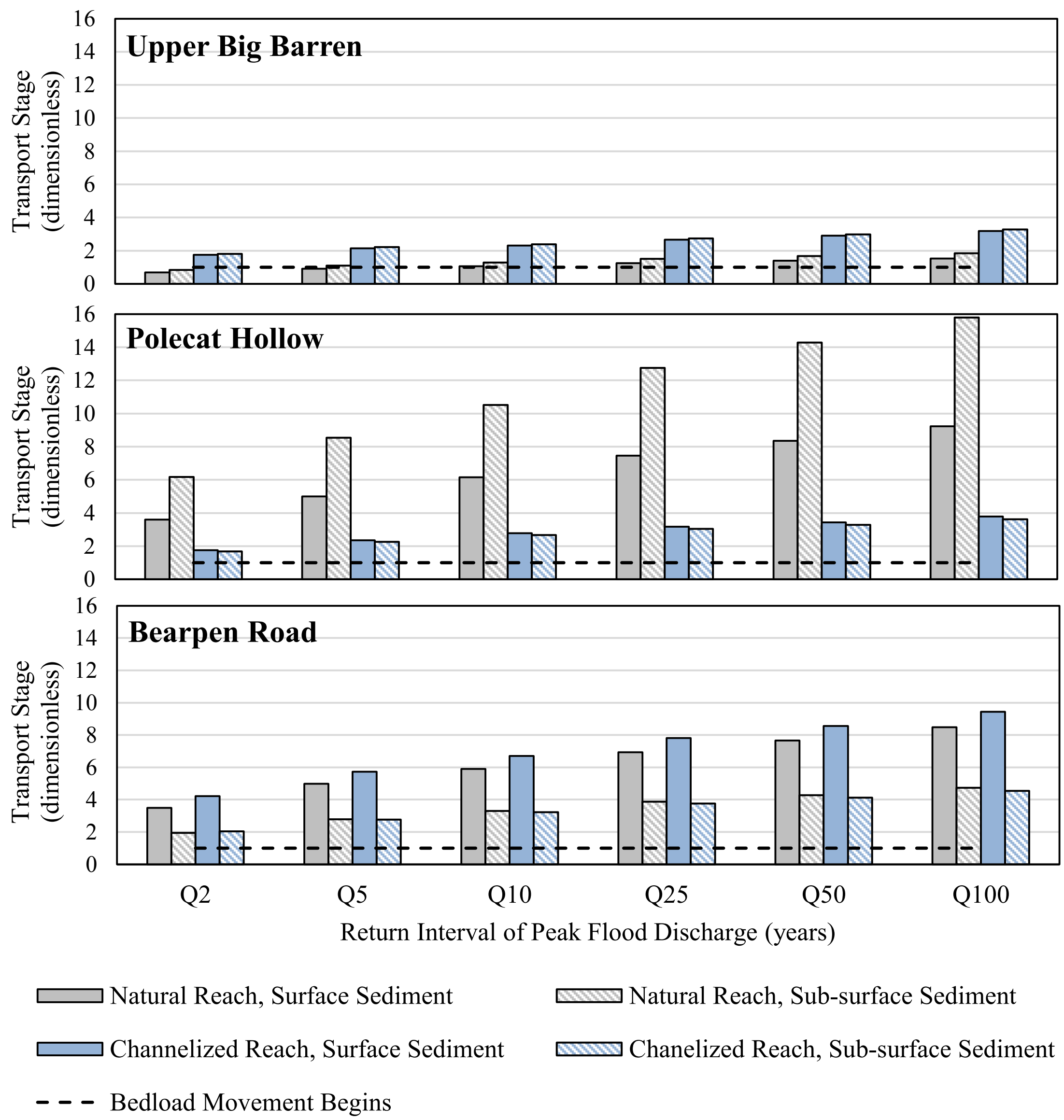

Figure 21. Sediment transport stage of natural and channelized model reaches.

The greatest differences in transport stage are found at the PH site, where the transport stage for the surface sediment in the natural reach is twice that of the channelized reach and the transport stage for the sub-surface sediment in the natural reach is four times greater than that of the channelized reach. Typically, high shear stress ratios are found in streams with a high fine-grained sediment supply that aggrades on the channel bed (Pfeiffer et al., 2017). Because critical shear stress decreases with grain size, the high surface and sub-surface sediment transport stages can be attributed to the fine-grained sediment pulse that covers the channel bed at the PH natural reach.

BAGS Model Accuracy and Limitations. While the BAGS model provides important estimates of sediment transport capacity and shear stress, there are limitations to bedload transport modeling that must be considered when evaluating the model output (Wilcock et al., 2009). Due to the non-linear nature of sediment transport equations, small inaccuracies in the input data can cause exponential overestimates of sediment transport rates and shear stress (Pitlick et al., 2009). Generally, bedload transport equations overestimate transport rates when compared to empirical bedload transport rates (Haschenburger, 2013; Vázquez-Tarrío and Menéndez-Duarte, 2015). In forested environments, bedload transport equations often overestimate transport rates by an order of magnitude (Hassan et al., 2005). Bedload transport rates can be overestimated if there is not a constant sediment supply, if there is spatial heterogeneity in the grain size distribution of the bed material, or if obstacles are present that dissipate flow energy and promote sediment deposition (Haschenburger, 2013; Vázquez-Tarrío and Menéndez-Duarte, 2015).

A major assumption of the BAGS model is that the entire channel bed is occupied by active sediment that is available for transport (Pitlick et al., 2009). However, bed mobility is limited by boundary conditions, including vegetation and overlying sediment. The bed surface sediment must be mobilized by high flows in order for significant sub-surface sediment transport to occur (Wilcock et al., 2009). Thus, sub-surface sediment transport is limited by bed surface sediment mobility. Additionally, vegetation, trees, and large woody debris stabilize the active channel bed of the natural reaches and can restrict sediment movement (Hassan et al., 2005). During dry periods, vegetation can increase the critical shear stress of the bed material, reducing sediment mobility (Wilcock et al., 2009). At the BP natural reach, cohesive, non-mobile soil makes up 30% of the channel bed, which limits the amount of available sediment for transport. In the natural model sites, trees cover between 0.15 and 0.60% of the total area of the active channel bed. While these percentages are low, small amounts of vegetation can offer significant flow obstruction in natural stream channels (Gregory, 2006). In contrast, the channelized reaches that were modeled are made up of loose, unconsolidated sediment that is not stabilized by tree roots and woody vegetation. As a result, the channelized reaches have a greater active width with more available sediment for transport than the natural reaches. Correcting the model results to include these effects would lead to even greater relative differences in sediment transport capacity and excess shear stress between natural and channelized reaches of Big Barren Creek.

