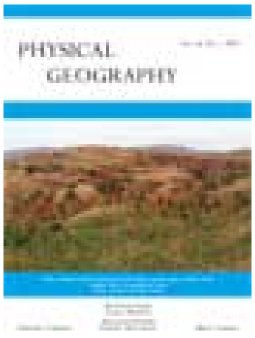

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SPATIAL PATTERNS OF CHANNEL INSTABILITY ALONG AN OZARK RIVER, SOUTHWEST MISSOURI

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Abstract: In the Ozark Highlands of Missouri, unstable river reaches that display rapid planform change are described as active reaches. While active reaches can be part of the natural morphodynamic regime, accelerated gravel bar deposition and bank erosion have been linked to historical and recent anthropogenic activities. Relationships between geomorphic controls and specific forms of channel instability are poorly understood in the Ozarks. The objectives of this research were to (1) develop an active reach classification scheme that provides an objective means of identifying and evaluating longitudinal patterns of instability in this and other Ozark rivers, (2) identify active reaches and different forms of instability along 80 km of the Finley River in southwest Missouri, and (3) investigate physical controls on active reaches. Historical aerial photographs and geographic information system (GIS) analysis showed that active reaches occur along 21% of the length of the main stem, preferentially in valleys with confinement ratios between 10 and 30 and near major tributary confluences. Four active reach forms were identified with proportion of length as follows: extension (8%), megabar (6%), cutoff (5%), and translation (2%). Depositional megabar-type active reaches tended to form directly downstream of erosional extension-type active reaches, probably due to excess gravel supply by reworking of historical floodplain deposits. The lack of a dominant active reach form, along with a stable main stem sinuosity over time, suggests that the Finley River is a semi-stable, self-organized system in balance with watershed inputs since at least 1955, the date of the earliest photo series.
[Key words: channel geomorphology, channel disturbance, channel classification, channel instability, megabar, aerial photography, Ozark Highlands.]

INTRODUCTION

River planform characteristics and change comprise an important subject of inquiry in the field of fluvial geomorphology (Leopold et al., 1964; Rosgen, 1996; Schumm, 2005). Analysis of the channel planform typically involves quantification and classification of the spatial organization of channel, bar, and floodplain features at the reach- or segment-scale (Frissell et al., 1986), typically using GIS-based

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aerial photography (Downward et al., 1994; Montgomery and Buffington, 1998; Montgomery and MacDonald, 2002). The channel planform can be dynamic and change over periods of years to decades by width adjustments, bar deposition, and bank erosion in response to variations in discharge and sediment load (Montgomery and MacDonald, 2002). If planform changes occur at a faster rate or in a different manner as compared to the natural or reference regime, they can be identified as channel disturbances (Jacobson, 1995). However, it is difficult to identify disturbance within the natural variability of planform change. Therefore, in the present study, reaches exhibiting such change are simply referred to as active or unstable reaches in contrast to "stable" reaches, which have exhibited little, if any, channel location change over the period of observation.

Active reaches have been widely studied, most notably involving meander migration (Nanson and Hickin, 1983; Lawler, 1993; Gilvear et al., 2000) and wandering river behavior (Church, 1983). Further, active reaches can behave differently in different physiographic settings (Schumm, 2005). For example Brice (1974) classified 16 different meander loop patterns occurring on stream reaches throughout the United States according to changes in arc length and bend radius. Attempts to quantify and characterize channel planform have often been successful, but limited to systems of specific alluvial and geologic conditions (Leopold and Wolman, 1957; Brice, 1974; Schumm, 1981; Harvey, 1989; Gurnell et al., 1994; Rosgen, 1996; Thorne et al., 1996; Alabyan and Chalov, 1998; Lancaster and Bras, 2002; Hooke, 2003; Richard et al., 2005; Kumar and Bhattacharya, 2006). In general, it is understood that channel response and reach-scale instability vary according to geological, valley-scale variables, such as bedrock control, valley confinement, and sediment characteristics (Montgomery and Buffington, 1998; Montgomery and MacDonald, 2002).

Channel instability can be linked to fluctuations of both local riparian and watershed conditions (Montgomery and MacDonald, 2002). Variations in watershed inputs of discharge, sediment, and large woody debris can initiate a geomorphic response that often results in changes in channel pattern, such as channel widening, narrowing, or migration (Montgomery and Buffington, 1998; Kondolf et al., 2003). Classification of such patterns provides the foundation for comparison among streams by imposing order on a continuum of natural stream types or morphologies (Montgomery and Buffington, 1998; Montgomery and MacDonald, 2002). Examples of classification systems for stable and unstable channels include the straight, meandering, and braided channels of Leopold and Wolman (1957), the sediment transport-based continuum by Schumm (1977), and the channel morphology, sinuosity and slope, and substrate classification by Rosgen (1996). However, it has been shown that form-based classification systems such as Rosgen's fail to consider the open-system nature of rivers and could result in ineffective mitigation when used for stream rehabilitation (Simon et al., 2007). Further, form-based approaches to geomorphic classification may ignore the history of channel development and the change trajectory, which is vital for understanding and managing river systems (Montgomery and MacDonald, 2002). Moreover, while most channel classification schemes intentionally impose a series of discrete forms to describe geomorphic variation, it is well understood that a continuum of channel patterns should exist, with each pattern associated with a particular combination of continuous variables (Leopold and Wolman, 1957).

The purpose of this study was to identify and understand the spatial distribution of active reaches in an Ozark river to better understand channel stability trends in Ozark watersheds. Streams in the Ozarks of Missouri and Arkansas have been classified as manifestly underfit by Dury (1964) because, typically, the wavelengths of Ozark streams are much smaller than those of the valleys, though there is speculation as to the cause of this condition (Shepherd et al., 2011). Streams are generally characterized by having a gravel or cobble bed and by banks composed of either sand and gravel or silt and clay (Jacobson, 2004). Valley-scale channel patterns normally exhibit long, straight, stable reaches, separated by shorter unstable, active reaches; active reaches are spaced at distances substantially greater than typical riffle/pool sequences (Jacobson and Gran, 1999). In the Ozark Highlands in Missouri and Arkansas, active reaches are located along a river where excessive erosion or deposition has taken place, often resulting in extreme changes in channel pattern (Jacobson, 1995). Rapid channel migration often forms large, rapidly aggrading, unvegetated gravel bars in active reaches. The sinuosity of Ozark rivers is typically low when measured over a kilometer or more (<1.1 km) due to the high frequency of straight, stable reaches (Jacobson, 1995). Although historical land clearing and agricultural disturbances in the late 1800s and early 1900s are reported to be responsible for the excess gravel supply and bar sedimentation in large tributaries and main stem valleys, no link has been found between land use history and the pattern of alternating stable and unstable reaches (Jacobson, 1995).

