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Coarse sediment storage and connectivity and off-highway vehicle use, Board Camp Creek, Arkansas

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ABSTRACT

Upper Board Camp Creek (BCC) in western Arkansas drains the Wolf Pen Gap (WPG) Trail Complex, a designated Off-Highway Vehicle (OHV) area in use since the 1990s. The mixed bedrock-alluvial channel is quite active, with extensive bars and eroding banks present within the higher-order, main-valley channels. This study was conducted to determine the relative magnitudes of sediment storage and production within the channel, and whether geomorphic changes are synchronous with establishment and increasing OHV use levels on the trail system. Fourteen geomorphically active reaches within the main-valley channels, representing the range of conditions of BCC within the WPG complex, were examined in detail. All sites had significant alluvial storage in the form of point, lateral, or mid-channel bars dominated by cobble and gravel. Sediment storage volumes ranged from 140 to nearly 10,000 m^3 per kilometer of channel, with a mean of about 3400. Eleven of 14 reaches also had actively eroding banks. Ten reaches (71%) exhibited net sediment storage. Two are possible net sources, and two may be in approximate steady state (storage ≈ erosion). The imbalance between local bank erosion sources and in-channel storage, and the evidence of activity and mobility of most of the bars indicates a connected system, with coarse sediment mobile during banktop flow events, and no evidence of sediment starvation. Finer (<8 mm) sediment from the trail system does not seem to be accumulating in the stream, suggesting that most is either sequestered before reaching BCC Creek, transported downstream, or deposited on floodplains during overbank flow. Many of the channel bars predate the trail complex, and most are active. This suggests that these features constitute mainly transient storage and are an inherent feature of the channel. At only two reaches could geomorphic changes be confidently attributed to the trail system. Like many streams, BCC has an active channel, independent of the WPG trail system. These results highlight the difficulty of attributing fluvial change to specific causes or forcings in active fluvial systems.

1. Introduction

Changes in land use, erosion, and sediment transport within a watershed inevitably impact stream channels. However, these impacts can be quite variable, depending on numerous factors, including the sediment size involved, the magnitude of sediment inputs relative to sediment transport capacity, and the adjustability of the stream system. In addition, as fluvial systems are often quite dynamic even with fixed boundary conditions and between disturbances, it is not always straightforward to link geomorphic (and related hydrological and ecological) changes to specific disturbances or watershed modifications.

The management responses to slugs or pulses of bedload sediments in streams was reviewed by Sims and Rutherfurd (2017), who identified four general responses if managers determine action needs to be taken. These are reducing sediment supply at the source (typically upland erosion control); trapping sediment within the channel using, e.g., check dams; accelerating sediment transport through a channel; or directly removing sediment. An additional option is to do nothing; Sims and Rutherfurd (2017) indicate that the decision should be based on knowledge of potential effects of sediment pulses on channels such as widening, avulsions, and tributary interactions. This in turn requires knowledge of the sediment storage and transport dynamics of the affected stream, including confirmation that a perceived pulse of sediment input has actually occurred, and whether human agency is indeed the cause. Given the complexities referred to above, this is no small task.

This study examines sediment storage and production in the main channel of Board Camp Creek (BCC) within the Wolf Pen Gap (WPG) off-highway vehicle (OHV) trail complex in the Ouachita National Forest, Arkansas. OHV is a blanket term for a variety of off-road vehicles; most of the usage of the WPG trails is by all-terrain vehicles (ATVs); also referred to as quads and four-wheelers. The main channel is here defined as the higher-order channel segments occurring in the main valleys of the study area (Fig. 1). The goal was to determine the relative magnitudes of sediment storage and production within the channel,

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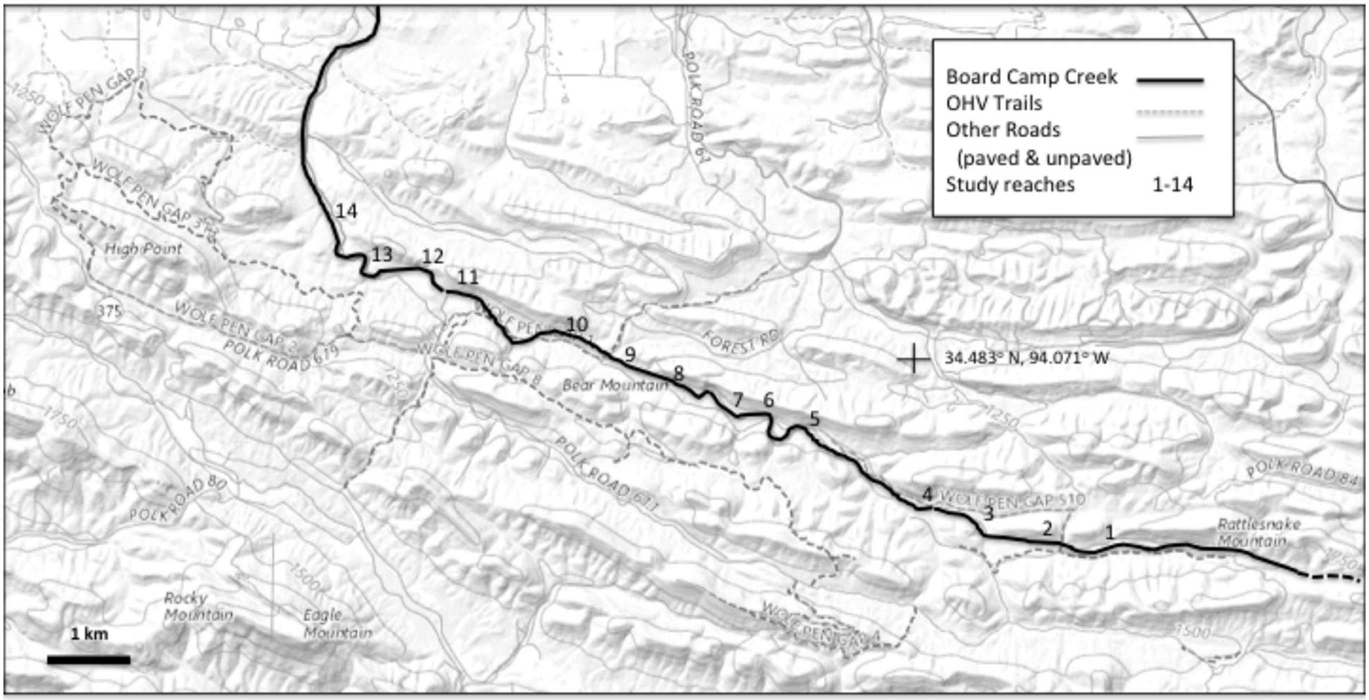

Fig. 1. Board Camp Creek; flow is southeast to northwest. Numbers indicate study reaches; base map from U.S. Geological Survey National Map. Main OHV trails in Wolf Pen Gap are shown; others also exist within the area. For a detailed current trail map see https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5212722.pdf (last accessed 15 July 2019).

and whether geomorphic changes are synchronous with establishment and increasing OHV use levels of the trail system. Therefore, the specific objectives of this paper are to (1) quantify production and storage in main-channel reaches; (2) assess the sediment connectivity of main-channel reaches; (3) and evaluate if storage and connectivity characteristics have changed since the establishment of OHV use. We do not assess tributary inputs, but note that the only significant change in the catchment since the early 1990s has been greatly increased OHV use.

The WPG trail complex comprised about 69 km of loop trails at the time of field work in March 2014, with all study sites within the complex boundaries and potentially impacted by trails. These trails are available for use by all OHVs. All-terrain-vehicles are by far the most popular, and the trails are in fact referred to in Forest Service signage and literature as *ATV* trails. The term 'ATV' is used below when the more restrictive classification is intended.

Previous work (see below) has documented increased erosion and sediment production from the WPG trail system, and geomorphic changes in channels associated with trail crossings of the streams (Marion et al., 2014, 2019). Past work shows OHV use can increase sediment production and result in morphologic impacts to channels directly affected by trails. It remains unclear whether these increases cause downstream responses in main-valley channels. There exist anecdotal reports of geomorphic changes to BCC, such as bank erosion and sediment deposition in cobble bars, since establishment of the trail system in the 1990s that could be plausibly related to increases in runoff and erosion from the trails. However, these impacts have not been documented.

We used field indicators of recent change to estimate in-channel sediment inputs and storage. The methodology and conceptual framework presented by Hooke (2003) and described in the Study area and methods section provides the basis for interpreting these indicators. We evaluated in detail 14 reaches of BCC representative of channel sections undergoing recent channel change—that is, observable erosion and/or sediment storage/deposition—along the reach of the stream in and immediately downstream of the WPG trail complex. The assumption of this approach is that reaches not exhibiting evident change have recently experienced only minor net sediment loss or storage. We recognize that this is a "snapshot" approach, but results are directly relevant to the issue of fluvial impacts of the WPG OHV trails.

1.1. Previous work

Impacts of unpaved forest roads and vehicle trails, of which OHV trails are one type, include effects on runoff, soil erosion, stream sedimentation, and water quality. Recent reviews of these effects of unpaved forest roads are provided by Eisenbies et al. (2007), Neary et al. (2009), and Anderson and Lockaby (2011). Robinson et al. (2010) reviewed the direct and indirect erosion impacts of unpaved hiking, horse, and bicycle trails.

