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Stream channel responses and soil loss at off-highway vehicle stream crossings in the Ouachita National Forest

Daniel A. Marion [a,b,*], Jonathan D. Phillips [b], Chad Yocum [a], Stephanie H. Mehlhope [c]

[a] USDA Forest Service, Southern Research Station, P.O. Box 1270, Hot Springs, AR 71902, United States
[b] Department of Geography, University of Kentucky, Lexington, KY 40506-0027, United States
[c] Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, KY 40506, United States

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ABSTRACT

This study investigates the geomorphic effects of ford-type stream crossings in an off-highway vehicle (OHV) trail complex in the Ouachita National Forest, Arkansas. At a total of 15 crossing sites, we used a disturbed vs. undisturbed study design to assess soil truncation and an upstream vs. downstream design to assess in-channel effects. The 15 sites ranged from OHV crossings active for over 20 years to those on trails that have been closed to regular use for >5 years. All of the sites designated for OHV use (14 sites) exhibit soil loss of ~30 to 45 cm within the trail segments on either side of the crossings. In-channel responses attributable to the crossings were observed at 14 (93%) of the sites and include increased bank erosion, increased 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. However, while every site but one shows at least one channel impact, only one site exhibits all of them. Despite the relatively homogeneous geographic area sampled, only limited generalizations are evident. Sediment impacts seem to predominate over runoff impacts from the trails. Small channels (basin areas <0.4 km^2) show greater consistency in their response behavior than larger channels. Where OHV use is currently allowed, downstream increases in mud coatings and sediment deposition features are more common. What seems more certain is that individual effects are strongly contingent on local details of channel and valley geomorphology.

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1. Introduction

Off-highway vehicle (OHV) use is a large and growing outdoor recreation activity in the United States. As used here, OHV is an umbrella term that includes all-terrain vehicles (ATVs, four-wheelers, quads), utility or recreational off-highway vehicles (UTVs, ROVs, side-by-sides), and off-highway motorcycles (snowmobiles are excluded). In 2003, the estimated number of ATVs and off-highway motorcycles in the United States was over 8 million (8,010,000) and had increased 174% since 1993 (Cordell et al., 2008). By 2007, 19.2% of all persons above the age of 16 years participated in OHV recreation nationwide (Cordell et al., 2008). Much of the recreational OHV use in the United States occurs on public lands (Cordell et al., 2008). Balancing the desire to provide recreation opportunities to OHV users and promote related economic benefits to local communities against the mandate to prevent adverse environmental change presents a growing challenge to public-land managers. Environmental impacts from OHV use can result from visitor traffic on formal (designated) and informal (visitor-created) trails and includes the compaction, erosion, and displacement of soils, vegetation loss, and degraded water quality owing to trail-generated sediment (Foltz, 2006). In this study, we examine the potential geomorphic responses of channels and soils at ford-type stream crossings of OHV trails within the Wolf Pen Gap Trail Complex (WPGTC), near Mena, AR (Fig. 1).

Recreational OHV use is extremely popular in Arkansas and its surrounding states. In 2007, over half a million OHV users were identified in Arkansas (557,100) and Oklahoma (695,500), representing about 25% of the state populations age 16 or older (Cordell et al., 2008). A significant fraction of these users—as well as those from Texas, Louisiana, Mississippi, and elsewhere—utilize the WPGTC.

The WPGTC is a designated OHV use area in the Ouachita National Forest. The trail complex is open year-round and currently offers 56 km of OHV loop trails for varying skill levels (http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5212722.pdf). Also within the complex are unpaved roads that are accessible to high-ground clearance, highway-legal, two- and four-wheel-drive vehicles, as well as ATVs (hereafter we use 'ATV' to include all vehicles specifically designed for off-highway trail use and lacking features required for legal on-highway use, and 'OHV' as a broader term encompassing ATVs and 'street legal' vehicles that can be used off-highway). The trail system was originally developed in the early 1990s from existing unpaved logging roads and with additional OHV trails added. Since its development,

* Corresponding author.
E-mail addresses: dmarion@fs.fed.us (D.A. Marion), jdp@uky.edu (J.D. Phillips), cmyocum@fs.fed.us (C. Yocum), stephanie.houck@uky.edu (S.H. Mehlhope).