Excess gravel bar deposition has been perceived as a problem in many Ozark rivers throughout the historical period (Jacobson and Primm, 1994; Jacobson, 1995). Early explorers to the region described stable conditions with lush riparian vegetation, and rarely mentioned the existence of gravel bars. Now, long-time residents of the region describe greater magnitudes and recurrences of floods and describe gravel as filling in their “fishin hole” and “choking” the streams (Jacobson and Primm, 1994). Although Ozark streams deposited substantial quantities of gravel under pre-settlement conditions (Jacobson, 2004), researchers have determined that the post-settlement gravel sediment input has overwhelmed the transport capabilities of most Ozark streams and that rates of bank instability appear to be well beyond that of the expected natural variability (Jacobson and Primm, 1994; Jacobson, 1995; Jacobson and Pugh, 1997; Jacobson and Gran, 1999; Panfil and Jacobson, 2001). While it is difficult to identify human-induced channel instability as distinct from the natural variability of Ozark streams, areas of instability are quite distinguishable from areas of relative stability. In the Ozarks, channels exhibiting an actively changing planform are usually associated with severe bank erosion and deposition of large longitudinal, point, and center bars composed of relatively mobile fine gravel (Panfil and Jacobson, 2001). In some instances, excessive gravel deposition can result in local and/or temporary areas of bed aggradation of up to a 1 m or more on main stem channels (Jacobson, 1995).

The Finley River, located in Southwest Missouri, is a typical Ozarks-karst-region stream that is experiencing an increased gravel load due to land-use changes of the past 100 years. Watershed stakeholders have identified channel instability as one of the primary problems affecting their watershed. However, research suggests that local instabilities may contribute to a broader-scale order in the sense that

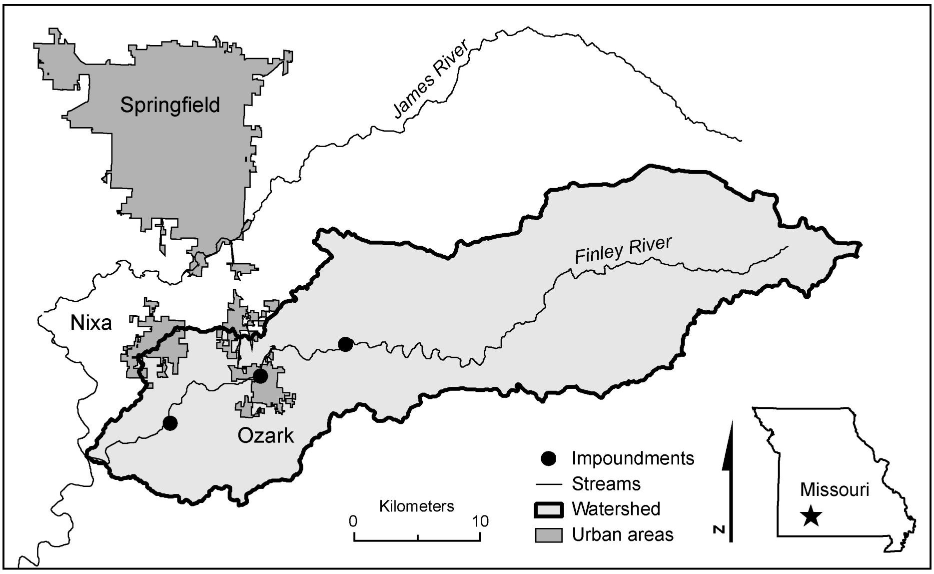

Fig. 1. Location of the Finley River and the Finley River watershed near Springfield, Missouri.

reach-scale bank failures and planform adjustments act in concert to contribute to a watershed-scale dynamic equilibrium, a concept often referred to as self-organized criticality (Fonstad and Marcus, 2003). In the Ozarks, the relationship between local instabilities and broad-scale order is poorly understood. The ability to classify and explain patterns of instability is essential for understanding the broader-scale watershed stability trends in Ozark streams. This study takes the first step to address the causes of channel instability in the Ozarks by quantifying the locations and types of active reaches along 80 km of the main stem of the Finley River. The objectives of this research are to (1) develop an active reach classification scheme based on current channel pattern classification models with which other Ozark streams can be investigated, (2) identify active reaches and different active reach types along 80 km of the Finley River in southwest Missouri, and (3) investigate physical controls of active reach formation. An improved understanding of active reach characteristics will provide a framework for understanding sub-regional differences in Ozark river morphology and behavior and will also help to develop geomorphic models of watershed-scale influence on reach-scale channel adjustment over historical and recent timescales.

STUDY AREA

The Finley River drains approximately 266 km^2 with the border area of the Springfield and Salem Plateaus of the Ozark Highlands in southwest Missouri (Fig.1). The Ozarks Region is delineated by the broad geologic uplift of Paleozoic sedimentary rocks in southern Missouri and northern Arkansas. The sedimentary bedrock, mostly composed of carbonate limestone and dolomite, is responsible for the region's karst development, which supports features such as springs, sinkholes, caves, and the chert gravel that dominates the bedload of most streams. The chert content of these carbonate rocks is relatively high and thus residual soils and underlying saprolite accumulations formed by carbonate rock dissolution often contain large quantities of chert gravel. Colluvial deposits containing relatively high percentages of chert gravel are stored in headwater valleys and at the base of valley slopes along larger rivers and are therefore an available source of gravel sediment to the river system during periods of channel instability (Jacobson, 2004).

Watershed disturbances related to land clearing activities nearly 100 years ago are thought to be responsible for the excess gravel load found in Ozark streams today (Saucier, 1984; Jacobson and Prim, 1994; Jacobson, 1995; Jacobson and Gran, 1999; Panfil and Jacobson, 2001; Jacobson, 2004). Land use in the Finley River watershed has changed, from subsistence farming prior to the Civil War, logging from 1870 to 1930, and row cropping in the late 1800s and early 1900s, to primarily pasture and grazing since the 1950s (Rafferty, 1980; Jacobson and Primm 1994; Jacobson, 1995, 2004). During the period from 1870 to 1930, three impoundments were constructed on the Finley River using small run-of-river dams that are still in existence today. The most intense historical land-use disturbance probably occurred during the period of 1880 to 1920, at which time land clearing and cultivation of upland and riparian areas caused gully erosion and headward migration of tributary channels, accelerating the release of gravel from colluvial and reworked floodplain deposits. Increased gravel loads to main-stem reaches caused excess gravel bar deposition, local channel aggradation, and accelerated lateral channel erosion. Ozark rivers are believed to have recovered from these previous sediment-related disturbances to some degree since 1950 (Jacobson and Primm 1994; Jacobson, 1995). However, increases in flood frequency and suburban development expansion in the Finley River watershed over the past 30 years may be contributing to recent problems with gravel inputs and channel instability in the tributaries. Currently, these unstable reaches are topics of great concern to watershed stakeholders, and government managers are currently planning sediment control measures for the Finley River.