Studies specifically focused on impacts of OHV use, particularly with respect to humid environments (as opposed to dryland settings) are more recent. Fischman et al. (2017) reviewed planning documents for 313 U.S. National Wildlife Refuges with respect to OHV impacts, finding that while OHVs are a significant concern, the plans often failed to consider known impacts of OHV use, including accelerated erosion, stream sedimentation, and water quality degradation. Relatively few studies have directly examined channel responses to erosion from OHV trails. A tracer study in north Georgia found major impacts on water quality, sediment yield, and stream bed sedimentation (Reidel, 2006). Channel bed sedimentation associated with OHV crossings was documented in Victoria, Australia, by Brown (1994). Her field experiments involving simulated OHV convoys found a mean bed sedimentation rate of about 1 kg m^{-2} over 30 days (Brown, 1994). Ricker et al. (2008) found that local disturbances, including ATV trail crossings of streams, played a major role in watershed sediment fluxes in Virginia.

Miniat et al. (2019) compared total suspended solids (TSS) export from otherwise similar watersheds with and without OHV trails in a national forest in Georgia. They found higher TSS concentrations for all sampled storm events in the OHV area. Miniat et al. (2019) found TSS concentrations seven times lower in the OHV area when the trails were closed for maintenance as compared to periods when they were open to riders.

Past work in the BCC basin has shown that OHV use has impacted streams crossed by or downstream of trails. Chin et al. (2004) compared pool characteristics of two watersheds in the WPG area with two nearby control watersheds with no OHV trails. They found that the OHV-impacted pools had higher proportions of fine sediment than the control streams. Marion et al. (2014) investigated the geomorphic effects of ford-type stream crossings of OHV trails in the WPG complex. The 15 study sites ranged from crossings active for >20 yr to those on trails that had been closed to regular use for 5 yr. All sites currently or previously designated for OHV use exhibited soil loss of ~30 to 45 cm of soil thickness within the trail segments on either side of the crossings. In-channel responses attributable to the crossings were observed at all but one site and included increased bank erosion, mud coatings on coarse channel clasts, increased in-channel fine-sediment accumulations, changes in the size distributions of coarse bed material, and occurrence of large channel-filling sediment plugs. Seventy-three percent of the sites exhibited two or more responses.

Trail and unpaved road surfaces in general produce more runoff than adjacent vegetated and undisturbed ground. Soils on the trail system are highly compacted, and Luckow and Guldin (2007) showed that a 15% increase in density of soils on the Ouachita National Forest resulted in a decrease in infiltration of >60%. Thus the trail surfaces experience increased runoff relative to unaffected soils.

Marion et al. (2014) showed that sediment impacts seem to predominate over runoff impacts from the WPG trails at crossing sites, and small channels (basin areas < 0.4 km^2) showed greater consistency in their responses than larger channels. Downstream increases in mud coatings and sediment deposition forms are more common where OHV use is currently allowed. Overall, individual effects were strongly contingent on local details of channel and valley geomorphology.

Excessive erosion and sedimentation in the complex were recognized in an environmental assessment of the trail system (Ouachita National Forest, 2014), and reduction in erosion, sediment flux, and runoff from trails is the main priority of the management options considered. In a study of erosion processes occurring on the WPG trails, Marion et al. (2019) identified seven processes producing sediment directly from the OHV trails. Of these, sheet and rill erosion and dust and splash transport were most important in delivering sediment off-trail. The trails are all worn down to or near underlying bedrock, with mean soil profile truncation of about 0.4 m. Erosion features exhibit a mean density of >16 per km of trail, and more than two-thirds were found to have high or very high connectivity to drainage features. Despite exposure of bedrock, both natural and traffic-related weathering maintain a continuous supply of transportable debris and ongoing sediment loss rates from the trails of 75 to 210 t ha^{-1} yr^{-1} (Marion et al., 2019).

2. Study area and methods

2.1. Board Camp Creek and Wolf Pen Gap

The BCC/WPG study area is in the Ouachita Mountains of western Arkansas (Fig. 1). The Ouachitas are generally east-west trending, parallel ridges. Peak elevations in the study area are typically about 420 to 480 masl. The climate is humid subtropical, with hot summers, relatively mild winters, and year-round precipitation. Mean annual precipitation in the WPG area is about 1350 mm, almost all in the form of rain.

The Ouachita Mountains are geologically complex, composed of Paleozoic sedimentary rocks that have undergone extensive tectonic deformation. Steeply dipping and contorted strata of interbedded sandstones, shales, cherts, and novaculites are common, as are numerous faults and related structures. Soils are generally thin, with depths of <1 m to weathered bedrock, and often <0.4 m. Weathered bedrock is often exposed in eroded areas such as ridgelines and along unpaved roads and trails.

The study area is almost entirely forested (>99%). Other than trails and parking areas, a few scattered clearings associated with campsites and a small former novaculite mine site are the only unvegetated areas. Predominant forest types are white oak-northern red oak-hickory (*Quercus alba*, *Q. rubra*, and *Carya* spp., respectively), and shortleaf pine (*Pinus echinata*)-oak. Sweetgum (*Liquidambar styraciflua*), alders (*Alnus* spp.), willows (*Salix* spp.) and sycamore (*Platanus occidentalis*) are common along the valley bottoms.

When the trail complex was first opened in the early 1990s, trails were comprised of existing unpaved Forest Service roads and former logging roads. At various times since then, trails specifically intended for ATV use have been constructed, and other trails have been modified to make them more appropriate for ATV use and to minimize erosion and sediment loss. All trails and roads have unpaved, native surfaces (in the sense that any construction or maintenance has used local materials).

BCC has a length of 15.9 km through the WPG study area. Drainage area ranges from about 4 km^2 at the uppermost sample site to nearly 30 km^2 at the farthest downstream site. The stream is bedrock controlled, having a mixed bedrock-alluvial channel throughout the study area, with bed material a combination of exposed bedrock and (more commonly) a thin alluvial cover dominated by cobble and gravel sized material but ranging from fines to boulders. Bedrock occasionally outcrops along the stream bank, but banks are mainly alluvium or hillslope colluvium. The average channel slope of the creek from its headwaters to our downstream study site is 0.008, with a valley slope of 0.011. The channel is confined, with an overall sinuosity of 1.3.

2.2. Site selection

A combination of field reconnaissance and examination of aerial photographs covering the 1994–2012 period and accessed via Google Earth™ were used to evaluate lateral channel change, bank erosion, incision, aggradation, and development and movement of channel bars. From this population of potential study reaches, sites were selected so as to include the entire length of BCC within the WPG area, with a rough guideline of one per km of channel. Some sections of the channel did not have any reaches experiencing visibly evident erosion or deposition. In cases where there was >1 potential study section in a km of channel, we randomly selected the reach to be examined. The reach boundaries were defined based on the up- and downstream limits of visible channel change; thus the variable sample lengths of 119 to 216 m (mean 146 m).

2.3. Field measurements

Measurements at each site were designed to (1) characterize reach morphology via a longitudinal channel profile, representative cross section, and general channel description; (2) measure or estimate the quantity of in-channel sediment storage or erosion; (3) assess the stability or activity of channel bars; and (4) determine the likelihood of coarse sediment transport at high flow.

Each study reach was surveyed to determine the morphologic dimensions and characteristics. At each site a longitudinal profile of the channel banktop was surveyed using a laser level and prism rod. Measurement locations were restricted to sites where the bankfull elevation could most confidently be identified (for methods see USDA Forest Service, Rocky Mountain Research Station, 2003). In this paper, the bankfull elevation is used to define a discharge magnitude that is assumed to have a 1- to 3-yr return period and can be identified using morphologic and vegetative indicators (USDA Forest Service, Rocky Mountain Research Station, 2003). Bankfull elevation is used to determine the maximum local shear stress at a discharge frequency that is relatively consistent between sites. Channel cross sections were located where bankfull elevation could be confidently identified.

The banktop elevation is a morphologic feature used as a local reference elevation for determining in-channel feature dimensions such as thalweg depth and bar heights, and estimating the channel slope. Banktop elevation is the distinct slope break that is visually obvious along one channel side or the other, is above the baseflow elevation, and occurs where bank erosion or vegetation characteristics change markedly. This may or may not correspond with the bankfull elevation as commonly defined in many stream assessment and classification methods. The discharge frequency associated with the banktop elevation is not known. However, at cross sections where both bankfull and banktop elevations could be determined, the banktop elevation was either similar or somewhat lower, thus the channel slope derived from the banktop measurements would be similar to that at bankfull flow. We use the banktop elevation for defining channel slope and feature dimensions because the bankfull elevation could not be consistently determined throughout the study reaches, whereas the banktop elevation could be.

A representative cross section at each reach was surveyed using the laser level and prism or a measuring tape and stadia rod. A general geomorphic description of the reach was also made, including hydraulic units present (pools, runs, high-gradient riffles and low-gradient riffles), predominant bed material size, bank conditions (general vegetation cover, bank-slope shape, and presence of erosion scarp or cutbank features, undercuts, etc.), and alluvial sediment storage features evident.