Model accuracy can be improved when empirical bedload transport rates are available to calibrate sediment transport equations (Wilcock, 2001; Vázquez-Tarrío and Menéndez-Duarte, 2015; Schneider et al., 2015). If empirical bedload measurements are

unavailable to calibrate the BAGS model, the model developers suggest that the maximum transport rate per unit width should not exceed 10 kg/m/s, and is typically between 0.01 and 0.1 kg/m/s in stable gravel-bed streams (Mueller et al., 2005; Pitlick et al., 2009). Assuming an average particle density of 2.3 g/cm^3, a unit-width transport rate of 0.1 kg/m/s would move about 43 cm^3 of sediment over a 1-meter width of the channel bed in one second; enough sediment to hold in one's hands. The unit-width transport rates (kg/min/s) were calculated at the maximum discharge that is contained in each model reach by dividing the transport rate (in kg/s) by the top width of the channel at the respective discharge (Appendix F). At each model site, the unit-width transport rate is below 10 kg/m/s, but the transport rates become less accurate with increasing discharge. These results could be refined by adjusting the hydraulic roughness coefficient in the BAGS model for different discharge values. For this project, a reach-averaged hydraulic roughness coefficient was estimated at the bankfull stage for each model site. However, hydraulic roughness can change with increasing discharge, and high-discharge flows often interact with vegetated surfaces that increase flow resistance (Ferguson, 2010). Accounting for varying hydraulic roughness at different discharge values could result in more accurate BAGS modeling results.

BAGS Model Summary. The BAGS model was used to compare differences in sediment transport capacity and shear stress properties between pairs of natural and channelized reaches of Big Barren Creek. Results indicate that channelized segments of Big Barren Creek have a greater sediment transport capacity and greater amounts of excess shear stress than nearby natural reaches. The Polecat Hollow natural reach has greater bed mobility than the Upper Big Barren and Bearpen Road natural reaches due to

the sand and fine-gravel that blanket the channel bed. Overall, the modeling results support the hypothesis that channelization alters sediment transport capacity and shear stress properties that cause channel instability, which is manifested through incision at headcuts. The sediment that enters the drainage network from incision, in addition to winnowed bed material from channelized reaches, aggrades in downstream segments of Big Barren Creek that have a natural channel morphology. As shown at the Polecat Hollow natural reach, this sediment is highly mobile and can be transported downstream during high flows. Correcting the modeling results for the influence of vegetation and active sediment supply on transport rates would likely lower the sediment transport capacity of natural reaches, further reinforcing the findings that channelization alters sediment transport capacity and shear stress properties that can lead to instability.

Land Management and Channel Instability in Big Barren Creek

Landowners in the Big Barren Creek watershed have observed disturbance-induced incision and sediment aggradation that is often perceived to be linked to upland erosion from prescribed burning. However, results of this study indicate another cause of channel instability. A geomorphic assessment of the upper 20 kilometers of Big Barren Creek has shown that sediment aggradation occurs below channelized reaches that have been modified for flood control. This sediment is generated from upstream incision at headcuts and bed winnowing by selective transport in channelized reaches. Similar effects have been observed in streams where channel geometry and bed resistance are altered from channelization (Simon and Rinaldi, 2006).

Incision and sediment aggradation play a critical role in the natural response to channelization (Chin et al., 2014). Larger channel dimensions are capable of conveying deeper flows, which increases the available shear stress in the channel (Chin et al., 2014). Excess shear stress causes incision, which increases the sediment supply in the channel (Chin et al., 2014). This sediment is transported and deposited to reshape the channel morphology, gradually reducing the effects of incision (Chin et al., 2014). In the Big Barren Creek watershed, some landowners respond to channel instability by removing gravel that accumulates in channelized reaches. While gravel mining prevents overbank flooding by maintaining large channel dimensions, it may prolong channel instability because it removes sediment from the fluvial system that would aid in the natural recovery from channelization (Figure 22) (Kondolf, 1997; Surian and Rinaldi, 2003).

Direct channel modification has upstream and downstream effects that extend beyond the modified channel segment (Gregory, 2006). Channelization can cause upstream incision by headcut migration, downstream sediment aggradation, and increased flood intensity in downstream reaches that are not channelized (Bravard et al., 1999). Therefore, the land management practices of one stakeholder may have negative consequences for other stakeholders in a watershed. Understanding of the effects of land management in a watershed context is an important first step in developing strategies to reduce stream channel instability (Wohl et al., 2015; Gregory, 2006).

In addition to understanding the physical processes that regulate stream channel stability, understanding the local perspective of streams and the history of land use can assist in setting realistic goals for stream restoration projects (Wohl et al., 2015). Channelization and gravel mining have been used in the Ozarks for the past century, and

will probably continue to be used to manage streams for flood control (Jacobson and Primm, 1997). Furthermore, restoration projects should also consider the future effects of climate change on stream channel instability (Wohl et al., 2015). Changing rainfall patterns in the Ozarks over the past decade may be accelerating stream channel instability in the Big Barren Creek watershed (Pavlowsky et al., 2016). This trend is expected to continue as climate patterns change in the Midwest (Mallakpour and Villarini, 2015).

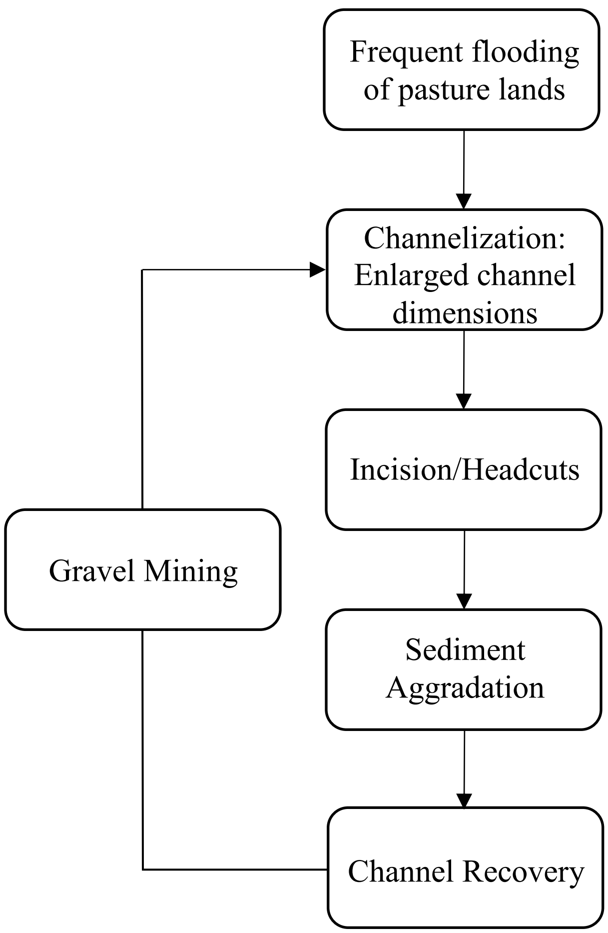

Figure 22. Natural adjustment of streams to channelization through incision and sediment aggradation. Gravel mining can prolong incision by maintaining large channel dimensions that are normally reduced by sediment aggradation.

The natural recovery from instability may take decades as streams adjust to change through incision and sediment aggradation (Chin et al., 2014). Grade-control structures and floodplain reconnection can also be used to remediate the effects of channel instability, but these methods are costly and can be ineffective if the amount of incision is irreversible (Bravard et al., 1999). Simpler approaches like limiting gravel mining activity or lowering the height of agricultural levees could be more resilient to increased flooding as the climate changes, and help promote the natural recovery of unstable reaches of Big Barren Creek.