The Finley River is the largest tributary to the James River, which was listed on Missouri's 303(d) list in 1998 for nutrient impairment. This resulted in the development of a watershed management plan for the Finley River watershed. Within the plan, "sedimentation" and "channel degradation" were listed as the primary concerns by the watershed stakeholder group (Jenkins, 2009). While it has been determined that channel instability has been intensified by excess gravel inputs, our understanding of the watershed's response versus the natural erosion regime is quite poor. Understanding individual types of active reaches and how they relate to watershed characteristics and disturbance factors would greatly benefit watershed stakeholders by providing the knowledge needed to manage local instabilities in a manner that recognizes both the natural erosion regime as well as human impacts. For example, the stakeholder's interest in local bank stabilization practices may not be cost effective as a result of natural erosional tendencies or because they do not address the actual cause of the problem such as sediment supply.

MATERIALS AND METHODS

Historical aerial photography is a useful tool for studying river planform change. A large amount of information can be digitally extracted from aerial photographs in a GIS and used for multi-scale spatial analyses. However, consideration must be given to the errors associated with the digitization and georectification process, as these errors could result in the inaccurate quantification of channel planform changes. Other considerations when working with multi-year aerial photograph sets are differences in scale, resolution, and time of year.

Aerial Photography

Geographic information systems (GIS) and aerial photograph (AP) analysis have become a widely accepted method for measuring changes in channel pattern over time (Jacobson and Pugh, 1997; Lawler, 1993; Downward et al., 1994; Gurnell et al. 1994; Mossa and McLean, 1997; Hooke, 2003; Urban and Rhoads, 2003; Hughes et al., 2006; Buckingham and Whitney, 2007). Depending on scale and photograph quality, the overlay of multiple historical photograph series in a GIS provides a means to easily identify changes in channel planform and depositional features and to measure relative changes in active channel widths (Mount et al., 2003). An advantage to using a GIS/AP methodology is that all historical photographs are georectified to a known base projection. This makes it possible to quantify error and therefore limit the chance for erroneous data extraction and a resultant erroneous classification or migration measurement.

Aerial photographs for this project were acquired through the Missouri State University Map Library. Imagery was acquired for the years 1955 and 2006. 1955 was the oldest photograph date that provided nearly full coverage of the main stem of the Finley River. The 1955 photo series was in hardcopy format and required scanning and georectification. Hardcopy photographs were scanned at 600 DPI to take full advantage of the resolution of the original hardcopy photographs. Due to the spatial resolution and spatial coverage, 18 photographs were needed to cover the main stem of the Finley River for the 1955 photo series. The relatively low flight altitude of the 1955 photo series produced a relatively high-resolution photograph. For the 2006 photographs, full digital coverage with 1-m resolution was provided by the National Agriculture Imagery Program (NAIP, USDA). The 2006 imagery was downloaded from the Missouri Spatial Data Information Service (MSDIS, 2009). Table 1 contains a list of the hardcopy photographs and their associated georectification errors.

Georectification was accomplished using ArcGIS®'s Georeferencing utility. With this utility, a minimum of four ground control points (GCPs) was needed to rectify each photograph. Ideally, a wide spatial distribution of GCPs is used to accomplish the least georectification error. Hard (distinct) points were used as often as possible, but GCPs comprised both hard and soft points. Error was assessed using root mean square (RMS) error and point-to-point error collectively. Point-to-point error is simply the measured distance between a known point on the rectified image and the same point on the base map. Three to five point-to-point error measurements were made on each photograph, depending on availability of such points. All points used

Table 1. Georectification Errors Associated with Scanned and Georectified Aerial Photographs

Photo acquisition date	RMS error (m)	Test point error (m)
9/1/55	0.83	2.02
9/1/55	0.78	0.54
10/10/55	1.11	2.26
9/1/55	1.01	1.83
9/1/55	0.70	3.47
9/1/55	1.86	1.40
9/1/55	0.20	1.31
9/12/55	0.86	2.14
9/12/55	0.51	2.79
9/12/55	1.66	1.14
9/12/55	1.66	0.72
7/27/55	2.37	1.54
8/31/55	0.47	1.33
8/31/55	0.67	2.38
8/31/55	1.04	2.00
8/31/55	0.02	0.46
8/31/55	0.67	1.28

to measure point-to-point error were hard points. RMS error is typically used as the primary, and in most cases the only, measure of photo rectification error, however, it has been suggested that independent test points (point-to-point) should be used in addition to RMS error to evaluate georectification error (Hughes et al., 2006). Therefore, RMS error was used as a working guide during the rectification process. When an acceptable RMS error was achieved (3.0 or below), point-to-point error was then measured. This process was repeated until the maximum point-to-point error was minimized. All photographs were georeferenced using the 2006 NAIP imagery as the base image.

Channel Extraction

The channel was extracted from the aerial photographs using ArcGIS® 9.2. Channel bank lines were approximated by the wetted channel boundary and hand digitized along the entire length of the main stem. Given the size of river and the aerial photograph resolution, the wetted channel edge provides the best proxy for the true bank location. However, the wetted channel edge changes with stage. Therefore, historical USGS gage stage measurements were acquired for each of the photograph acquisition dates to confirm that the stage differences were negligible. Then, using an ArcGIS utility, the centerline was calculated based on the bank lines.

Error Assessment

There has been much attention given to the analysis and assessment of digital image rectification error as it relates to stream channel investigations (Downward et al. 1994, Mount et al. 2003, Hughes et al. 2006). Such publications, however, have not suggested a solution to the problem of falsely identifying planform change as a result of the rectification error beyond identifying more control points with a better spatial distribution. Unfortunately, the number of adequate GCPs is often limited and a certain level of rectification error inevitably exists.

To account for the rectification error and avoid the misidentification of channel change a buffer was created around the channel centerline (Urban and Rhoads, 2003). The buffer width was made equivalent to the maximum point-to-point error from the 1955 photo series. Point-to-point error distance was used as opposed to the RMS error, as in Urban and Rhoads (2003), because Hughes et al. (2006) determined that the improvements in georectification accuracy that result from using a greater number of GCPs is not captured by RMS error. Further, the maximum point-to-point error was used to create the buffer with the understanding that the heads-up digitizing process is based solely on the user's visual interpretation of the channel boundaries; therefore, the visually based error measurement (point-to-point) was used instead of the computation-based error measurement (RMS). When buffers were overlain, channel change was identified as areas where the buffers did not overlap. This ensured that the greatest possible error between the photo series was accounted for. The obvious problem that this method creates is that there is now the possibility that some smaller scale disturbances will not be recognized, causing the overall number of disturbances to be underrepresented. However, reach-scale instability features are the primary focus of this study, so the buffer criteria also reduce the noise of local, small-scale variation in channel process and form.

Active Reach Classification

Active reaches were identified as areas where the buffers, developed from 2006 and 1955 data, did not overlap (Fig. 2). The process of identifying active reaches was automated with tools in ArcGIS. Following the application of these tools, each active reach was individually evaluated by visual inspection of channel location, buffer separation between the two photo years, and channel pattern. The beginning and end of the active reach was then determined on the basis of the location of buffer separation or channel inflection points. Patterns of channel change in each active reach were then classified according to a new scheme developed for this study.