Current sediment storage was quantified within each sample reach. Sediment storage features included point, lateral, and mid-channel bars (Fig. 2). These were field surveyed using the laser level and prism, measuring tape, and folding ruler or stadia rod, depending on their size and characteristics. The longitudinal length was measured, along with 3 to 12 width measurements (depending on size and geometric complexity) to determine mean width, and mean elevation relative to the channel thalweg and to the nearest banktop. Measurements were to the nearest 0.1 m for length and width, and 0.01 m for height. Total storage volume (m^3) was computed as the product of length, mean width, and mean height relative to the channel bed.

Channel substrate was examined to determine its representative size and mobility characteristics. The size class (boulder, cobble, small gravel, fine) of the modal grain size was determined by field measurement based on the median diameter. These were measured at 1 m intervals along identified erosional (e.g., cutbanks) or depositional (e.g., bars) landforms. Bedrock outcrops were recorded in field notes but not included in measurements. Descriptions of vegetation type and density within the channel and along its banks were recorded. The bar features were also examined to determine the median diameter (mm) of the largest mobile clast (LMC). This was based on surficial clasts that were not embedded in fine sediments, partially buried by other coarse sediments, or anchored by vegetation, and with the entirety of the clast below the banktop elevation. Clasts that appeared to have been delivered to a bar by mass wasting from the adjacent hillslope were excluded. The percentage of embedded clasts on the bar surface was estimated based on point counts. Embeddedness is commonly determined in stream bed sediments due to its importance for aquatic habitats, and is often based on partial burial in or by fine sediments. Here a particle was classified as embedded if it was partially buried by sediment of any size. Following Recking et al. (2012), we also considered limited imbrication and absence of moss or vegetation cover on individual clasts as indicators of mobility. We also assessed roundness/angularity of clasts (classes of rounded, subrounded, subangular, angular).

The critical shear stress ($N\ m^{-2}$) required to entrain the LMC was estimated using the Shields function:

$$\tau_{cr} = k\, g\, (\rho_s - \rho_w)\, D \quad (1)$$

where g is the gravity constant, ρ_s, ρ_w are the densities of sediment and water, respectively (assumed to be 2.65 and 1.00 g cm^{-3}, respectively), and D is median particle diameter (mm). The constant k is typically taken as 0.045 for mixed grain-size populations, but here $k = 0.03$, the recommended value for steep cobble-bed mountain rivers (Jarrett, 1990). This was compared to the maximum local shear stress at bankfull flow, based on the depth of the thalweg below banktop level for each bar, and the maximum banktop slope of any subreach within the study reach. The reasoning is that this provides a reasonable estimate of the plausibility of mobility within the reach. Local shear stress is

Fig. 2. Point (top), lateral (middle), and mid-channel (bottom) bars in Board Camp Creek.

$$\tau = \gamma\, d\, S \quad (2)$$

where γ is the specific weight of water (9810 N m^{-3}), d is depth (m), and S is energy grade slope, estimated as channel slope along the banktop as described above. Depth was calculated as height of the bar above the thalweg plus the height of the local banktop above bar height. This method is somewhat oversimplified, but is widely used, and produces results within the range of those yielded by more sophisticated analyses such as those of Recking et al. (2008).

Vegetation age and the degree of soil development were used to judge the relative age and stability of sediment storage features. Vegetation age was assumed to be related to tree size as indicated by diameter at breast height (dbh; measured at 1.3 m from the ground). For sweetgum (*Liquidambar styraciflua*) on more productive, non-stressed sites in the region (based on site index of the mapped soils; Olson, 2003), the mean dbh after 20 yr of growth is about 15 cm, according to models of Schultz et al. (2010). Shropshire et al. (1987) found that on well-managed stands on average or better sites in the region (based on site index, the Board Camp sites are below average), sweetgum dbh was typically about 5 cm after seven years, and 25 cm at 30 yr. Thus trees with dbh of 20 cm or more as of 2013 indicate surfaces established before the early 1990s. Given the slower growth at stressed sites such as active bars, and other factors (e.g., genetics) influencing dbh, only rough estimates are possible. However, it is reasonable to conclude that a 15-cm sweetgum growing on a bar is >20 yr old (S. Meadows, Principal Silviculturalist, Southern Research Station, USDA Forest Service, Stoneville, MS, personal communication).

With respect to soils, sites were assessed for presence of a loamy surface (A) horizon, and development of structure in the surficial layer, as these characteristically develop relatively rapidly on stable alluvial surfaces in the region (Olson, 2003). Some floodplain and alluvial terrace soils in the WPG area also develop an argillic horizon (Olson, 2003).

Sediment production from channel banks was quantified using active cutbanks, erosion scarps, or hillslope mass wasting scars, straight or concave bank profile shapes, exposed tree roots, and toppled trees. Any contiguous length of channel bank >5 m^2 in surficial area that exhibited obvious sediment removal was recorded as a single erosion feature. The bank height relative to the adjacent channel was measured with a stadia rod or folding ruler, at 2- to 5-m intervals depending on variability. Erosion length was measured by tape. Root plates, root-supported overhangs, or other suitable root exposures were measured as shown in Fig. 3 to determine bank retreat, based on the conservative assumption that the original bank position corresponded with the end of the exposed roots. Where vegetation was absent, retreat was measured by measuring concavities or indentations relative to adjacent uneroded banks. Measurements were to the nearest 0.1 m for length, 0.01 m for height, and 0.05 m for retreat depth.

The largest of the measured retreats was used to estimate bank retreat for each erosion feature. As measured, the depths account for the minimum amount of retreat, as the original position of vegetation relative to the bank or actual bank extent cannot be known, and as ongoing erosion or lateral migration progressively eliminates morphological and vegetation evidence. Therefore, despite being the maximum, the largest value for each feature provides a conservative estimate of erosion depth.

The eroding surface area was determined as the product of length and mean height (or of length, mean depth, and mean width for the perimeter of chute channels across point bars). This eroding surface area can be compared to sediment storage in the reach by determining the amount of bank retreat necessary to balance the reach storage. For convenience, this is termed "steady state erosion" (SSE): SSE = storage volume/eroding surface area.

Fig. 3. Arrow indicates example measurement of minimum bank erosion based on exposed tree roots.

2.4. Data analysis and interpretation

The concept of sediment connectivity (Bracken et al., 2015) was used to assess the potential for and frequency of coarse sediment movement between reaches, and thereby provide a basis for linking apparent storage surplus (or lack thereof) in a reach to possible upstream sources (or barriers). As Lisenby and Fryirs (2017) have noted, controls on bedload sediment and connectivity may vary considerably between fluvial systems, implying that no *a priori* assumptions can be made about BCC or any other given system. They further argue that sediment (dis) connectivity may be of comparable importance to drainage basin and channel size. There exist several approaches for connectivity analyses; we chose that of Hooke (2003) because it applies specifically to coarse sediment in channels, and identifies connectivity scenarios directly relevant to the research objectives.

Hooke's (2003) approach is based on the premise that the presence of coarse-grain bars indicates that coarse-sediment transport occurs. The absence of such bars indicates that one of three conditions occurs: (1) limited coarse sediment flux due to lack of competence; (2) flushing or throughput due to high competence; and (3) potential coarse sediment transport, but limited by exhaustion of supplies or lack of availability. This premise and the three explanatory conditions are then used to define five classes of connectivity (Hooke, 2003):

Unconnected systems are characterized by localized sources and storages, with reaches operating somewhat independently. Reach-to-reach propagation of effects requires very large flood events, or operates very slowly. In BCC the signature of this state would be local sediment accumulations (e.g., cobble/pebble bars) closely associated with nearby bank erosion, and a close relationship between SSE and observed bank retreat.

Partially or episodically connected systems have little coarse sediment transport between reaches except in extreme events. According to Hooke (2003), this is distinguished from unconnected systems by evidence that the coarsest material is occasionally transported. In our study we assess this by determining whether the LMC could be transported given the local shear stress at banktop flow, as described above.

Potentially connected systems are limited by coarse sediment supply. That is, transport between reaches is possible, but does not occur due to lack of availability.

Connected systems are those in which coarse sediment moves regularly through, transported by flow events with recurrence intervals of five years or less (Hooke, 2003). Sediment may be stored in bars, but is readily remobilized. Bar mobility is assessed in our study based on vegetation, embeddedness, soil development, and potential LMC mobility as described above.

Table 1
Characteristics of BCC study sites (in upstream-downstream order).

Reach	Upstream drainage area (km^2)	Reach length (m)	Observed bank erosion[a] (m)	Number of storage features (bars)	Channel slope ($\times 10^{-3}$)
1	4.08	132	2.90	1	4.7
2	4.81	119	0.90	2	10.0
3	11.65	175	2.50	2	7.1
4	12.79	131	1.85	1	1.1
5	13.86	117	1.90	3	6.2
6	14.02	197	1.45	1	4.1
7	14.22	109	0.00	4	0.7
8	15.79	216	1.90	2	2.0
9	17.24	152	0.72	5	0.4
10	18.79	121	3.00	1	3.3
11	19.74	120	2.47	3	12.3
12	29.12	158	2.80	2	12.7
13	29.56	147	0.00	1	3.0
14	29.95	148	0.00	2	0.7

[a] Horizontal bank retreat based on exposed roots, root mat or vegetation overhangs, or bank morphology.