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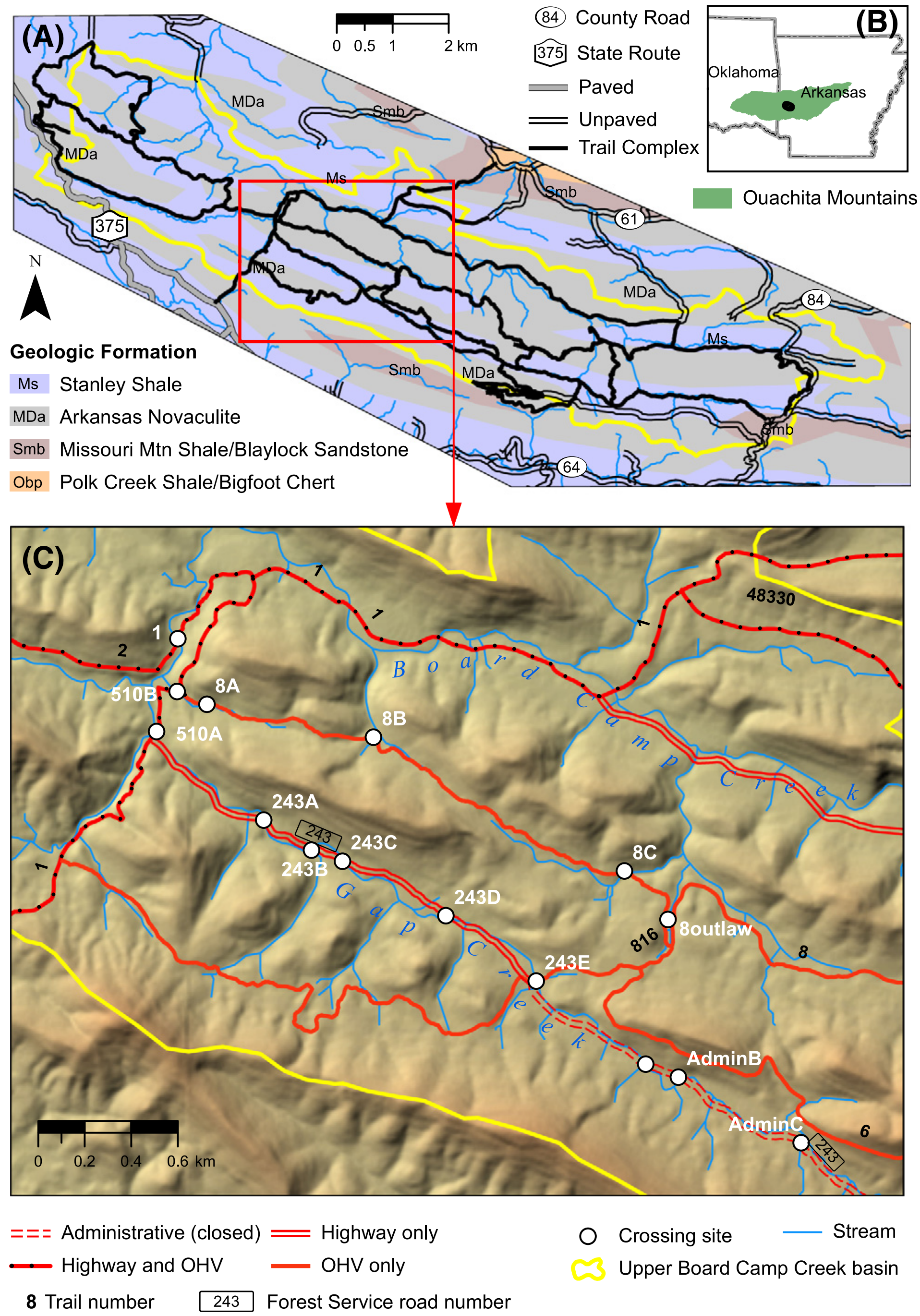