An active reach classification scheme was developed specifically for this study and was largely based on existing models of channel change. Hooke's (1977) channel change models identify some 70 types of change related to various stages of channel change evolution. However, the basic movement processes underlying all of these changes can be described by easily measured lateral movements, longitudinal movements, and channel forms. As applied in this study, four classes are used to describe the range of active reaches in the Finley River: (a) extension, (b) translation, (c) cutoff; and (d) megabar. A more detailed description of each of these active reach

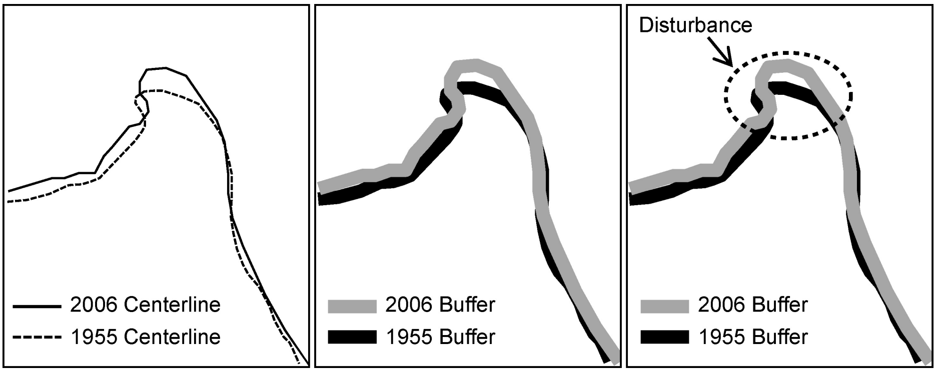

Fig. 2. Active reaches were determined based on overlapping channel centerline error buffers to account for errors in the source data.

Table 2. Description of Active Reach Types and the Processes Involved

Active reach type	Planform description	Process	Literature reference
Extension	An arc that increases in height with time, often later to the valley trend	+ amplitude + path length + sinuosity – channel gradient	Hooke (1977)
Translation	Arc shifts downstream or upstream without altering its basic shape	= path length = sinuosity	Hooke (1977)
Megabar	Lateral shift of relatively straight channel, often the result of growing point, or medial bar	= path length =sinuosity	Hooke (1984) Church and Jones (1982)
Cutoff	Bend amplitude and tightness increase beyond a sinuosity threshold, bend is cutoff by new channel	– path length – sinuosity + channel gradient	Hooke and Redmond (1992)

types as well as a graphic representation of these active reach types follow (Fig. 3, Table 2):

(1) *Extension type:* The unobstructed lateral growth of a bend. Extensions will have the effect of increasing reach sinuosity and path length, while decreasing overall gradient and, potentially, sediment transport capacity. However, bank erosion along channel bends can release relatively large inputs of reworked channel and overbank sediment to downstream reaches.

(2) *Translation type:* The downstream or upstream movement of a bend. The distinguishing factor for this active reach type is maintenance of the original center-line form. Effects of this instability are primarily local, as path length remains relatively unchanged, as do sinuosity, gradient, and transport capacity.

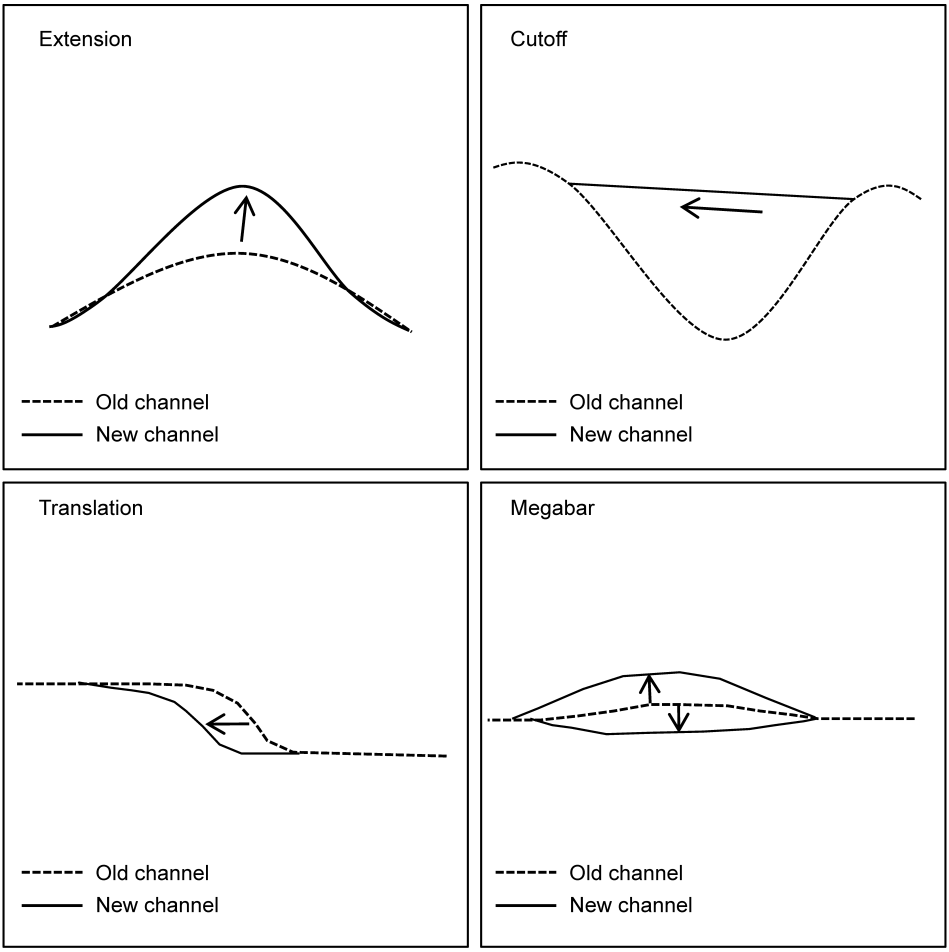

Fig. 3. The four active reach classification types. A. Extension. B. Megabar. C. Cutoff. D. Translation.

Compared to Extension-type reaches, Translation reaches generally do not have such lengths of eroded bank for a given channel size.

(3) *Cutoff type:* The formation of a chute or neck cutoff channel at the base of a meander when a certain radius of curvature threshold is surpassed. Cutoffs have the effect of dramatically shortening path length and decreasing sinuosity while increasing overall gradient and transport capacity.

(4) *Megabar type:* The lateral shift of a relatively straight reach due to the growth of a medial bar into a stabilized megabar form. This form is often referred to in reference to braided conditions and over-widening of gravel bed streams (Church and Jones, 1982; Kiss and Sippos, 2006) Effects of this instability are also primarily local. Path length remains unchanged, as does sinuosity and gradient. However, it should be noted that this only applies at baseflow conditions.