CHAPTER 5—CONCLUSIONS

The purpose of this project was to evaluate the downstream trends in channel morphology and substrate of Big Barren Creek, and evaluate channelization as a driver of channel instability. Channelization can cause abrupt changes in channel geometry and bed resistance that alter sediment transport processes and shear stress, causing incision and selective transport of bed material (Simon and Rinaldi, 2006). A geomorphic assessment was conducted to characterize the downstream trends in channel morphology and sediment of the upper half of Big Barren Creek and identify locations of instability. Additional geomorphic analysis and sediment transport modeling were used to compare differences in channel geometry, hydrology, hydraulics, sediment transport capacity, and shear stress between three pairs of natural and channelized reaches of Big Barren Creek.

The following three key findings support the hypothesis that channelization may be linked to channel instability on Big Barren Creek:

1. A reoccurring sequence of incision and sediment aggradation was observed on the upper half of Big Barren Creek. Incised reaches were found upstream of channelized reaches and aggraded reaches were found downstream of channelized reaches. Incised, channelized, and aggraded reaches have different channel dimensions and substrate properties than natural reaches that not been channelized. Similarly, other studies have shown that channelization can alter the hydraulics and hydrology of modified streams, causing upstream incision through headcuts that delivers sediment downstream (Simon and Rinaldi, 2006; Surian and Rinaldi, 2003; Ortega et al., 2014; Rinaldi et al., 2005; Martín-Vide et al., 2010; Landemaine et al., 2015; Rhoads, 1990).

2. Channelized reaches have different channel morphology, sediment, and hydraulic properties than natural reaches of Big Barren Creek. These differences in channel geometry and boundary conditions can cause an imbalance between the sediment supply and transport capacity in channelized reaches that can lead to incision (Simon and Rinaldi, 2006). Three pairs of natural and channelized reaches of Big Barren Creek were selected for additional geomorphic analysis of channel geometry, vegetation, surface sediment, and sub-surface sediment. It was found that channelized reaches are deeper than nearby natural reaches, and can convey greater flood discharges as a result.

Additionally, channelized reaches have coarser beds than natural reaches, suggesting that the channelized reaches have a greater sediment transport capacity than natural reaches that results in bed armoring from the winnowing of fine-grained sediment. Vegetation and tree roots stabilize the active channel bed of natural reaches in Big Barren Creek, forming a resistant horizon that is not present in channelized reaches. Because instream wood and vegetation regulate channel stability by increasing hydraulic roughness, dissipating flood energy, and acting as a site for sediment deposition, the integrity of the natural vegetated bed should be preserved during any future channel management practices (McKenney et al., 1995; Keeton et al., 2017).

3. Sediment transport modeling shows that sediment transport capacity and shear stress properties differ between natural and channelized reaches of Big Barren Creek. At the UBB and BP model reaches, the ratio of available shear stress to the critical shear stress of the channel bed is consistently greater in channelized reaches than natural reaches. The opposite was found at the PH model reach, where a fine-grained sediment pulse has covered the channel bed of the natural reach. These differences translate to differences in the amount of sediment that can be transported by a reach. At all model sites, the channelized reaches have a greater surface sediment transport capacity that the natural reaches, with the greatest differences occurring at low flows. The sub-surface sediment at each model reach has a similar transport capacity, with the exception of the fine-grained sediment pulse at the PH model reach. During large flood events (RI > 2 years), the channelized reach at the UBB model site can transport up to 100 times more sediment than the natural reach. The channelized reaches the PH and BP model sites can transport between 2 and 4 times more sediment than their respective natural reaches. While the model results are currently uncalibrated, they agree with field observations and show that there are large relative differences in available transporting power between natural and channelized reaches, which could drive channel incision and sediment aggradation during large floods in the Big Barren Creek watershed.

These findings have implications for land management and channel instability in Big Barren Creek. In a broader context, the findings of this project identify channelization-induced incision as a sediment source to watersheds in the Ozarks. Future work could significantly improve the accuracy of the BAGS modeling by using empirical sediment transport rates to calibrate modeling results (Wilcock, 2001; Pitlick et al., 2009). Further, better discharge records could help to better refine the timing of flood frequency that initiates bedload transport in the Big Barren Creek watershed. Continued monitoring of channel morphology and substrate is necessary to evaluate the any

management actions that are taken to reduce channel instability, as well as understand the response of Big Barren Creek to instability.

There is a repeating pattern of disturbance that is limited to channelized zones of Big Barren Creek. Channel instability can be managed by understanding the geomorphic response of stream channels to instability. Headcuts are typically found within 300 meters of channelized reaches, and sediment aggradation is limited to 1,000 meters downstream of channelized reaches that range in length from one to two kilometers. From field observations, it appears that tree roots and woody vegetation stabilize the natural channel bed and offer resistance to instability. Instream and riparian vegetation have been shown to assist in the recovery of other Ozark streams to instability (Jacobson and Pugh, 1998). Future land management practices and channel stability measures should aim to maintain natural bed characteristics by not disturbing the soil and vegetation in the active channel bed and riparian zone that promote channel stability.

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APPENDICES

Appendix A1—Base Manning's n selection guide (modified from Arcement and Schneider, 1989)

Bed Material	Median size of bed material (mm)	Base n value	
		Straight uniform channel	Smooth channel
Sand	0.2	0.012	-
Sand	0.3	0.017	-
Sand	0.4	0.020	-
Sand	0.5	0.022	-
Sand	0.6	0.023	-
Sand	0.8	0.025	-
Sand	1.0	0.026	-
Concrete	-	0.012 - 0.018	0.011
Rock cut	-	-	0.025
Firm soil	-	0.025 - 0.032	0.020
Coarse sand	1.0 - 2.0	0.026 - 0.035	-
Fine gravel	-	-	0.024
Gravel	2.0 - 64	0.028 - 0.035	-
Coarse gravel	-	-	0.026
Cobble	64 - 256	0.030 - 0.050	-
Boulder	> 256	0.040 - 0.070	-