Fig. 1. Wolf Pen Gap Trail Complex showing (A) surface geologic formations and trail network; (B) location within Arkansas; and (C) sample crossing site locations and trail vehicle restrictions.

trail system use has grown steadily from an estimated 8000–10,000 users per year in 1998 to over 13,000 users per year in 2010 (Tim Oosterhous and Christopher P. Ham, Ouachita National Forest, Hot Springs, AR, personal communications, 2012). Since the late 1990s, concerns have developed about potential on-site sediment impacts from the trail system as well as downstream impacts to threatened and endangered mussel species in the Ouachita River (USDA Forest Service, 2005).

The purpose of this project was to investigate the potential geomorphic responses to OHV use at ford-type stream crossings within the WPGTC. Specific objectives were to (i) Determine whether soil loss or in-channel responses are evident; and if so, (ii) determine the up- and downstream extent of channel responses.

1.1. Previous studies

An extensive literature exists on the effects of logging roads and other unpaved forest roads on runoff, soil erosion, and sedimentation (see recent reviews by Eisenbies et al., 2007; Neary et al., 2009; Anderson and Lockaby, 2011) that would seem relevant in considering OHV effects. Likewise, many studies exist of the direct and indirect erosion impacts of unpaved hiking, horse, and bicycle trails (see review by

Robinson et al., 2010). However, studies have also found that OHV effects can differ substantially from those of other types of trail and unpaved road use (Olive and Marion, 2009). One implication of several studies is that the presence or absence of OHV traffic, independent of the intensity of use, has more effect on response occurrence than varying levels of OHV use (Foltz, 2006; Meadows et al., 2008; Olive and Marion, 2009). These effect differences may result from design differences between OHVs and other vehicles (e.g., tire tread designs, gear ratios), variation in use patterns (trail riding for its own sake vs. transport to sites for logging, hunting, camping, etc.), or higher use levels on unpaved roads used by recreational OHVs (Sack and da Luz, 2003; Foltz, 2006; Meadows et al., 2008; Welsh, 2008; Olive and Marion, 2009).

A number of past OHV studies in arid and semiarid environments in the western U.S. have examined how trail use by OHVs affects hydrologic responses, soil erosion, sediment production, and sediment delivery, any of which would be expected to have potential impacts on streams. A Colorado study (Welsh, 2008) compared sediment delivery along 17 km of native-surface forest roads and 10 km of OHV trails. The sediment production during the study period was six times higher per unit surface area, on average, from the OHV trails as compared to the forest roads, and sediment delivery to streams from the trails was proportionately greater because of more OHV trails being located in valley bottoms (Welsh, 2008). Increased soil compaction, erosion, runoff, and sediment delivery to streams have been documented in several other studies (e.g., Snyder et al., 1976; Webb and Wilshire, 1983; Lovich and Bainbridge, 1999; Goossens and Buck, 2009).

Similar geomorphic responses to OHV use have been observed in humid forested environments more relevant to our study. Ayala et al. (2005) monitored suspended solids and modeled soil erosion and sediment loads using the Water Erosion Prediction Project model on OHV trails in Alabama. Their work indicated mean annual sediment loads from stream crossings of nearly 127 t ha^{-1}, well in excess of Forest Service standards for temporary roads. They also found—not unexpectedly—that most of the sediment reaching streams comes from steep hillslope trail sections near the stream crossings (Ayala et al., 2005). Studies by Sack and da Luz (2003) in Ohio; Foltz (2006) and Meadows et al. (2008) in Kentucky, Louisiana, and Minnesota (and several drier western sites); and Olive and Marion (2009) in Tennessee and Kentucky have also documented increased runoff, soil erosion, soil compaction, and sediment delivery to streams affected by OHV trails as compared to undisturbed areas or unpaved roads and trails not used by OHVs.