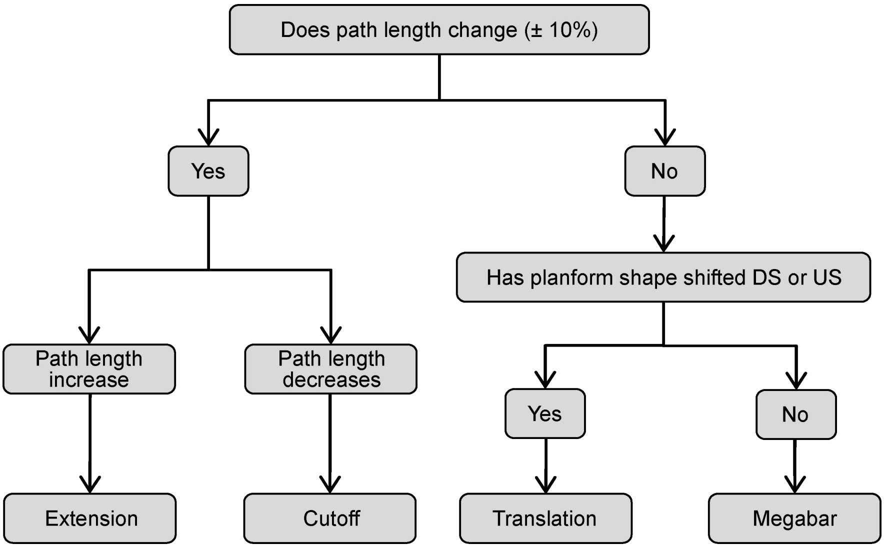

Fig. 4. Active reach classification decision tree schema.

During flood flows, path length and sinuosity would actually decrease as the bar becomes inundated.

Based on the above active reach descriptions and characteristics, we produced a decision-tree schema to objectively evaluate each active reach (Fig. 4). The decision tree begins with the underlying indicator of planform change: the increase or decrease in path length. Increases in path length will yield an increase in sinuosity, a decrease in channel gradient and a decrease in transport capability. A decrease in path length yields the opposite. This simple indicator provides the basis for which the decision-tree options are based. If path length increases, it is an extension. If path length decreases, it is considered a cutoff. If path length stays the same, it is either a translation or a megabar-type reach (Fig. 4).

Controlling Geomorphic Variables

A combination of variables acting at many different scales is ultimately responsible for how channels adjust their form. At the watershed scale, changes in channel planform are often measured as changes in segment-scale sinuosity. Though river channels naturally adjust sinuosity to maintain an energy balance, extreme changes in sinuosity could indicate perturbations in sediment supply or flood regime. For this study, main-stem sinuosity was measured on aerial photographs taken in 1955 and again in 2006. Sinuosity measurements were broken down into three areas: upper watershed, middle watershed, and lower watershed, based on changes in main-stem slope, to facilitate detection of higher resolution changes in sinuosity.

At each active reach several geomorphic variables were measured: (a) contributing drainage area, (b) wetted channel width, (c) channel path length, and (d) valley width. The contributing drainage area was determined using a watershed delineation model applied to a 10-m digital elevation model (DEM). The central point of the active reach was used as the pour point of the delineation model. Channel width was calculated as the average of 10 equally spaced wetted channel measurements along the reach. Channel width was determined by identifying the wetted channel on the aerial photograph and was therefore dependent on the stage at the time of the photo. Both the 1955 photo series and the 2006 photo series were taken during near-average baseflow conditions; therefore, stage differences were negligible. Nevertheless, water- and bank-edge lines often coincided in stable reaches and along cut-banks of active reaches. Path length was measured simply as the length of the center line within the reach. Valley width was determined by calculating the average of 10 equally spaced valley width measurements along the reach. The valley floor was identified by overlaying a 100-year floodplain layer, an alluvial soils layer, and the DEM. With the assumption that channel migration is ultimately controlled by the confining, bedrock-defended valley walls, at least in modern history, wetted channel widths and valley widths were used to calculate a channel confinement ratio, W_v/W_c, which is simply the ratio of valley width to channel width. Typically, the confinement ratio is determined using the active or bankfull channel width. However, wetted width is used in this study based on the geospatial analysis involved. Therefore, while confinement ratio values are comparable within this study, they will tend to be larger than those reported in other studies that were calculated using the active channel width.

Channel-Change Metrics

The degree to which active reaches changed or migrated was measured using a specific metric for each of the classification types assigned. Migration rates at extensions were measured as the distance between meander apexes (m) over the period between photograph years to give a migration rate of m/yr. Translation migration rates were also measured as the distance between meander apexes (m) over the period between photograph years. The nature of the other two active reach types requires a different measurement approach, as these changes tend to take place more rapidly, often occurring as the result of a single event. Cutoffs were quantified as the path length that was abandoned as a result of the newly formed cutoff, and megabars were quantified as the maximum distance of lateral channel shift, or, the maximum width of the megabar feature. Caution is warranted in the interpretation of these data, as calculations of this nature assume constant change between photo dates.

RESULTS AND DISCUSSION

Active Reach Classification

The four active reach types occurred semi-uniformly in the downstream direction along the 80-km channel length of the Finley River. Extensions and megabars occurred most often, each occurring 18 times, followed by cutoffs, which occurred

Table 3. Active Reach Characteristics

Reach type	Count	Mean length (km)	% of total length	Mean valley width (m)	Mean wetted channel width (m)
Extension	18	0.39	7.9	418.1	17.2
Translation	5	0.33	1.9	476.2	18.4
Cutoff	12	0.39	5.4	398.6	20.4
Megabar	18	0.30	6.0	388.2	20.6
Stable	45	1.58	78.8	357.5	25.1

12 times, and translations, which occurred 5 times (Table 3). Extensions and megabars each accounted for 34% of all active reaches. Cutoffs accounted for 23% and translations accounted for 9% of the total. The predominance of one active reach type might indicate a widespread watershed disturbance (Hooke, 1984), but this does not seem to be case in the Finley River. The lack of one dominant type may indicate an uncoupled or discontinuous process of channel adjustment, suggesting that active reach type is likely linked to some local or as yet not understood control. The types of active reach observed represent two processes: (1) channel migration (extension and translation), and (2) channel formation (cutoff and megabar). Channel migration is often related to stream energy dissipation due to decreasing slope and increasing roughness, whereas channel formation indicates the increase in channel energy and bed sediment transport. These processes function collectively to attain energy equilibrium at the watershed scale (Langbein and Leopold, 1964). This equilibrium, or order, has recently been attributed to the concept of self-organized criticality (SOC), the idea that local instabilities function to generate broader-scale order (Fonstad and Marcus, 2003). As applied here, local instabilities may be represented by the active reaches.