Fig. 4. Range of particle sizes exposed in eroding alluvial stream bank and adjacent lateral bar.

Disconnected systems have physical barriers to movement. Hooke (2003) cites dams and weirs as examples, but some non-human phenomena such as beaver dams, large woody debris jams or dams, and landslide blockages could also result in coarse sediment disconnectivity.

Thus the key criteria applied in the study area are the spatial relationships and relative magnitudes of in-channel sediment storage and bank erosion features, evidence of activity or stability of storage features, and their apparent mobility.

3. Results

General characteristics of the study reaches are shown in Table 1. Alluvium ranges in size from fines to boulders, but is dominantly coarse-pebble to small-cobble size (Fig. 4). Bedrock outcrops in the channel bed and banks are common. The channel is flanked by relatively narrow floodplains on one or both sides along most of its length.

3.1. Bank erosion

Erosion features occur at 12 of the 14 study reaches, with a total of 26 features (Table 2). Cutbanks are the most common form ($N = 15$). As cutbanks are directly related to adjacent bars, they may be associated with net sediment storage, net erosion, or approximate steady-state, depending on erosion rates relative to rates of bar growth. The three chute channels all occurred on active bars. Five bank slope failures were identified, and the remaining three cases were eroding banks not associated with point or lateral bars (Table 2). As the latter cases are not locally offset by sediment storage in point bars, they represent a local channel sediment source.

The height of eroding banks or failures was generally <1.5 m, except at one site where lateral stream erosion of an alluvial terrace has created cutbanks >4 m high, at reach 12. The streamwise length of the features ranged from <10 to >120 m, with non-eroding bank sections not included. Bank erosion area (eroding length × height) ranged from <5 m^2 for a short cutbank at reach 1, to about 285 m^2 for a cutbank at reach 12. The largest erosion feature was a chute channel at reach 13.

Only minimum bank retreat could be measured, based on the indicators described in the Study Area and Methods section. Where these indicators existed, retreat ranged from <1 m to 2.9 m. Retreat amounts based on exposed roots and overhangs were all <2 m, suggesting a limiting size for these features—that is, it may be that larger overhangs cannot be maintained.

For almost every feature (24 of 26), the bank material being eroded was cobbly and pebbly alluvium. Rock fragment content ranged from about 30 to >70%, though sometimes with a silty surface layer with lower rock fragment content. The remaining two features (at reach 9) were eroding upland valley walls composed of shale bedrock and colluvial soil.

3.2. Sediment storage

All sites had sediment storage in the form of bank-attached or mid-channel bars, with a total of 27 bars inventoried (Table 3). Seventeen of these were lateral bars, and two were point bars. However, some of the

Table 2
Bank erosion features, BCC study reaches.

Reach	Feature[a]	Length (m)	Mean height (m)	Bank erosion area (m^2)	Bank retreat feature(s)	Bank retreat (m)
1	Cutbank	7.0	1.00	7.00	Morphology, exposed roots, tilted tree	1.30
1	Bank slope failure	11.7	1.16	13.57	Morphology	2.90
1	Cutbank	10.9	0.81	8.77	Exposed roots	0.80
2	Cutbank	13.6	1.38	18.70	Exposed tree trunk & roots	0.90
2	Cutbank	18.4	0.90	15.64	Exposed roots; morphology	0.85
3	Cutbank	16.0	1.30	20.80	Exposed roots; morphology	1.70
3	Cutbank	14.50	1.10	15.95	Morphology; exposed roots	1.10
3	Cutbank	82.60	1.44	119.18	Exposed roots	2.50
4	Cutbank	116.7	1.46	170.58	Exposed roots; root mat	1.85
5	Cutbank	61.8	4.24	262.07	Exposed roots	1.90
5	Cutbank	29.5	4.68	138.06	Exposed roots; root mat	1.93
6	Cutbank	57.5	1.30	74.75	Exposed roots; root mat	1.45
7	None					
8	Eroding bank	19.1	1.28	24.45	Tilted tree	24.45
8	Eroding bank	6.0	0.80	4.80	None	
9	Chute channel	9.9	1.47	14.44	None	
9	Chute channel	35.0	1.41	49.35	None	
10	Eroding bank	9.9	1.00	9.90	None	
10	Cutbank	20.0	0.95	19.0	None	
10	Cutbank	121.0	1.46	176.86	Root plate of uprooted tree	3.00
11	Bank slope failure	13.3	1.00	13.30	Morphology	2.47
12	Bank slope failure	18.85	1.37	25.92	Morphology	2.60
12	Bank slope failure	15.9	0.60	9.54	Morphology	2.80
12	Bank slope failure/cutbank	9.9	0.90	8.91	Morphology	1.20
12	Cutbank	124.1	2.30	285.34	Morphology	2.00
13	Chute channel	110.8	1.91	532.36	None	
14	None					

[a] An eroding bank is characterized as a cutbank if it occurs immediately opposite a point bar or lateral bar.

Table 3
Sediment storage in bars at BCC sites. Blank cells = missing data.

Site	Feature	Length (m)	Mean width (m)	Elev. below banktop (m)	Elev. above thalweg (m)	Total storage volume (m^3)	EP[a]	LMC[b] (mm)
1	Lateral bar + bank failure deposit	11.7	2.9	0.48	0.55	18.7	70	193
2	Lateral bar	23.5	3.7	0.22	1.18	101.7	<5	254
2	Lateral bar	22.0	3.5	1.32	1.18	90.9	15	200
3	Point bar	11.2	4.0	0.00	1.50	67.2	<5	144
3	Lateral bar	31.2	4.9	1.37	1.24	189.6	<5	188
4	Point bar	116.7	4.9	0.85	1.04	594.7	17	140
5	Lateral bar	49.6	4.6	0.67	1.41	322.0	25	222
5	Lateral bar	20.6	5.3	0.88	0.79	86.9	30	235
5	Point bar	20.3	6.6	0.82	1.31	175.3	<5	138
6	Lateral bar	61.5	5.0	1.08	1.04	321.1	20	245
7	Lateral bar	15.1	1.3		0.80	16.3	25	123
7	Lateral bar	113.0	5.3	0.38	0.77	464.6	20	349
7	Lateral bar	12.2	2.2	0.13	1.31	35.7	25	160
8	Forced bar	12.0	6.0	0.50	1.07	77.0		251
8	Lateral bar	29.6	7.7	0.88	1.16	265.5		
9	Mid-channel bar	13.9	7.8	0.28	0.77	83.7	<5	251
9	Crevasse splay	17.8	5.4	0.41	0.87	83.1	<5	134
9	Mid-channel bar	21.2	4.5	0.25	1.12	106.8	<5	
9	Crevasse splay	13.9	3.8	0.41	0.87	46.4	<5	169
10	Lateral bar	121.0	7.1	0.68	0.97	827.5	14	255
11	Bank slope failure deposit	12.4	2.4		2.50	73.4	36	210
11	Lateral forced bar	5.0	1.6		2.50	20.0	20	119
12	Mid-channel bar	29.0	2.8	0.83	1.05	81.2	52	275
12	Lateral bar	72.5	6.0	1.12	0.52	226.2	44	300
13	Lateral bar + mid-channel bar	110.8	5.5	0.74	2.37	1446.8	<5	350
14	Lateral bar	64.3	5.2	0.30	1.13	376.4	22	273
14	Lateral bar	113.6	4.1	1.01	0.41	191.0	10	209

[a] EP = percentage of clasts on bar surface embedded.
[b] LMC = largest mobile clast (median diameter).

lateral bars occurred on the inside of minor bends and were therefore similar to point bars. Only three mid-channel (as opposed to bank–attached) bars were inventoried; other features included bank slope failure deposits and crevasse splays (fan deposits associated with overbank flow).

The amount of sediment stored in the bars (recall that only the apparently active portions of the bars were assessed) varied widely, but 25 of 27 deposits had volumes <600 m^3 (Table 3). Reach 1 had an order of magnitude less storage than any other reach (18.7 m^3 vs. 192.5 for the second-smallest reach). Reach 13 (about 1467 m^3) is characterized by a lateral bar complex that is almost 1.8 times larger than the second-largest storage feature (827.5 m^3 at reach 8) and nearly 2.5 times that of any other reach. It is possible that upper portions of this bar had been recently reactivated by high flows.

The mean and maximum elevations of the bars were all below the elevation of the local bank top, indicating that these are indeed bars and not islands with cover deposits, and that they are inundated at banktop flows. Mean elevation of the bar surfaces relative to the adjacent thalweg was 1.19 m (std. dev. = 0.57 m), ranging from 0.51 to 2.50 m. Streamwise length of the bars ranged from 5.0 to 121.0 m (mean = 39.2 m, std. dev. = 38.4 m), and widths from 1.3 to 7.8 m (mean = 4.5 m, std. dev. = 1.7 m).