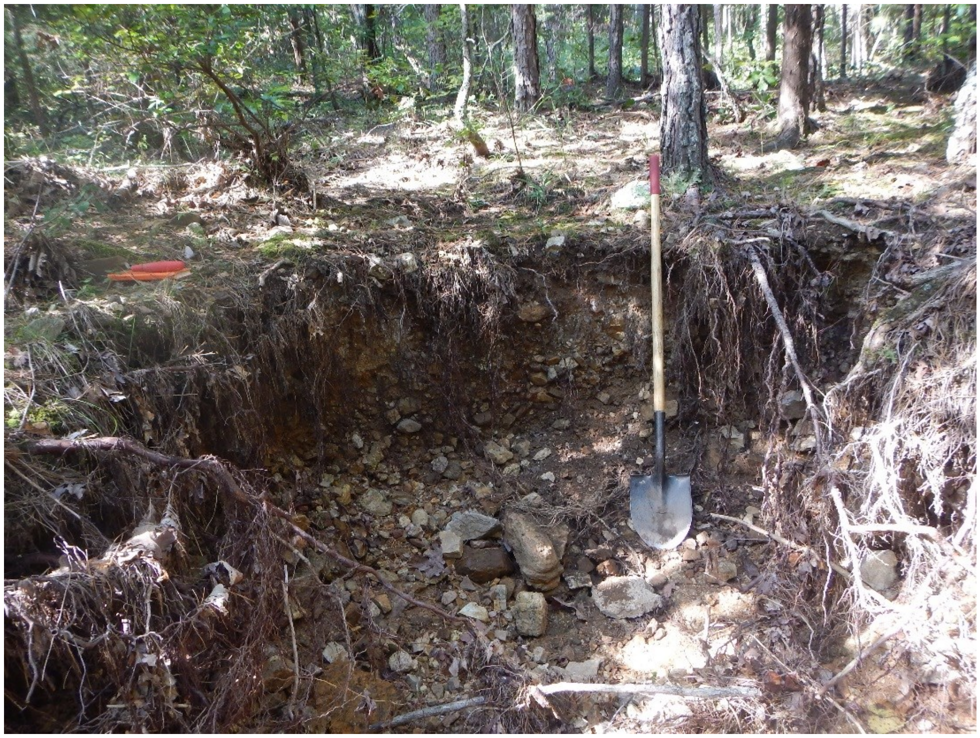
Appendix A-2—Manning's n adjustment factor selection guide (modified from Arcement and Schneider, 1989)

Channel conditions		n value adjustment	Example
Degree of irregularity (n1)	Smooth	0.000	The smoothest channel attainable in a given bed material.
	Minor	0.001-0.005	Carefully dredged channels in good condition but having slightly eroded or scoured side slopes.
	Moderate	0.006-0.010	Dredged channels having moderate to considerable bed roughness and moderate sloughed or eroded side slopes.
	Severe	0.011-0.020	Badly sloughed or scalloped banks; unshaped, jagged, and irregular surfaces.
Variation in channel cross section (n2)	Gradual	0.000	Size and shape of channel cross sections change gradually.
	Alternating occasionally	0.001-0.005	Large and small cross sections alternate occasionally, or the main flow occasionally shifts from side to side.
	Alternating frequently	0.010-0.015	Large and small cross sections alternate frequently, or the main flow frequently shifts from side to side.
Effect of obstruction (n3)	Negligible	0.000-0.004	A few scattered obstructions, including debris deposits, stumps, roots, logs, or boulders, occupy less than 5% of the cross-sectional flow area.
	Minor	0.005-0.015	Obstructions occupy less than 15% of the cross-sectional flow area.
	Appreciable	0.020-0.030	Obstructions occupy between 15 and 50% of the cross-sectional flow area.
	Severe	0.040-0.050	Obstructions occupy more than 50% of the cross-sectional flow area.

Appendix A-2, continued

Channel conditions		n value adjustment	Example
Amount of vegetation (n4)	Small	0.002-0.010	Average flow depth is at least three times the height of the vegetation on the channel bed.
	Medium	0.010-0.025	Average flow depth is two to three times the height of the vegetation on the channel bed.
	Large	0.025-0.050	Average flow depth is about equal to the height of the vegetation on the channel bed.
	Very Large	0.050-0.100	Average flow depth is less than half of the height of vegetation on the channel bed.
Degree of meandering (m)	Minor	1.00	Channel sinuosity between 1.0 and 1.2.
	Appreciable	1.15	Channel sinuosity between 1.2 and 1.5.
	Severe	1.30	Channel sinuosity greater than 1.5.

Appendix B-1—Photo Log of Select Geomorphic Assessment Sites



Site 3: Upper Big Barren headcut, R-km 37.60 (September 2016)

Site 8: Bank erosion at a channelized reach, R-km 35.13 (March 2016)

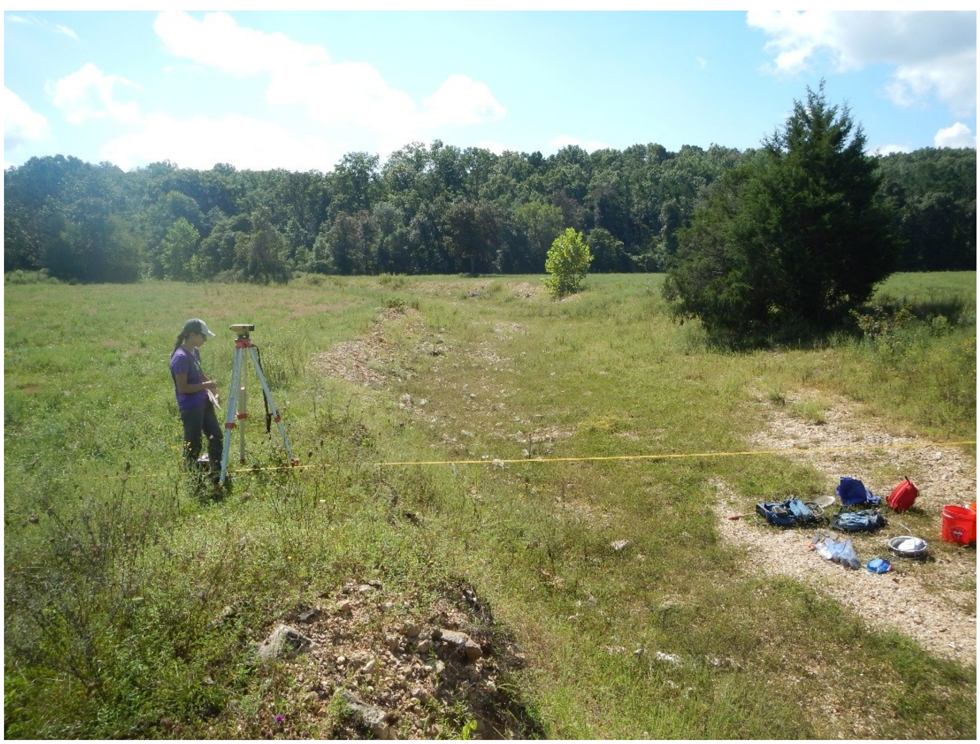
Appendix B-1, Continued

Site 15: Sand aggradation downstream of a channelized reach, R-km 29.67 (March 2016)

Site 20: Bearpen Road headcut, R-km 24.82 (March 2016)

Appendix B-2—Photo Log of Sediment Transport Modeling Sites

Site 2: Upper Big Barren Model Site, Natural Reach (September 2016)



Site 4: Upper Big Barren Model Site, Channelized Reach (September 2016)

Appendix B-2, Continued

Site 11: Polecat Hollow Model Site, Natural Reach (March 2016)

Site 13: Polecat Hollow Model Site, Channelized Reach (March 2016)

Appendix B-2, Continued

Site 19: Bearpen Road Model Site, Natural Reach (March 2016)

Site 21: Bearpen Road Model Site, Channelized Reach (September 2016)