Longitudinal Trends

The combined length of all active reaches accounted for 21% of the entire main stem of the Finley River (Table 3). Therefore, 79% of the Finley River's planform has remained stable over the 50-year period. Most of the active reaches were located alternately with longer stable reaches. This alternation of stable and active reaches has persisted in many Ozark streams, at least since the 1920s (Jacobson, 1995) and may indicate a dynamic equilibrium condition imposed by discharge, sediment supply, and valley controls. The longitudinal trend of alternating stable and active reaches, though not necessarily understood, may be an example of the concept of hierarchical patch dynamics. This concept from landscape ecology identifies a stream network as a longitudinal discontinuum of discrete units with alternating stream segments containing different geomorphological structures (Poole, 2002).

In the context of this study, active and stable reaches represent an example of the longitudinal discontinuity described by the patch dynamics concept, whereby active and stable reaches are the alternating stream segments with different

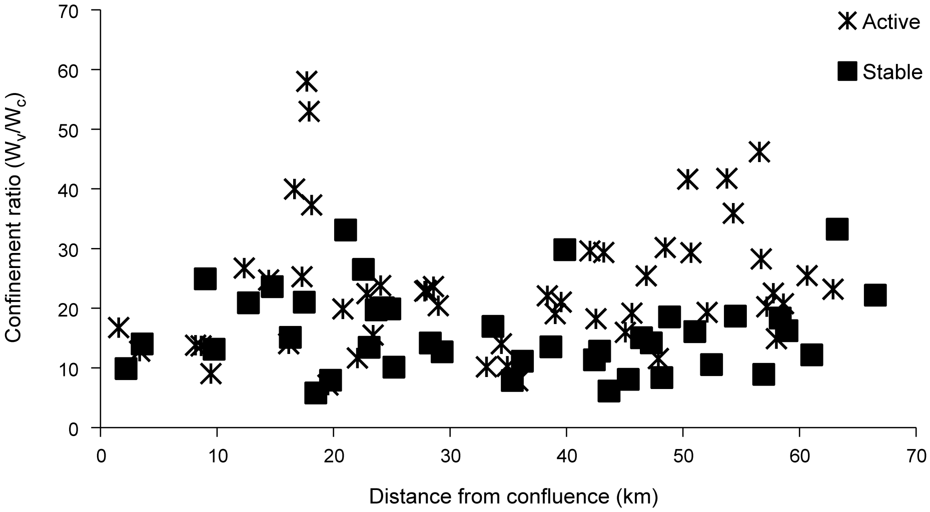

Fig. 5. Confinement ratios at active reaches as compared to stable reaches.

geomorphological structures. In the case of the Finley River, the formation of active or stable reaches may be controlled by valley-scale structure, in this case, confinement. While there is no obvious correlation between confinement ratios and downstream location, higher confinement ratio segments tend to contain more active reaches as compared to stable reaches (Fig. 5). Further, statistical comparison of confinement ratio values between stable and active reaches confirmed this observed difference (alpha = 0.05). Thus, where the valley is relatively wide in relation to channel width, active reaches are more likely to occur, possibly due to a decrease in slope, lack of bedrock control, or decrease in alluvial bank resistance.

The linear relationship of riffle/pool and meander bend spacing with channel width is quite familiar (Knighton, 1998). We hypothesized that active reaches form in a similar manner, equilibrating over time to some equal spacing. In the case of the Finley River, 54% of all active reaches are located less than 1 km from the previous active reach (Fig. 6). The median distance was 0.83 km and the inter-quartile range was 0.5 km to 1.9 km (e.g., approximately 10 to 50 channel widths). While this observation implies a relatively frequent occurrence of individual active reaches, it does not indicate equal spacing.

Active reach spacing may also be controlled by tributary inputs and/or valley confinement trends. Jacobson and Gran (1999) performed a spectral analysis of gravel bar accumulations along the Current River, Missouri, and determined that peaks of the spectrum were far in excess of what would be expected for riffle/pool sequences, indicating that disturbance reach spacing was controlled by something other than riffle/pool scale dynamics. Along the Finley River, active reaches tend to cluster near confluences with larger tributaries (Fig. 7) and in segments with confinement ratios between 10 and 30 (Fig. 8). Indeed, 83% of active reaches with a confinement ratio greater than 20 are within 5 km of a 4th order tributary, and 42% of all

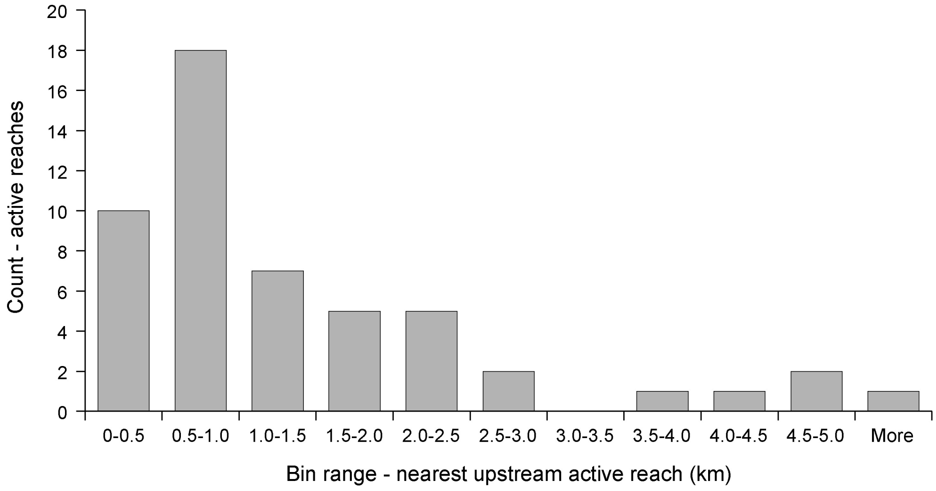

Fig. 6. Histogram of active reach spacing.

Fig. 7. Histogram of active reach proximity to 3rd or 4th order tributary junctions.

active reaches occur within 1 km of a 3rd or 4th-order tributary (Fig. 7). Jacobson (1995) suggested that specific disturbance reaches seem to be independent of tributary junctions. However, although not statistically confirmed, Jacobson and Gran (1999) and Jacobson (2004) found that the area of gravel bar deposits in disturbance reaches seems to increase below large tributaries. In the Finley River, active reaches tend to form closer to 3rd and 4th order tributary junctions (Fig. 7). These results may indicate that higher-order tributary junctions (3rd and 4th), in combination with specific confinement ratios, provide structural elements conducive for the formation

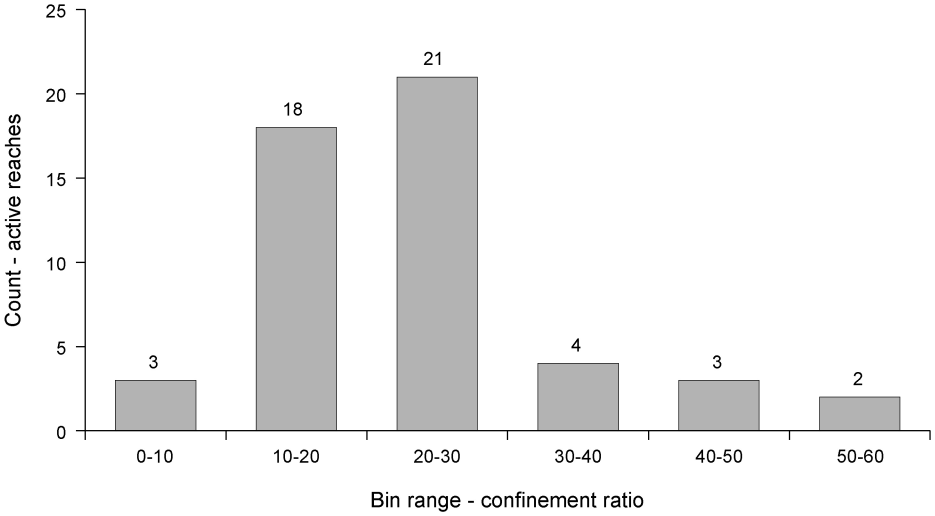

Fig. 8. Histogram of active reach confinement ratios.