Relationships between bar and channel dimensions were examined to determine the extent to which the former scale with channel size.

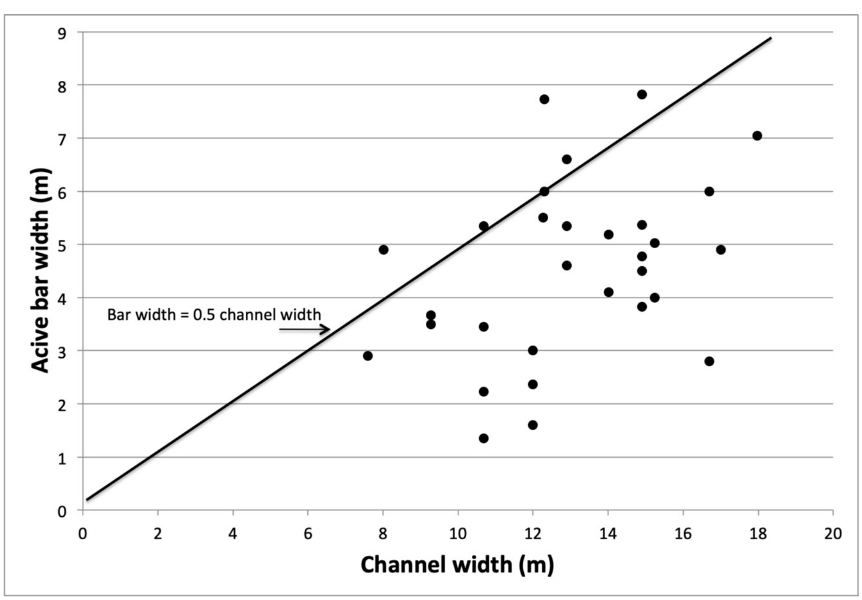

Fig. 5. Relationship between bar and channel width.

While bar width must be locally limited by channel width, it is not otherwise related to the banktop channel width of the representative cross section for each reach. Fig. 5 shows that all but 5 of the 31 storage features lie on or below a line representing a bar width equal to half of banktop channel width, illustrating the very general scaling relationship. Otherwise, there is considerable scatter. Similarly, Fig. 6 shows that all but three points fall below a line representing bar height = mean depth × 2, but with otherwise no apparent relationship between mean depth and bar height or thickness. Recall, however, that all bar tops are below the banktop channel elevation. Overall, results suggest weak scaling representing the constraints of channel size on bar size, but also reflecting local variations in sediment supply vs. transport capacity relationships.

Substrate angularity was highly consistent for all storage features. Clasts were dominantly subangular, with a significant number of subrounded clasts, though occasional angular and rounded stones could be found.

Observations indicate channel bars have relatively small amounts of fine sediment. Ten of the 25 bars sampled had very few or no embedded particles (recorded as <5% in Table 3). Only four bars had >25% of surface clasts classified as embedded, and this includes partial burial by coarse as well as fine material.

All the measured bars appeared active, as indicated by the presence of clean-washed sediment, low embeddedness at most sites, minimal vegetation cover and fine sediment deposits, and presence of wrack and flow indicators on the bar surfaces. The ratio of critical shear stress to estimated local maximum bankfull shear stress is shown in Fig. 7. Most ratios are ≤1, indicating mobility at banktop flows. Four of the cases where the ratio is >2 (bars 17, 18, 19, in Fig. 7) are at one reach (9) which has undergone significant recent geomorphic change, as discussed below. At reach 13, the LMC for bar 28 was found within a chute channel dissecting a lateral bar, and may represent deposition during a flood event significantly above banktop stage. The ratio of 1.8 for bar 13 at reach 7 reflects an anomalously large clast compared to the other two bars at the site, and the four other values >1 are all ≤1.4. In general, then, all bars appear to be potentially fully mobile at flow levels likely to be encountered at least several times per decade.

Few of the storage features showed evidence of pedogenic development, and none exhibited an argillic or other B horizon (Table 4). The point bar at site 4 had some soil development on the older, upper, inner part of the bar, characterized by development of a thin (<20 cm) gravelly loam A horizon with weak fine granular structure. Lower, younger portions of the bar had no soil development. The lateral bar at reach 6 has similar pedogenic features on its upper, vegetated portion, though the lower, active portion of the bar had no soil. A similar pattern was observed on the lateral bars at reaches 10 and 13.

The storage features were generally sparsely vegetated. Some herbaceous plants were sporadically encountered, and may have been more numerous in the summer (sampling occurred in late winter). The typical case was sparse woody vegetation, with trunk diameters <10 cm, and many <2 cm. However, some of the point and lateral bars had larger trees. These were generally sweetgum (*Liquidambar styraciflua*) and American sycamore (*Plantanus occidentalis*); both are common in valley bottom and riparian settings in the Ouachita Mountains. These larger specimens had dbh of 20 cm or more, indicating surfaces established before the early 1990s.

3.3. Sediment production vs. storage

Sediment storage, bank erosion, and computed SSE values for all reaches are given in Table 5. Three reaches had no evident sediment production, and at eight others the bank retreat necessary to balance sediment storage (i.e., SSE) is more than a fifth of channel width (Fig. 8). To put this in context, bank retreats of this magnitude (0.2 times banktop channel width) are at least four times annual bank retreat rates reported in the literature for laterally migrating alluvial rivers (Nanson and Hickin, 1986; Richard et al., 2005; Nicoll and Hickin, 2010).

Fig. 8 shows the sediment function of the reaches. Three sites have storage and no erosion (7, 13, 14), thus are deemed storage sites. For 7 of remaining 11 reaches the SSE was greater (by up to nearly eightfold) than the observed retreat (Fig. 8). Therefore, a total of 10 reaches exhibit net storage. In all of these cases SSE ≥ 0.21 W, and SSE is >1.5 to nearly eight times the observed erosion (Fig. 8). Reaches 3 and 5 may be in approximate steady-state. Bank erosion necessary to balance measured storage is 0.21 W and 0.11 W, respectively, but in both cases less than observed bank retreat. Reaches 1 and 12 are net sediment sources.

3.4. Bar age and stability

Eleven of the 27 field-measured bars were not visible on aerial photographs taken in 1994, 2001, 2006, 2009, and 2012. In these cases forest cover obscures details of the creek channel (Table 4).

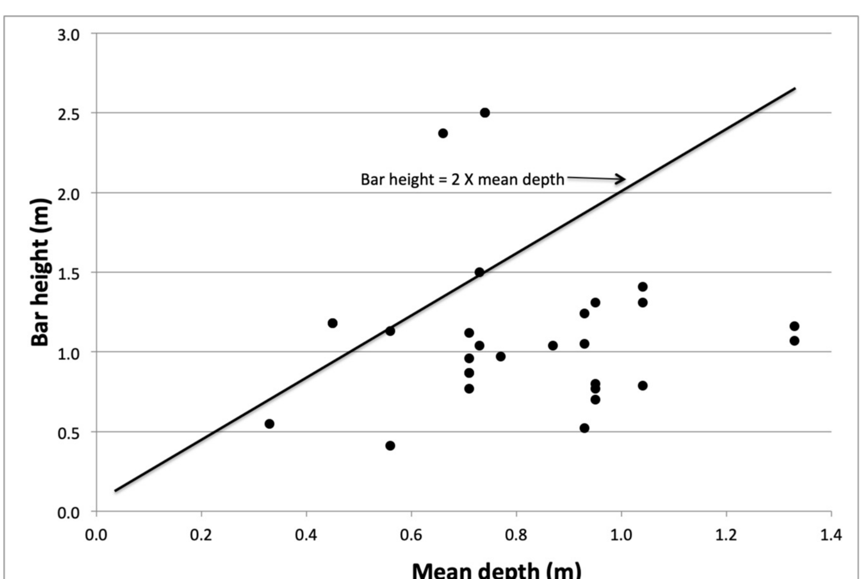

Fig. 6. Relationship between bar height and adjacent mean channel depth.