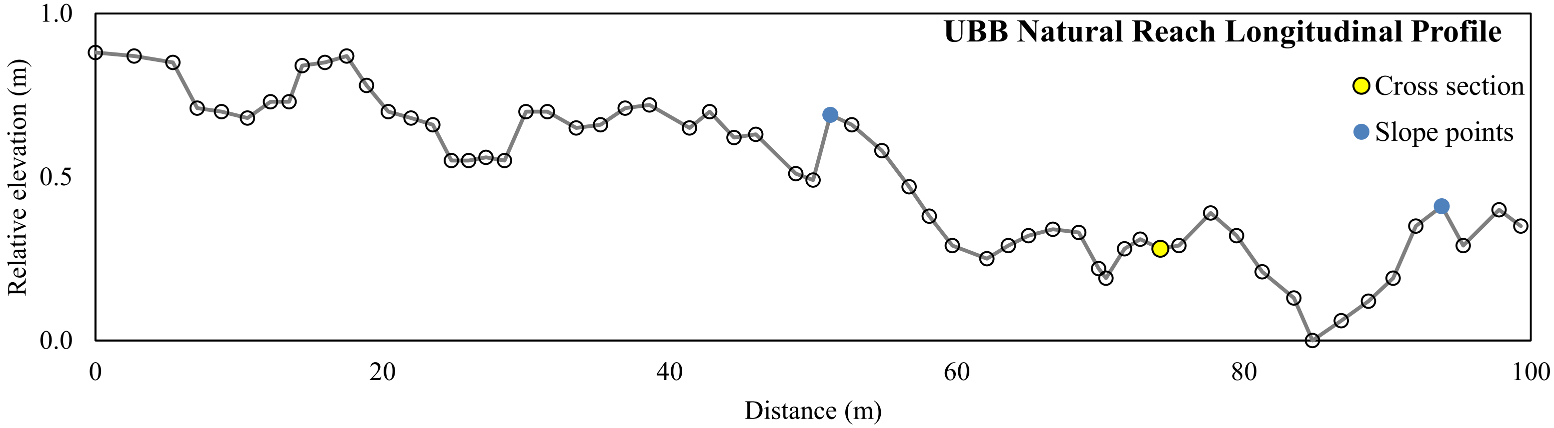
Appendix C—Big Barren Creek Channel Assessment Site Data

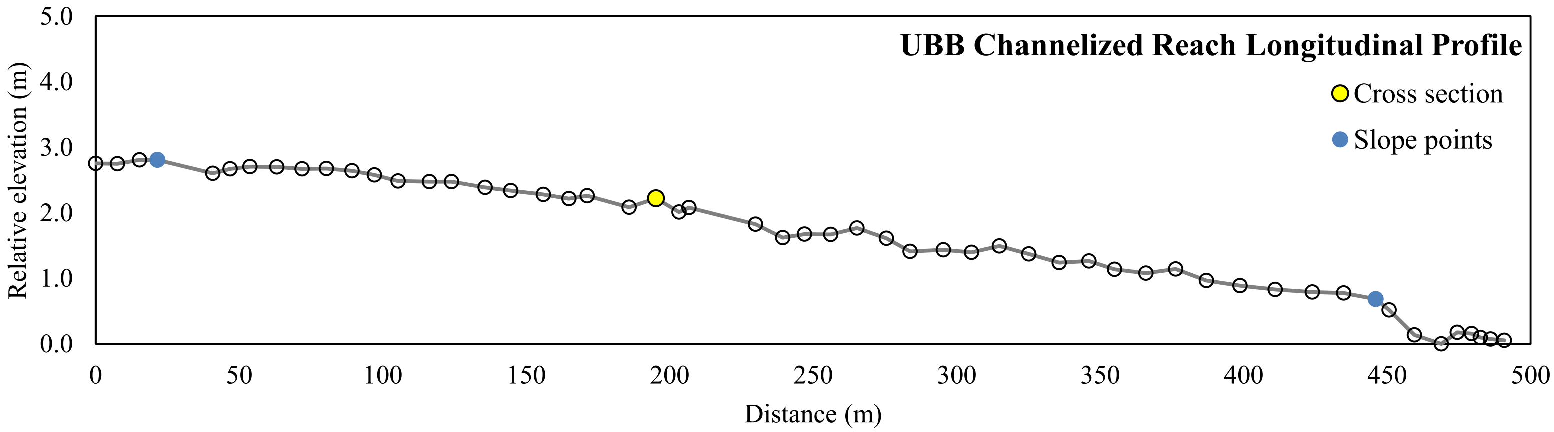
Site	Classification	R-km	Ad (km^2)	LWD vol (m^3)	CSA[1] (m^2)	Width[1] (m)	Max depth[1] (m)	Mean depth[1] (m)	Width-depth ratio	D50 (mm)	Dmax (mm)	Slope (%)
1	Natural	39.20	1.6	0.5	7.7	38.7	0.7	0.2	195.2	16	170	0.92
2*	Natural	37.87	2.5	0.0	6.6	15.0	0.8	0.4	34.2	22.6	150	0.67
3	Incised	37.60	3.7	0.0	10.1	8.6	1.9	1.2	7.4	22.6	295	1.24
4*	Channelized	37.30	3.9	0.0	12.9	14.3	1.4	0.9	15.8	16.9	200	0.50
5	Aggraded	36.80	8.4	0.6	4.7	14.5	0.9	0.3	45.0	5.6	170	0.63
6	Aggraded	36.70	8.8	0.4	6.5	9.9	1.0	0.7	15.1	5.6	170	N/A
7	Channelized	36.44	8.9	0.0	8.4	29.2	0.7	0.3	102.4	0.063	N/A	0.13
8	Channelized	35.13	19.0	1.1	16.5	16.7	1.6	1.0	16.9	22.6	350	0.19
9	Channelized	34.28	22.7	0.0	13.2	18.6	1.6	0.7	26.2	22.6	250	N/A
10	Natural	33.75	23.1	0.1	9.7	17.7	1.3	0.5	32.3	2	450	0.61
11*	Aggraded	32.82	23.8	0.0	14.8	25.5	1.4	0.6	44.0	0.063	100	0.28
12	Channelized	32.47	25.4	0.0	17.6	25.0	1.7	0.7	35.4	32	320	0.48
13*	Channelized	31.85	32.2	0.0	76.5	56.2	2.4	1.4	41.3	36.9	250	0.45
14	Channelized	31.05	41.4	0.0	45.1	22.1	2.7	2.0	10.8	32	310	0.28
15	Aggraded	29.67	42.3	1.8	22.1	18.5	1.9	1.2	15.5	45	300	0.45
16	Natural	28.80	43.8	0.0	25.7	34.8	1.6	0.7	47.1	N/A	N/A	N/A
17	Natural	27.70	44.5	0.4	32.4	41.0	2.0	0.8	51.8	16	150	0.34
18	Natural	25.77	48.0	0.0	28.9	37.1	1.5	0.8	47.8	32	300	0.12
19*	Natural	24.95	51.8	0.5	19.4	33.0	0.9	0.6	56.0	7.8	180	0.38
20	Incised	24.82	51.8	0.0	25.6	20.7	2.1	1.2	16.8	32	210	0.38
21*	Channelized	24.35	52.6	0.0	68.1	31.7	3.1	2.1	14.8	18.9	200	0.41
22	Natural	22.30	85.0	0.1	27.1	21.4	1.8	1.3	16.9	22.6	450	0.54
23	Natural	21.05	97.7	0.1	23.4	37.2	1.2	0.6	59.2	22.6	600	0.70