Table 4. Active Reaches Near the Finley River Impoundments

Impoundment	A_d (km^2)	Nearest upstream active reach		Nearest downstream active reach	
		Distance (km)	Type	Distance (km)	Type
Lindenlure Dam	422	3.5	Transl	0.7	Cutoff
Ozark Mill Dam	514	1.1	Mega	0.2	Mega
Riverdale Dam	614	2.5	Mega	0.3	Extens

of active reaches. Jacobson (1995) reported that large gravel bars probably migrated through and out of some Ozark watersheds with drainage areas <1,400 km^2 (about the area of the Finley River watershed) between 1920 and 1940. However, in some present-day Ozark rivers, the largest gravel bars are typically located near or below tributary confluences and downstream of cleared land areas underlain by chert-rich carbonate bedrock (Panfil and Jacobson, 2001). Thus, it is quite possible that the pattern of active reaches found in the Finley River today was formed due to human or natural disturbances prior to 1955 (earliest photo year evaluated), but have been maintained or reactivated by recent sediment and discharge inputs.

The downstream distribution of active reaches may also be affected locally by the three impoundments along the Finley River. As expected, impounded segments classified as stable reaches as a result of reduced channel energy due to dam control and backwater effects. The distance of active reaches as measured from the dam ranges from 1.1 to 3.5 km upstream and 0.2 to 0.7 km downstream of the impoundments (Table 4). Further, there is no uniform active reach type pattern associated with the impoundments. Thus, while the impoundments probably influence bed load and

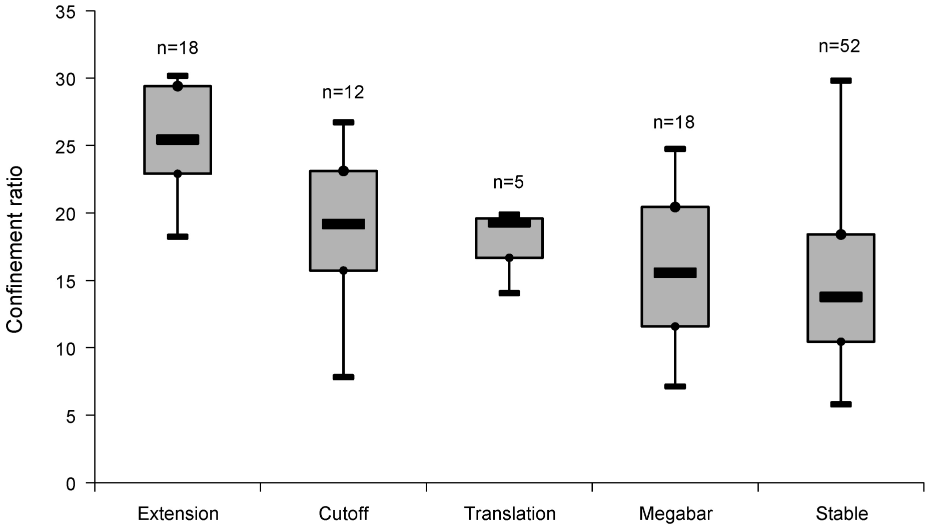

Fig. 9. Confinement ratios for each of the active reach types and stable reaches.

channel processes to some extent, they do not appear to control the specific types of active reaches present.

Reach/Segment Trends

Analysis of the reach-scale channel change metrics provides evidence in support of self-organizing processes (Table 5). Over the 51-year period, cutoffs reduced stream length an average of 75.3 m per cutoff. Cutoffs alone would substantially reduce local sinuosity and tend to increase slope and possibly gravel bed-load transport. Coincidentally, extensions migrated laterally an average of nearly 51 m over the time period and occurred more often than cutoffs. This increase in cross-valley migration would have the effect of increasing sinuosity, thereby cancelling out the effects of the cutoffs at the watershed scale. The megabar and translation disturbance types, while causing visible changes in channel planform, contribute little to the overall changes in channel length, slope, and sinuosity at the watershed-scale because these types tend to remain locked in narrow valleys with low confinement ratios (Fig. 9).

Self-organizing processes are further supported by evaluating the changes in sinuosity between 1955 and 2006. Virtually no change in sinuosity has occurred over the 51-year period, even when changes are examined for three watershed sections (Table 6). This analysis indicates that reach-scale instabilities such as cutoffs, which decrease sinuosity drastically, are compensated for by increased migration rates at extensions, which increase sinuosity. Examples from Hooke (1984) show either increasing or decreasing sinuosity over time, corresponding to land-use changes and land disturbance within those watersheds (Table 7). The lack of change in sinuosity in the Finley River, in comparison, may provide more evidence to support the

Table 5. Channel Change Metrics for Each Active Reach Type

Active reach type	Mean	Minimum	Maximum
Extension (m/yr)	1.0	0.7	1.6
Translation (m/yr)	2.7	1.0	6.0
Megabar (m)	49.5	22.0	92.0
Cutoff (m)	75.3	2.0	535.0

Table 6. Sinuosity of Each Section of the Finley River

Section	Year	Sinuosity
Upper	1955	1.22
	2006	1.21
Middle	1955	1.58
	2006	1.58
Lower	1955	1.32
	2006	1.31

Table 7. Examples of Sinuosity Change on Human-Impacted River Systems from Hooke (1984)

Kansas River, U.S. Dort and Ratzlaff (1970)		Sacramento River, U.S. Brice (1977)		River Bolin, UK Mosley (1975)		River Dane, UK Hooke and Harvey (1983)	
Date	Sinuosity	Date	Sinuosity	Date	Sinuosity	Date	Sinuosity
1856	1.45					1840	1.57
1870	1.47			1872	2.41	1870	1.64
1900	1.38	1896	1.56				
1905	1.23					1910	1.74
1942	1.14			1935	2.34	1947	1.77
1951	1.24			1969	1.97	1968	1.88
1959	1.20	1974	1.35	1973	1.37	1980	1.92

hypothesis that geomorphic processes are generally in balance in the river system. Though sediment deposition and transport are not directly addressed in this study, it is hypothesized that sinuosity balance is achieved through coupled extensions and cutoffs that, in combination, function as a geomorphic capacitor, whereby excess bed sediment builds up until a threshold is reached, a cutoff is initiated, channel slope is increased, and sediment is released downstream to build up on point or center bars within other active reaches.