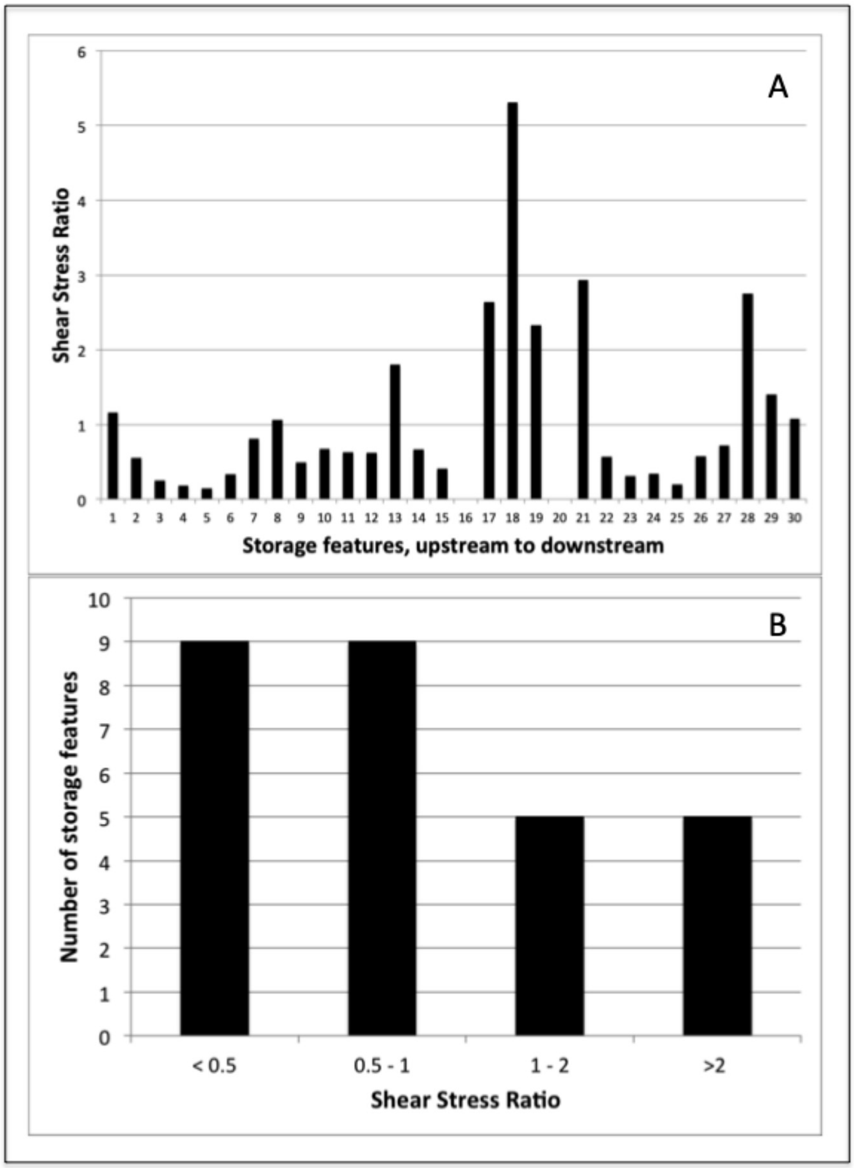

Fig. 7. Ratio of critical shear stress for largest mobile clast to estimated maximum shear stress at banktop flow. Largest mobile clast samples missing from bars 16 and 20 in A.

In 12 of the 16 cases where bars are visible, they are evident on the earliest (1994) photographs, indicating they were likely present when the WPG trail complex was established (ca. 1992). The four cases where bars are visible only on 2006 or later photographs are at sites 8 and 9. Earlier aerial photographs were examined, but the resolution was not sufficient to identify channel features.

Fifty percent of the sites had active or periodically active bar areas. At six reaches (4, 6, 10, 12, 13, 14) point or large lateral bars exist that had active, unvegetated lower areas with no soil formation, but with upper portions of the bar apparently semi-stabilized, as indicated by soil or vegetation characteristics (Table 4). This indicates initiation of these features by the early to mid-1990s or earlier. One of the bars at site 2 also suggests a degree of longevity: though there is no evident soil development, the trees present have dbh values up to 17 cm.

At site 7, the largest bar is associated with a high flow crevasse channel that during floods bypasses a structurally-controlled bend. This channel is periodically active, as indicated by presence of clean-washed cobbles and pebbles within the side channel, and wrack and flow-bent vegetation within or alongside-channel margins. However, the feature has apparently existed for some time. Evidence of it appears on 1994 aerial photographs, and the anabranching subchannels flow through an area with a number of relatively large trees (dbh 15 to 35 cm). These include sweetgum, shortleaf pine, and oaks. Some of these larger trees are rooted in alluvial material, with basal flares and root crowns clearly visible (indicating surface erosion or stripping), while others are partly buried by alluvium. This suggests local variability in the erosion and deposition effects of high flows.

A general summary of changes at each study reach is given in Table 6.

3.5. Geomorphic changes and OHV use

Determination of the potential role of the BCC channel as a sediment source, and coincidence of channel change with OHV use must be considered in the context of overall geomorphic changes of the channel. By assessing geomorphic change at the study reaches over the past two decades, some insight into the extent to which changes can be attributed to OHV impacts can be gained.

Table 4
Soil development, vegetation, embedding percentage (EP), and earliest aerial photography on which feature is visible (APV; NV = not visible on any photographs).

Site	Bar[a]	Soil	Vegetation	EP	APV	Notes
1	LB	None	Moss, sparse woody	70	NV	Litter abundant on bar surface
2	LB	None	Sparse woody < 2 cm	<5	NV	
2	LB	None	Sparse woody < 2 cm; (*Liquidambar styraciflua* up to 17 cm) on upper bar	15	NV	
3	PB	None	None	<5	1994	Apparent long term channel migration toward right side of valley
3	LB	None	Sparse woody < 4 cm	<5	1994	
4	PB	None to minimal	Woody < 7 cm; (*Liquidambar styraciflua* and *Quercus* spp. up to 32 cm) on upper bar	17	1994	Meander translation evident
5	LB	None	Very sparse woody < 1 cm	25	1994	
5	LB	None	*Plantanus occidentalis* seedlings	30	1994	
5	PB	None	None	<5	1994	
6	LB	Minimal	*Liquidambar styracaflua* up to 26 cm	20	1994	
7	LB	None	None	25	NV	
7	LB	None	Sparse woody < 2 cm	20	1994	Connected to crevasse channel with larger trees
7	LB	None	None	25	NV	
8	FB	None	Sparse woody < 2 cm		NV	Remnant floodplain adjacent
8	LB	None	None		2006	High flow/crevasse channel adjacent
9	MB	None	None	<5	2006	
9	CS	None	Sparse woody	<5	2012	Exposed roots in associated crevasse channel
9	MB	None	Sparse woody	<5	2006	Remnant floodplain adjacent
9	CS	None	Sparse woody	<5	NV	*Quercus alba* dbh = 5 cm with exposed roots in associated crevasse channel
10	LB	None to minimal	*Plantanus occidentalis* up to 20 cm on upper bar; seedlings on lower bar. *Carpinus caroliniana* ≤ 4 cm on mid bar	14	1994	Three lobes of bar evident, increasing in age away from channel
11	SF	None	Sparse woody < 2 cm	36	NV	
11	LB	None	None	20	NV	
12	MB	None	Woody < 5 cm	52	NV	
12	LB	None	Woody up to 20 cm	44	NV	
13	LB	None to minimal	Scattered woody < 10 cm; larger trees (*Liquidambar styraciflua* up to 30 cm) on upper bar	<5	1994	
14	LB	None	Scattered woody < 6 cm; larger trees (*Liquidambar styraciflua* and *Quercus* spp. up to 28 cm) on upper bar	22	1994	At least two alluvial terraces present
14	LB	None	None	10	1994	

[a] CS = crevasse splay; LB = lateral bar; MB = mid-channel bar; PB = point bar.

Study reaches varied in their evidence of recent geomorphic activity, based on field evidence and historical aerial photographs. Several reaches showed evidence of minor local changes such as some isolated cutbank erosion or bank failures and active bars, but were otherwise relatively stable (reaches 2, 11). Reach 3 also fits into this category, but the presence of a terrace indicates some longer-term incision that may be associated with increased runoff from early twentieth century logging activities. Terrace fragments and other evidence such as mouths of small tributaries well above the level of main stream beds elsewhere in WPG is consistent with this interpretation. Reach 14 also has at least two terrace levels, and active bars, but no significant erosion. These changes either predate establishment of the WPG trails, and/or would not necessarily require or imply increases in sediment input or runoff.

Table 5
Measured in-channel sediment storage and bank erosion, BCC study reaches.

Reach	Storage (m^3)	Storage/reach length (m^2)	Bank erosion surface area (m^2)	Bank erosion area/length (m)	Steady-state erosion (m)[a]
1	18.66	0.14	29.35	0.22	0.64
2	192.54	1.62	34.34	0.29	5.61
3	256.77	1.47	155.93	0.89	1.65
4	594.70	4.54	170.58	1.30	3.49
5	584.25	4.99	400.13	3.42	1.46
6	321.08	1.63	74.75	0.38	4.30
7	528.95	4.85	0.00	0.00	N/A
8	342.57	1.59	29.25	0.14	11.71
9	368.73	2.43	92.80	0.61	3.97
10	827.46	6.84	176.86	1.46	4.68
11	198.70	1.66	36.40	0.30	5.46
12	307.40	1.95	329.71	2.09	0.93
13	1466.89	9.98	0.00	0.00	N/A
14	567.34	3.83	0.00	0.00	N/A

[a] Amount of bank retreat necessary to equal storage amount, calculated as storage/bank erosion area.

Other reaches show evidence of active lateral channel migration (cutbanks and active lateral bars) along much of their length, but no other major changes (reaches 1, 3, 5, 12). Reach 5 occurs within a portion of BCC that experienced an upstream avulsion to the present channel sometime before 1994. Aerial photographs from 1994 show both channels still active; subsequent photographs show the original channel gradually becoming more infilled and vegetated. At the time of fieldwork it was still active as a high-flow channel, but did not normally carry flow. In reach 5 lateral migration is encroaching on an upland valley side slope. Again, observed changes were either initiated before the WPG trail complex opened, or do not necessarily reflect increases in sediment input or runoff.