[1]Dimensions at the estimated bankfull stage in natural aggraded sites, and at the highest stage in incised and channelized sites

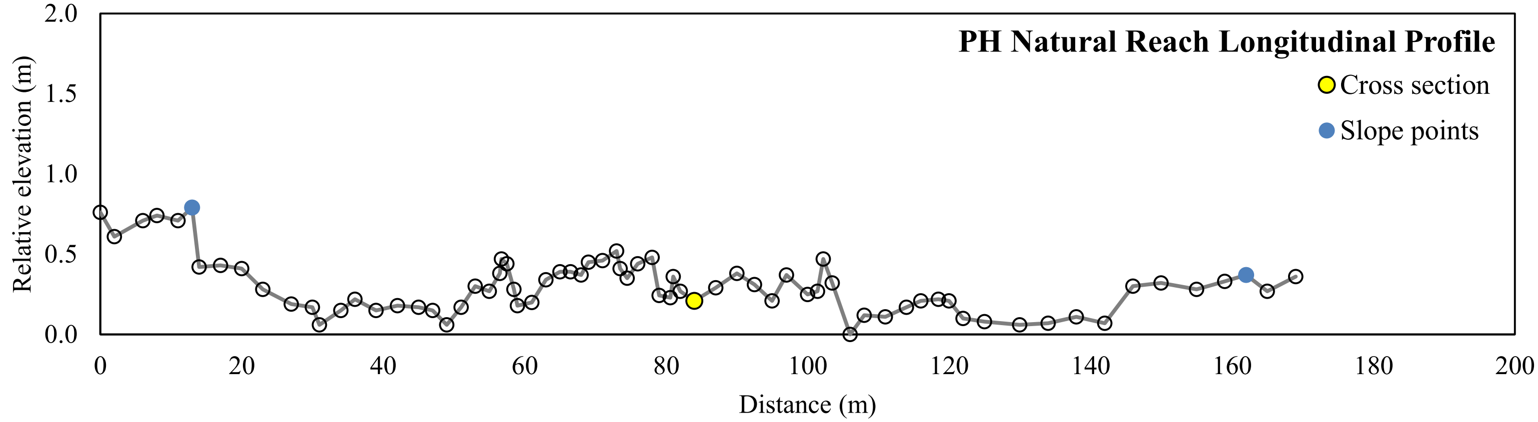
*Sediment transport modeling site

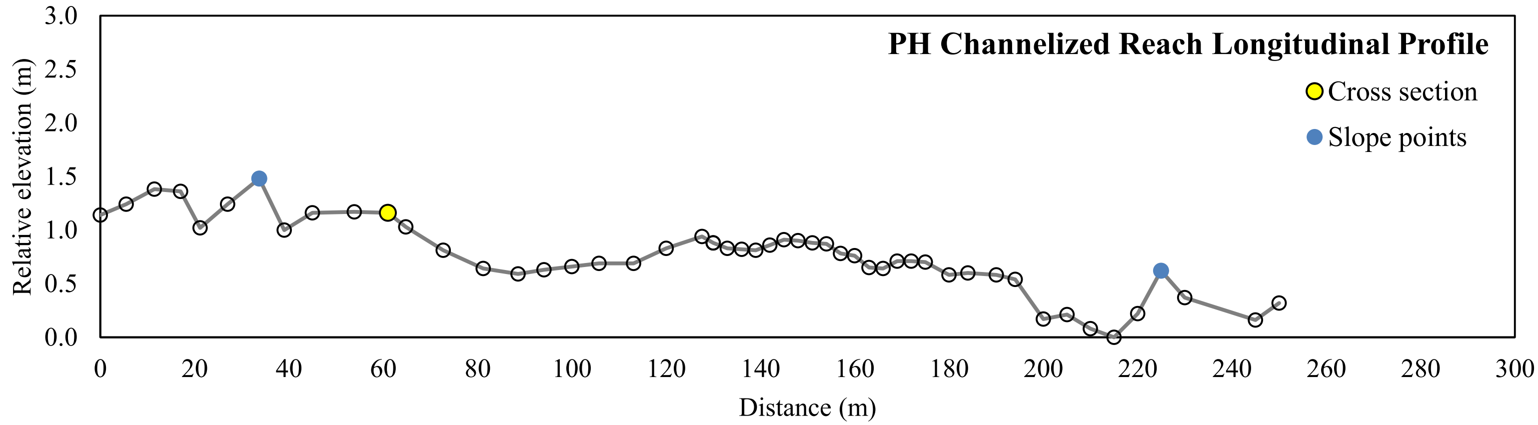
Appendix D—Model Site Longitudinal Profiles