The increased supply of channel sediment released from one active reach may ultimately become a source of instability at another active reach downstream. While channel extensions can counter cutoff rates, they also appear to directly regulate sediment supply directly and possibly control the location of excessive bar deposition. During the channel extension process, bank erosion rates can progressively increase over time as channel length increases along a growing bend. Thus, extension has the potential to release relatively large volumes of gravel by reworking previously buried channel and bar deposits stored within floodplains. Evidence to support this in-channel sediment supply process is provided by an evaluation of the downstream sequence of disturbance types. First, megabars (i.e., reaches of excessive bar deposition) represent key channel sediment zones that often occur in clusters with other megabars. Second, 89% of all megabar clusters and individual megabars occur immediately below extensions. This could be the result of the erosion of floodplain sediments at extensions and the subsequent deposition of that material downstream, initiating the formation of a megabar. The remaining 11% of megabars occur in various combinations with other reach types. While tributary gravel inputs may initially set the pattern of active reaches in the watershed, subsequent cycling of channel length and sediment reworking within active reaches transports sediment downstream and thus ultimately distributes active reaches further downstream.

The spatial distribution of active reaches might also reflect downstream changes in channel slope, transport capacity, and sediment load. Therefore, it is possible that specific active reach types would cluster in groups according to downstream location or drainage area. In the Finley River, different active reach types occur across a range of contributing drainage areas (Fig. 10). The range of values for each disturbance type is such that significant statistical differences cannot be established based on drainage area. However, cutoff and megabar types did not occur in the upper portion of the watershed with drainage areas less than 200 km^2 (Figure 10). A possible explanation for this observation is that both cutoff and megabar formation is driven by gravel bar deposition and related bed aggradation, which occur more frequently in lower slope channel segments and below tributary sources. As described previously, megabar locations reflect major sedimentation areas in the channel. Similarly, the chances for a cutoff occurrence increase with gravel deposition in bar or riffle areas at the upstream side of a bend when bed elevation increases by local aggradation, effective bank height decreases, and overbank flows are forced into backswamp or bar chute locations more frequently thus increasing the chances for floodplain erosion and the formation of a cutoff channel.

Development of an Objective Active Reach Classification

Our application of basic classifications based on current models has provided valuable information concerning watershed-scale stability. However, a problem that persists is the subjectivity of applying such models. The classification decision tree created for this study, based largely on Hooke's (1977, 1984) models, should alleviate some of this subjectivity while also providing a model for use on other Ozark streams. The decision tree introduced in the methods was developed specifically to

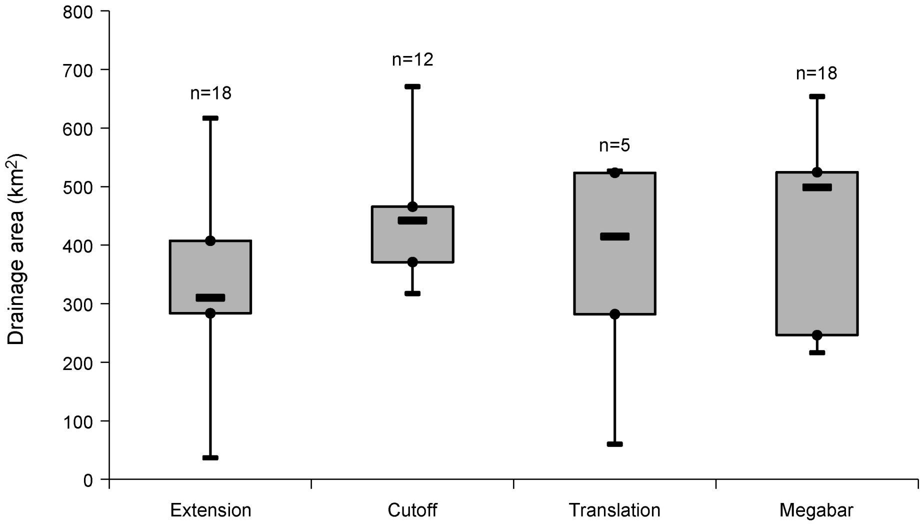

Fig. 10. Drainage areas for each of the active reach types.

accommodate the four active reach types used to classify the Finley River: Extension, Translation, Megabar, and Cutoff.

These basic classifications encompass the types of channel changes taking place in the Finley River and provide a preliminary model of planform instability along the main stem. The development of this objective classification scheme will allow for a similar view of other streams in the Ozarks region while providing an objective comparison. While this classification uses a form-based approach, it also recognizes the influence of valley-scale controls, history of channel change, and role of sediment supply and transport as important variables in understanding channel instability in Ozark rivers.

CONCLUSIONS

The analysis and classification of active reaches along the Finley River using historical aerial photographs provides an objective evaluation of the spatial distribution of active and stable reaches. Of the 80 km of the main stem evaluated for this study, only 21% of the channel length was identified as unstable. This demonstrates the high level of channel stability inherent in confined meandering river systems of the Ozarks. Nevertheless, the location of active reaches is spatially associated with water and sediment inputs of higher-order tributaries and wide valleys relative to channel width. Simply put, the channel will adjust its planform in areas where the confining valley walls allow it and where increases in discharge and sediment input instigate such a response.

There are indications that active reaches are linked in process and space. The Finley River has attributes of a self-organized critical system, in which local instabilities combine to form a broader-scale equilibrium. Of the four active reach types, there was no clear dominant type, which is an indication of uniform response within a stable river system. Over the past 50 years, there has been a relatively strong balance between active reach types that dramatically increase path length and sinuosity (extensions), and active reach types that dramatically decrease flow path length and sinuosity (cutoffs). Thus, channel extensions have been offset by channel cutoffs to maintain watershed-scale sinuosity. Further, there seems to be a strong link between channel extension, remobilization of stored gravel by bank erosion, and formation of megabars immediately downstream. The described connections among valley- and local-scale factors in controlling active channel processes are preliminary and need to be investigated further.

Based on measured active reach characteristics and distinct planform changes, a geospatial methodology and classification decision tree is presented to objectively identify stable and active reaches. The validity of the classification scheme for geomorphic analysis is also supported by relating active reach types to valley-scale controls, history of channel change, and role of sediment supply and transport to better understand channel instability in Ozark rivers. Ultimately, a better understanding of the interrelationships among specific active reach types within a greater variety of river systems is needed to be able to discriminate between channel changes caused by human activities and natural conditions. Nevertheless, objectivity of this classification scheme is essential for precise classification and valid comparisons to other river systems. In fact, an important next step will be to apply this classification to other rivers in the Ozark Highlands.

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