Relatively few studies have directly examined how channels respond at stream crossings by OHV trails. Two studies in the United States found evidence that OHV stream crossings resulted in increased in-channel sedimentation. Chin et al. (2004) conducted a preliminary study of OHV effects on streams in the WPGTC, comparing pool characteristics in two watersheds with OHV trails to those in two control watersheds. The OHV-affected streams were found to have pools with higher percentages of sand and fine sediments. The trail-crossed streams also had shallower pools with reduced volumes. Higher turbidity was also observed in OHV-affected areas. The second, a tracer study in north Georgia (Riedel, 2006), found that an OHV trail had'enormous impacts on water quality, sediment yield, and stream bed sedimentation,' and through these, an impact on stream ecology. However, still open to question is the extent to which channel responses are localized to the trails and the immediate vicinity of stream crossings.

Stream bed sedimentation associated with OHV crossings was documented in Victoria, Australia, by Brown (1994). She found that increased sediment resulted from creation of wheel ruts and concentration of surface runoff on OHV tracks, exposed soil on tracks, compaction and resulting infiltration reductions on track surfaces, backwash from vehicle crossings, and bank undercutting by bow wave action. Field experiments involving simulated OHV convoys found a mean bed sedimentation rate of about 1 kg m^{-2} over 30 days (Brown, 1994).

Stream channel responses to localized geomorphic and hydrologic impacts from trail crossings may be propagated downstream (and possibly upstream) by fluvial transport processes and by hydraulic and morphologic adjustments. Downstream responses may be extensive but are ultimately limited by distance decay effects. The latter are associated with dilution from tributary or other downvalley water inputs that eventually mask the local disturbance, lag times and storage effects, and limiting controls (for example, an erosional response may be limited by exposure of resistant bed or bank materials). Ricker et al. (2008) found that local disturbances, including ATV trail crossings of streams, played a major role in watershed sediment fluxes in Virginia. Different types of effects are likely to vary in their propagation. Brown (1994), for instance, found that most coarse size sediment that deposited on stream beds as a result of OHV fords occurred within the first 10 m, while fine size sediment made its way kilometers downstream.

To our knowledge, no one has reported the occurrence of upstream channel responses associated with OHV stream crossings. Where stream gradients are steep and bed material is coarse size, the spatial extent of upstream effects would likely be restricted and would not extend long distances upstream from the site of disturbance. If upstream responses do occur, they would likely be associated either with backwater effects (ponding), or with the upstream propagation of erosional features such as knickpoints initiated at the initial site of OHV disturbance (the crossing).

In addition to possible downstream changes in sediment characteristics reported in previous studies, we also examined potential changes in bank erosion and channel dimensions. These could potentially occur in concert with increased sediment inputs (as in Andrews, 1979) or increased runoff (as in Merritt and Wohl, 2003) from the trail surfaces, or propagation of morphological changes associated with the topographic modification of the crossing itself.

2. Study area and methods

2.1. Study area

The WPGTC study area is located in the Ouachita Mountains of western Arkansas (Fig. 1). The Ouachita Mountains are generally east–west trending, parallel ridges with typical peak elevations in the study area of about 420 to 480 m. The climate is humid subtropical, with hot summers, relatively mild winters, and year-round precipitation. Mean annual precipitation in Mena (about 15 km west of the WPGTC) is about 1350 mm, almost all in the form of rain.

The geology of the Ouachita Mountains is complex. The area is composed of Paleozoic sedimentary rocks that have undergone extensive tectonic deformation. Steeply dipping and contorted strata 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, including roads and trails.

The study area is almost entirely forested, with roads, trails, and scattered clearings associated with campsites and a small former novaculite mine site covering <1.0% of the area. Shortleaf pine (*Pinus echinata*), white oak–northern red oak–hickory (*Quercus albus*, *Q. rubra*, and *Carya* spp., respectively), and shortleaf pine–oak are the predominant forest types in the area (unpublished Stands database, on file at the Ouachita National Forest Supervisor Office, Hot Springs, AR). Sweetgum (*Liquidambar styraciflua*), alders (*Alnus* spp.), willows (*Salix* spp.), and sycamore *(Platanus occidentalis)* are common along the valley bottoms.