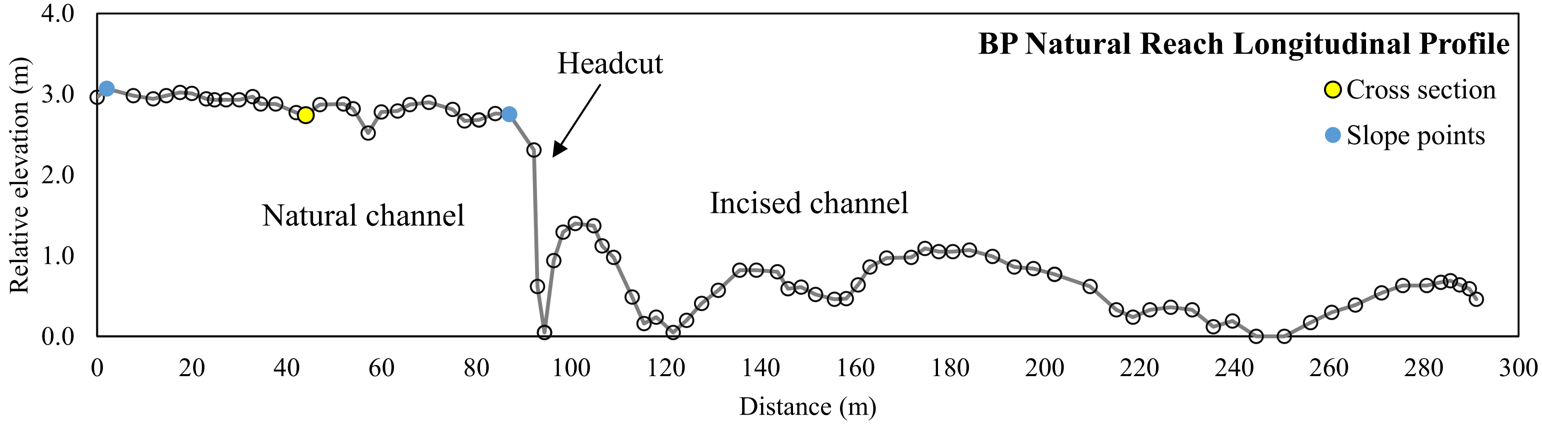


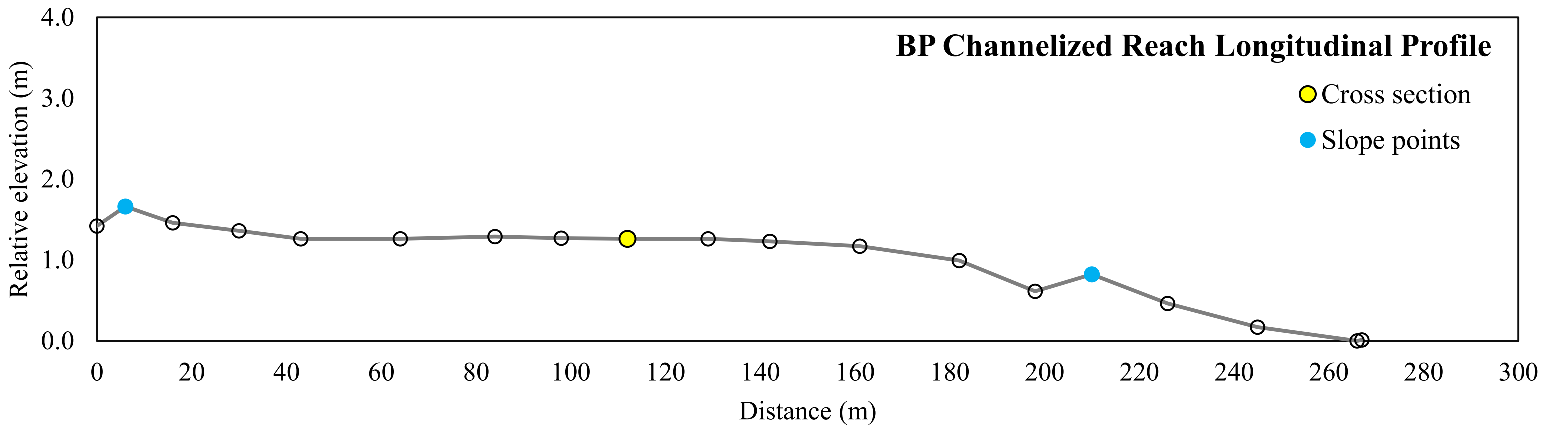
Appendix D, Continued





Appendix D, Continued





Appendix E—BAGS Model Input Data

Upper Big Barren: Natural Reach BAGS Model Input Data

Cross Section		Surface sediment		Sub-surface sediment	
Lateral distance (m)	Elevation (m)	Grain size (mm)	% Finer	Grain size (mm)	% Finer
0.0	1.15	2	3.3	0.0019	0.1
1.3	1.16	4	6.7	0.0039	0.2
2.5	0.90	11	20.0	0.0078	0.3
3.3	0.78	16	30.0	0.0156	0.4
4.4	0.49	22.6	50.0	0.0311	0.4
5.1	0.39	32	73.3	0.125	1.3
6.5	0.37	45	90.0	0.25	6.7
8.0	0.36	64	93.3	0.5	14.4
9.2	0.28	90	100.0	1	20.1
10.7	0.28			2	28.8
12.2	0.33	Slope (m/m)	0.0067	4	40.2
12.6	0.24	n	0.065	8	53.1
13.2	0.15	Min Q (cms)	1.2	16	67.1
13.7	0.16	Max Q (cms)	28.9	25.4	85.5
14.1	0.04			45	100.0
14.3	0.00				
15.0	0.04				
15.4	0.06				
17.5	0.50				
18.7	0.86				
20.0	1.64				

Appendix E, Continued

Upper Big Barren: Channelized Reach BAGS Model Input Data

Cross Section		Surface sediment		Sub-surface sediment	
Lateral distance (m)	Elevation (m)	Grain size (mm)	% Finer	Grain size (mm)	% Finer
0.0	1.08	0.063	1.1	0.125	0.7
0.8	1.18	2	2.3	0.25	6.9
2.0	1.45	2.8	3.4	0.5	14.2
3.2	0.42	4	4.5	1	20.9
4.1	0.01	5.6	10.1	2	30.4
5.0	0.00	8	16.9	4	43.1
6.0	0.09	11	30.3	8	56.1
7.0	0.16	16	49.5	16	69.8
8.0	0.17	22.6	62.9	25.4	85.8
9.0	0.24	32	74.2	45	93.1
10.0	0.23	45	86.6	63	100.0
11.8	0.38	64	100		
13.0	0.82				
14.2	1.17	Slope (m/m)	0.0050		
16.0	1.33	n	0.040		
17.6	1.71	Min Q (cms)	1.6		
18.4	1.63	Max Q (cms)	39.3		

Appendix E, Continued

Polecat Hollow: Natural Reach BAGS Model Input Data

Cross Section		Surface sediment		Sub-surface sediment	
Lateral distance (m)	Elevation (m)	Grain size (mm)	% Finer	Grain size (mm)	% Finer
0	1.83	0.063	63.3	0.00049	1.0
3	1.68	2	66.7	0.00098	1.9
4	1.58	4	70.0	0.0019	3.9
5.5	1.39	5.6	76.7	0.0039	6.1
6.6	1.15	8	90.0	0.0078	8.6
8.3	1.03	11	93.3	0.0156	11.4
9.7	0.64	16	100.0	0.0311	13.0
10.6	0.49			0.0625	13.7
11.4	0.34	Slope (m/m)	0.0028	0.125	22.2
12.4	0.25	n	0.063	0.25	42.0
13.2	0.16	Min Q (cms)	5.7	0.5	53.6
14	0.25	Max Q (cms)	146.421	1	60.4
14.6	0.38			2	66.2
15.5	0.44			4	74.6
16.3	0.55			8	80.5
17.3	0.47			16	84.2
18.6	0.53			25.4	89.8
20.0	0.47			45	96.3
20.2	0.32			63	99.9
21.0	0.65				
22.6	0.55				
24.0	0.47				
26.6	0.56				
27.7	0.38				
28.9	0.33				
30.0	0.47				
31.7	0.68				
33.3	1.13				
34.8	1.47				
36.4	1.91				

Appendix E, Continued

Polecat Hollow: Channelized Reach BAGS Model Input Data

Cross Section		Surface sediment		Sub-surface sediment	
Lateral distance (m)	Elevation (m)	Grain size (mm)	% Finer	Grain size (mm)	% Finer
0.0	3.36	0.063	6.9	0.0019	0.05
1.0	2.37	4	10.3	0.0039	0.09
3.0	2.37	8	13.8	0.0078	0.15
6.0	2.2	11	17.2	0.0156	0.19
11.0	1.71	32	41.4	0.0311	0.20
18.0	0.71	45	62.1	0.125	0.84
20.0	0.78	64	86.2	0.25	5.42
22.7	0.74	90	100	0.5	10.87
25.4	0.57			1	16.87
27.0	0.70	Slope (m/m)	0.0045	2	26.50
28.0	1.15	n	0.045	4	40.84
29.0	1.21	Min Q (cms)	7.1	8	59.09
30.3	1.09	Max Q (cms)	186.9	16	74.70
31.7	1.33			25.4	92.60
33.2	1.45			45	98.53
34.7	1.33			63	100
35.9	1.11				
36.9	0.89				
37.5	0.78				
38.5	0.32				
40.0	0.22				
42.1	0.08				
44.5	0.00				
46.0	0.02				
47.9	0.06				
49.5	0.17				
51.0	0.42				
52.0	0.36				
52.9	0.24				
54.1	0.57				
55.0	1.62				
57.0	2.32				
57.5	2.49				
58.0	2.74				
58.8	2.96				