All of the changes identified at reaches 4, 5, 6, 7, 10, and 13 could have occurred independently of any increased runoff or erosion from the ATV trails. Reach 4 encompasses a meander bend, which is experiencing active point bar accretion and cutbank erosion, as well as downstream translation of the bend. By contrast, reaches 6 and 13 include "bend bars" (lateral bars on the inside of low amplitude channel bends), with the outer bend encroaching on bedrock valley side slopes. The bedrock control limits bend migration, and in both cases aerial photographs indicate episodes in recent decades of stripping and re-establishment of vegetation cover. Both sites were relatively well vegetated at the time of fieldwork, and both included larger trees that persist through the vegetation removal episodes. This, plus the absence of any evidence of significant pedological development on the bars indicates that they are episodically active despite their relatively fixed locations. Reach 13 has an active high-water chute channel across the back of the bar, but no similar feature is present at reach 6. At reach 10, like reach 4, evidence suggests ongoing bar growth and cutbank erosion, though 10 features a lateral bar on a minor bend, with limited evidence of any downstream translation. Vegetation cover, soil development, and

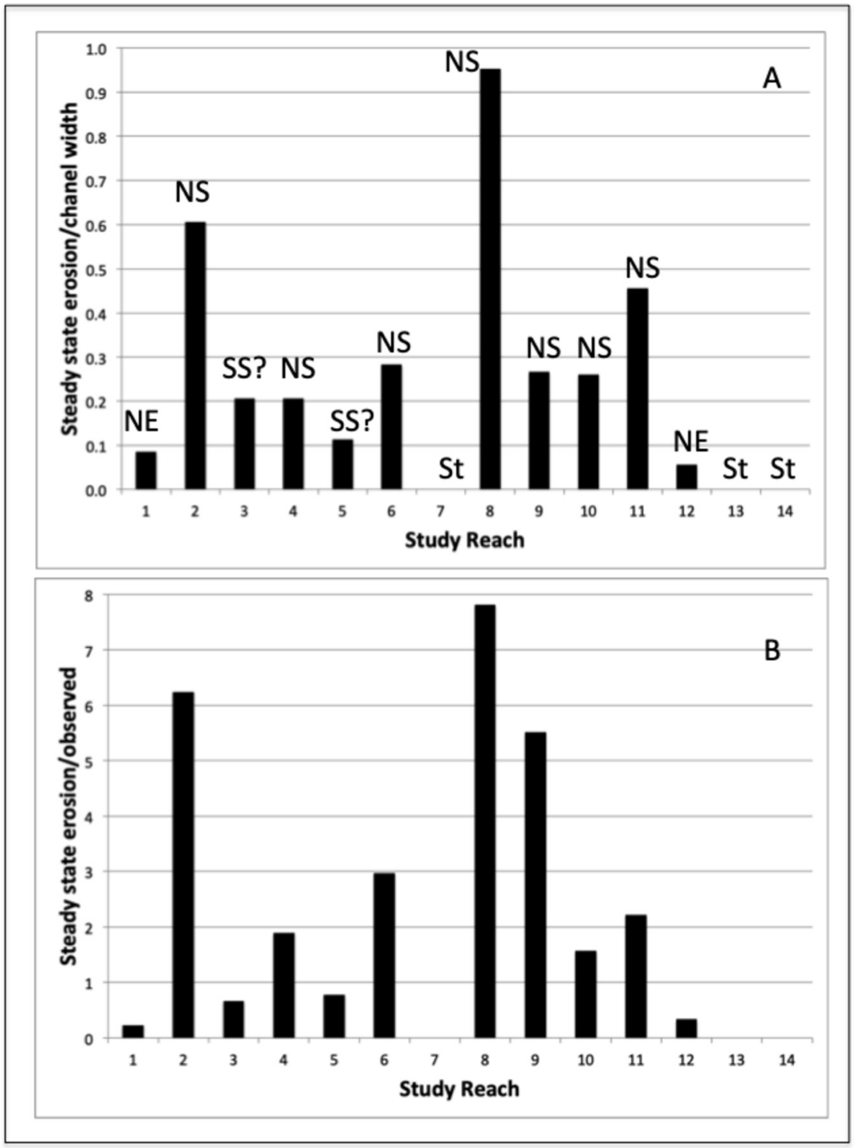

Fig. 8. Steady-state erosion relative to bankfull channel width (A) and to observed bank retreat (B). Top also shows the coarse sediment function of the reaches: NE = net erosion (sediment source); NS = net storage; St = storage only; SS = approximate steady-state.

topography indicate at least two levels of stabilized bar in addition to the currently active portion.

Reach 7 is characterized by a strong degree of bedrock control, and occurs just upstream of a structurally controlled bend. Accordingly, there is little or no bank erosion or obvious channel migration, though active bars are present. This site also has a high-flow distributary channel characterized by clean-washed cobble and pebbles, and including some wrack and flow indicators. At this site the bedrock constriction apparently provides a flow bottleneck during floods, displacing water and sediment through the high-flow channel. Broadly similar phenomena may account for the high-flow chute channels at site 13, and high flow occupation of the abandoned channel at reach 5.

Though sediment produced by the trail system is being and has been delivered to BCC, and local impacts are evident at current and former ford-type crossings, only at reaches 8 and 9 can changes be clearly linked to impacts of the trail system. Reach 8 features a former ATV trail crossing (now closed) at its upper end that apparently destabilized the stream bed. There exists a crevasse channel initiating near this crossing that cuts across a former floodplain surface (the floodplain remnant is characterized by mature trees and a floodplain soil with a silty surface horizon). The crevasse channel exhibited wrack lines showing that it conveys flow at high stages, while the woody vegetation present is <5 cm in diameter, suggesting relatively recent formation (<10 yr). A relatively short distance downstream, reach 9 has experienced the most extensive recent changes of any study reach. A chute cutoff of a bend occurred sometime between 2001 and 2006, probably closer to the latter date. The reach has been transformed into essentially a bar-braided reach that includes both floodplain remnants as described above, and active mid-channel bars. Two newer crevasse channels exist; one each at the upstream and downstream ends of the study reach. This is consistent with a rapidly aggrading channel. The recent changes in both sediment input and channel characteristics probably account for the lack of congruence between critical shear stress for the LMC and estimated bankfull shear stresses described earlier. Table 6 gives a summary of the changes discussed above for each reach.

At reach 8 the field evidence is clear, and at 9 (in addition to it being a relatively short distance downstream of 8), sediment from the trail system is the only plausible source of the recent aggradation. A trail parallels the stream in this vicinity, never >40 m away, and fords several Board Camp tributaries, with visually obvious erosional impacts. The

Table 6
Summary of apparent geomorphic change at study reaches. “Stable” does not imply inactive. See text for further information.

Reach	Geomorphic condition/recent trends
1	Lateral channel migration
2	Stable
3	Lateral channel migration; terrace indicates previous incision
4	Lateral channel migration & downstream meander bend translation
5	Lateral channel migration, some encroachment on valley side & triggering of slope failure; avulsion & subsequent channel abandonment.
6	“Bend bar” with lateral migration limited by bedrock; episodes of vegetation stripping & reestablishment
7	Bedrock control limits lateral change; high-flow distributary channel activated at high flows
8	Lateral channel migration, crevasse channel, floodplain dissection
9	Chute cutoff; transformation to bar-braided reach; crevasses; floodplain dissection
10	Lateral channel migration focused at minor bend; multiple episodes of bar growth
11	Stable
12	Lateral channel migration
13	“Bend bar” with lateral migration limited by bedrock; episodes of vegetation stripping & reestablishment; extensive sediment storage
14	Active bars, no erosion; terraces indicate two previous incision episodes

latter include erosional rills and small gullies originating on the trail, incisional knickpoints at tributary crossings, and sediment deposits on the downslope side of the trails.

3.6. Coarse sediment connectivity

Abundant small gravel to cobble size sediment is available to BCC in channel, bar, and floodplain deposits, via tributary inputs, and slope or valley side inputs. Thus the “potentially connected” category of Hooke (2003) does not apply; nor does the “disconnected” category, as no significant barriers to coarse sediment movement exist. The largest unanchored clasts in each measured bar are mostly potentially mobile at banktop flows (Fig. 8), and field evidence suggests that most of the bars are active. This places all sample reaches in the “connected systems” category of Hooke (2003). Because in many cases the bars were apparently present at the time of WPG trail system establishment, there is no evidence that the connectivity class was different before 1994.

4. Discussion

Results indicate that BCC is storing more sediment within the channel than is being supplied via bank erosion. This in turn indicates significant sediment inputs from tributaries and upland erosion within the watershed. Recking, 2012 pointed out that bedload transport rates in cobble and pebble bed mountain streams are strongly influenced by sediment supply, and suggested that bed stability and mobility is linked to sediment forcing. This suggests that, given the mobility of the bars in BCC, a consistent sediment supply must exist. Some inputs from slope erosion are inevitable even in undisturbed forests of the Ouachitas, but these are minor (Marion et al., 2019). The trail system is the only significant sediment source in the WPG area observed to be active, though we did observe some minor mass wasting features.