Appendix E, Continued

Bearpen Road: Natural Reach BAGS Model Input Data

Cross Section		Surface sediment		Sub-surface sediment	
Lateral distance (m)	Elevation (m)	Grain size (mm)	% Finer	Grain size (mm)	% Finer
0.0	2.97	0.063	35.0	0.00049	0.7
2.3	2.47	4	40.0	0.00098	1.2
4.6	1.97	5.6	45.0	0.0019	2.1
6.9	1.47	11	55.0	0.0039	3.1
9.2	0.97	16	60.0	0.0078	4.0
11.5	0.47	22.6	70.0	0.0156	5.0
13.1	0.40	32	75.0	0.0311	5.6
13.8	0.26	45	80.0	0.0625	5.8
17.0	0.19	64	95.0	0.125	10.9
18.2	0.24	90	100.0	0.25	23.5
21.0	0.23			0.5	30.9
23.5	0.17	Slope (m/m)	0.0038	1	38.9
24.9	0.08	n	0.065	2	47.2
26.1	0.23	Min Q (cms)	9.6	4	56.8
27.0	0.29	Max Q (cms)	249.3	8	67.4
28.5	0.11			16	77.8
29.5	0.02			25.4	90.9
30.5	0.14			45	98.0
31.3	0.00			63	99.9
33.0	0.00				
34.5	0.33				
37.0	0.68				
38.5	0.77				
40.8	0.92				
43.8	0.99				
46.5	1.05				
48.5	0.98				
49.9	0.93				
51.5	1.06				
53.5	1.23				
55.5	1.32				
58.3	1.29				
59.5	1.29				
61.5	1.52				
64.5	2.71				
66.5	2.71				

Appendix E, Continued

Bearpen Road: Channelized Reach BAGS Model Input Data

Cross Section		Surface sediment		Sub-surface sediment	
Lateral distance (m)	Elevation (m)	Grain size (mm)	% Finer	Grain size (mm)	% Finer
0.0	3.12	0.063	3.4	0.125	0.6
1.0	2.92	4	10.3	0.25	5.3
3.0	2.10	5.6	20.7	0.5	12.7
4.2	1.80	8	24.1	1	21.2
6.0	1.10	11	31.0	2	30.9
9.0	0.00	16	41.4	4	40.7
12.0	0.15	22.6	62.1	8	49.1
14.0	0.31	32	79.3	16	58.3
16.0	0.28	45	89.7	25.4	71.4
18.0	0.36	64	96.6	45	80.9
21.0	0.38	90	100	63	85.0
24.0	0.40			170	100
25.0	0.24	Slope (m/m)	0.0041		
27.0	0.90	n	0.040		
29.0	1.56	Min Q (cms)	9.6		
31.7	2.84	Max Q (cms)	250.0		
32.7	3.45				

Appendix F-1—Sediment Transport Rate (kg/min) at Different Flood Return Intervals

	Upper Big Barren				Polecat Hollow				Bearpen Road			
	Natural		Channelized		Natural		Channelized		Natural		Channelized	
Return Interval	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface
Q2	0.1	3.8E-02	34.0	252.1	36.0	1314.6	93.2	47.3	343.3	185.8	1330.3	1693.4
Q5	0.9	1.9	111.4	809.4	138.7	2829.1	519.0	225.7	1191.6	735.1	3903.2	6650.6
Q10	3.5	9.2	199.3	1373.3	271.8	4132.5	1114.8	435.6	2111.4	1299.6	6478.2	11865.3
Q25	16.0	35.2	397.5	2527.3	512.4	5962.6	2132.9	752.7	3611.8	2153.9	10571.2	20119.5
Q50	36.2	66.4	581.3	3507.8	719.2	7288.4	3030.7	1007.4	4908.5	2843.9	13873.7	26748.0
Q100	69.6	107.9	837.0	4746.8	963.7	8691.7	4328.3	1336.0	6499.4	3638.3	17817.3	34579.4

Appendix F-2—Sediment Transport Stage (dimensionless) at Different Flood Return Intervals

	Upper Big Barren				Polecat Hollow				Bearpen Road			
	Natural		Channelized		Natural		Channelized		Natural		Channelized	
Return Interval	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface
Q2	0.7	0.8	1.7	1.8	3.6	6.2	1.8	1.7	3.5	2.0	4.2	2.0
Q5	0.9	1.1	2.1	2.2	5.0	8.5	2.4	2.3	5.0	2.8	5.7	2.8
Q10	1.1	1.3	2.3	2.4	6.1	10.5	2.8	2.7	5.9	3.3	6.7	3.2
Q25	1.2	1.5	2.7	2.7	7.5	12.7	3.2	3.0	6.9	3.9	7.8	3.8
Q50	1.4	1.7	2.9	3.0	8.4	14.3	3.4	3.3	7.7	4.3	8.6	4.1
Q100	1.5	1.8	3.2	3.3	9.2	15.8	3.8	3.6	8.5	4.7	9.4	4.5

Appendix F-3—Unit-width Transport Rates (kg/m/s) at Different Return Intervals

Model Site	Reach Classification	Return Interval[1]	Top Width (m)	Max Depth (m)	Surface sediment unit-width transport rate (kg/m/s)	Sub-surface sediment unit-width transport rate (kg/m/s)
Upper Big Barren	Natural	Q2	15.7	0.8	0.0001	3.99E-05
	Natural	Q5	17.3	1.1	0.001	0.002
	Channelized	Q2	10.5	0.9	0.05	0.40
	Channelized	Q5	12.1	1.2	0.15	1.11
	Channelized	Q10	14.3	1.4	0.23	1.60
Polecat Hollow	Natural	Q2	35.9	35.9	0.02	0.61
	Channelized	Q2	39.2	39.2	0.04	0.02
	Channelized	Q5	44.7	44.7	0.19	0.08
	Channelized	Q10	48.0	48.0	0.39	0.15
	Channelized	Q25	52.7	52.7	0.67	0.24
	Channelized	Q50	56.6	56.6	0.89	0.30
	Channelized	Q100	57.1	57.1	1.26	0.39
Bearpen Road	Natural	Q2	55.7	55.7	0.10	0.06
	Natural	Q5	58.8	58.8	0.34	0.21
	Natural	Q10	61.2	61.2	0.58	0.35
	Channelized	Q2	24.5	24.5	0.90	1.15
	Channelized	Q5	27.6	27.6	2.36	4.02
	Channelized	Q10	29.3	29.3	3.68	6.74
	Channelized	Q25	31.6	31.6	5.57	10.61

[1]The unit-width transport rate was only calculated at discharges that are contained by the channel dimensions