With respect to Hooke's (2003) five connectivity classes, partially connected systems are limited by coarse sediment supply, which is not the case in BCC, and disconnected systems have barriers to movement, which are not present. The local imbalance between local sediment accumulations and inputs eliminates the unconnected class. The ability of banktop flows to mobilize the largest unanchored clasts in the bars is consistent with the partially/episodically connected or connected categories, with the apparent episodic mobility of the bars pointing to the latter. The coarse sediment connectivity, in turn, suggests that sediment inputs from trail erosion would be translated downstream.

Bracken et al. (2015) outlined four end-member scenarios for sediment connectivity, based on the extent to which sediment detachment and transport are hydrologically controlled. BCC and the WPG trail system are near the most strongly connected category, where both detachment and transport are hydrologically controlled. Detachment, however, is not fully hydrologically controlled, due to the role of slope processes and mass wasting in delivering sediment to the channel.

There are about 23 ha of trail surface in the WPG Trail Complex. Marion et al. (2019) determined that the annual erosion rate for the WPG trails is 75 to 210 t ha^{-1} yr^{-1}. Assuming a bulk density of 1000 kg m^{-3} for deposited sediment, this would account for 1590 to 4230 m^3 of sediment. This compares to about 6560 m^3 stored in bars in the studied reaches alone (additional alluvium is stored in floodplains, which were not measured). If all the trail sediment were delivered to BCC—and much is not—even several years worth of trail erosion is not sufficient to account for in-channel sediment storage. Total length of the sampled reaches is slightly over 2 km. Extrapolating to the entire 15.9 km length of BCC within the WPG complex implies >51,000 m^3 of storage in bars alone, equal to 12 to 32 yr of trail erosion at the rates indicated above. If the in-channel bars were part of a “conveyor belt” mechanism connecting trail erosion with downstream sediment transport, we would expect a closer match between erosion and storage, as well as the appearance of new bars after the mid-1990s. If the coarse sediment in the channel were associated primarily with a pulse input from the early days of the trail system, the bars would indicate greater longevity, and evidence of supply limitation (Hooke, 2003). The latter is not evident, as small gravel to cobble size sediment is ubiquitously available. It appears that contemporary erosion from the ATV trails is not the major factor accounting for the presence of the bars, though such erosion supplies some of the sediment stored therein.

This is *not* to say the ATV trails have no significant effects. Impacts at stream crossing sites have already been established (Marion et al., 2014), as have more general channel impacts (Chin et al., 2004). Erosion from the trail surfaces was documented in detail by Marion et al. (2019). Further, some legacy sediments from ATV impacts are a possibility. Three wide ford-type crossings of BCC were replaced by bridges, ca. 2005. Also, at least seven (and likely more) trail or road access points to the channel have been closed, and the former practice of riding ATVs within the channel has been prohibited. While these features and activities were not actively generating sediment or triggering geomorphic change during fieldwork for this project (based on their observed inactivity), some of our measurements may reflect their legacy effects. Portions of the study area were logged prior to and after establishment of the trail complex, and this may also have produced short-term sediment pulses (Marion and Ursic, 1993). However, past road construction and use likely produced more sediment than logging (Eisenbies et al., 2007; Neary et al., 2009; Anderson and Lockaby, 2011). Field evidence consistent with previous erosional periods is present in several parts of the WPG area, but the potential extent of such historic erosion has not been quantified. Erosion following fire is also a possibility, but these inputs are typically brief due to rapid vegetation recovery in forests of the southeastern US (Marion and Ursic, 1993).

In addition to bank erosion and some input from the trail system, some coarse sediment may be supplied by slope processes. Further, regolith stratigraphy in the study area and elsewhere in the Ouachitas indicates ongoing creep (Phillips et al., 2005). Field observations show that, due to the typical joint, fracture, and bedding plane characteristics of the rocks, cobble size fragments of the harder (i.e., non-shale) lithologies are commonly produced. This is reflected in the size and frequency of rock fragments found in soils in the area (Olson, 2003). Thus, even in the absence of accelerated upland erosion, particles of this size would be common (as they are in relatively undisturbed streams in the region; Marion and Weirich, 2003: Fig. 4). Due to the high shear stresses necessary to transport particles of this size (>30 N m^{-2}; from Eq. (1)), the bars may appear to be storage sites at normal and low flows, but function as active bedforms at higher flows. This is consistent with our connectivity analysis. Unfortunately, there is no hard evidence or baseline data to confirm whether detectable changes in BCC have occurred since the advent of concentrated ATV use. Because of the forest cover, and low resolution of some historical photographs, pre-1994 aerial photography is generally not sufficient to document historical in-channel change (or lack thereof). Anecdotal evidence—some from sources we consider highly credible—does suggest an increase in the number and size of cobble bars postdating establishment of the ATV trails. However, this could not be independently verified, and cobble bars are common in streams of the region regardless of ATV or other land-use impacts. Many of the bars (78% of those visible on imagery) examined in this study were apparently present in their approximate current location prior to the WPG trail system.

Arguably the most critical water quality and aquatic habitat impacts of erosion from the ATV trails are associated with fine sediments. Past work has shown that sediment produced by trail erosion is highly connected to nearby streams and produces obvious fine-sediment increases immediately downstream of channel crossings. Marion et al. (2014) found downstream increases in fine-sediment deposits and mud coatings on channel bedrock and rock clasts at 47% of OHV stream crossings they surveyed. Mud coats by definition were silt/clay coatings, but fine-sediment accumulations were predominantly sands to very-fine gravels. All of the Marion et al. (2014) crossing sites are upstream of the main-channel reaches sampled for the present study. Sediment accumulations dominated by fines (and then primarily by sand) occur only in backwater areas of the BCC channel, while siltier deposits are sometimes found on floodplain surfaces. Fines are present, but are a minor component, in the bars we surveyed. Thus the fine sediments clearly being produced by erosion of the trail system are either sequestered as colluvium or floodplain alluvium, stored in low-order channels, or being transported through the system when delivered to the Board Camp channel.

Independently of WPG Trail Complex impacts, the channel constructed by BCC is very active. Though our work specifically focused on apparently active reaches, these are quite common. Areas of active lateral channel migration or localized bank erosion are frequently observed, as is sediment storage in the form of cobble and gravel bars. While portions of these may eventually be stabilized, obviously mobile bars are common. Thus, as in almost any fluvial system, dynamic behavior and change is to be expected, and is not, in and of itself, cause for concern by resource managers and users.

In the absence of major transformations (such as the reach-scale metamorphosis at reaches 8 and 9) it is difficult to attribute changes in active channels to particular causes such as ATV trails. This is due to the fact that the system is inherently dynamic, the lack of historical baseline data for comparisons, and the changing nature of trail system impacts (and their legacy effects). In addition to the elimination of crossings and stream bed access mentioned above, trail reconstruction, installation of runoff and sediment control measures, and closure or relocation of problematic high-erosion trails has been ongoing throughout the trail system since 2011.

5. Conclusions

Fourteen geomorphically active reaches representing the range of conditions of BCC within the main-valley channels were examined in detail. Significant alluvial storage in the form of point, lateral, or mid-channel bars dominated by cobble and smaller gravel was present at all sites. Sediment storage volumes ranged from 140 to nearly 10,000 m^3 per kilometer of channel, with a mean of about 3400. Eleven of 14 reaches also had actively eroding banks. Ten reaches (71%) exhibit net sediment storage. Two are possible net sources, and two may be in approximate steady state (storage ≈ erosion). Fine (<8 mm) sediment from the trail system does not seem to be accumulating in the main-valley channel, suggesting that most is either being sequestered before reaching BCC, or transported downstream.

The imbalance between local bank erosion sources and in-channel storage, and the evidence of frequent clast mobility of most of the bars indicates a connected system in the sense of Hooke (2003), with coarse sediment mobile during banktop flow events, and no evidence of sediment starvation.

Many of the channel bars predate the trail complex, and most are active. This suggests that these features constitute mainly transient storage and are an inherent feature of the channel. Some of the apparent net accumulation of coarse sediment in channels could be attributable to erosion from the trail system, but at only two reaches could geomorphic changes be confidently attributed to the trail system. Like many streams in the Ouachita Mountains, BCC has an active channel, independent of the WPG trail system. These results highlight the difficulty of attributing fluvial change to specific causes or forcings in active fluvial systems.

In general, we find insufficient evidence to conclude that the presence and use of the OHV trail system has affected coarse-sediment storage or connectivity in the main-valley channel of BCC. However, two sites (reaches 8 and 9) do provide such evidence. Moreover, past work (Marion et al., 2014) demonstrates that direct impacts from ford crossings on the WPG trail system can change channel morphology, bed-material size, and fine-sediment accumulation. Therefore, past and current efforts to eliminate or mitigate ford crossings, and reduce fine-sediment delivery to channels from the trails seem well advised.

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