The WPGTC comprises about 56 km of loop trails, about 70% of which was open to ATV use during the spring and summer of 2011 when sampling was done (Fig. 1). The other 30% was either closed to the public or available only to highway-legal vehicles. When the WPGTC was first opened in the early 1990s, all trail stream crossings were unengineered, ford-type crossings. Around 2005, the three widest crossings were replaced with bridges owing to concerns about on-site channel impacts. In 2011, an extensive program of trail reconstruction began that will replace many of the narrower ford-type crossings on steeper trails with culvert and fill structures (Stinchfield et al., 2011). The 15 sample sites used in this study include most of the remaining ford-type crossings.

Sample sites were located at crossings on Gap Creek, a large tributary of Board Camp Creek which drains most of the WPGTC, and on a number of smaller, unnamed tributaries of Board Camp Creek (Fig. 1). The sites were selected in an effort to capture potential variability in channel responses and to reflect trails of varying use levels. Sites include most of the ford-type crossings within the WPGTC that have an upstream drainage area > 1.5 km^2 (9 sites) and an additional 6 sites with smaller drainage areas to provide more representation of different trail use conditions (Table 1; Fig. 1). Six of the 15 sites are on active OHV trails open to ATVs, and one is an illegal crossing. Three are on a former OHV trail that was closed to all traffic in 2008; the others are on trails now open only to highway-legal vehicles but used by ATVs prior to 2001. All trails and roads have unpaved, natural surfaces.

2.2. Study design

This study evaluates soil loss and in-channel responses, which are summarized in Table 2. An estimate of the soil loss associated with the trails was based on soil profile truncation and is evaluated using a disturbed vs. undisturbed study design. At each crossing site, depth to bedrock was measured at 10 randomly selected locations within the portion of the trail draining into the stream and at a minimum of 20 randomly selected undisturbed forest locations within 15 m of the trail. Soil truncation was based on comparing the mean depth of bedrock of the trail samples with those of the forest samples. Depth to bedrock was determined using a soil auger when possible, but the stony soils made excavation difficult, and a variety of tools were used (including pick, mattock, pry bar, and steel rebar hammered into starter holes) to determine bedrock depths. Depths were measured with a folding ruler to the nearest centimeter.

The evaluation of in-channel responses is based on comparing reaches immediately up- and downstream of trail stream crossings. This approach was used, rather than a comparison of OHV-affected vs. unaffected streams, to minimize the effects of geomorphic and hydrological variation between streams that are unrelated to vehicle use or stream crossings. Further, no unaffected stream reaches occur within the WPGTC other than low-order headwater tributaries. It is also important to note that upstream reaches are not necessarily undisturbed as other trail crossings may occur farther upstream (Fig. 1), though no trail crossings occurred within 200 m upstream of any of our sites.

The upstream vs. downstream approach for evaluating impacts from localized disturbances has been widely used in fluvial geomorphology and hydrology. This approach was used in studies of geomorphologic and hydraulic effects of both small run-of-river dams (Csiki and Rhoads, 2010) and larger impoundments (e.g., Phillips, 2001; Chin et al., 2002; Draut et al., 2011). Kang et al. (2010) used this method to determine geomorphic effects of urbanization up- and downstream of a stream confluence of an urbanized tributary. Comparisons of upstream vs. downstream reaches have also been used in previous studies of geomorphic (Brown, 1994), water quality (Sample et al., 1998; Aust et al., 2011), and stream habitat (Pépino et al., 2012) impacts from vehicle crossings on streams.

Table 1
Use designation, drainage area, and reach characteristics for OHV stream-crossing study sites.

Site[a]	Use category[b]	Drainage area (km^2)	Upstream + downstream reach lengths (m)	Upstream reach slope
2A	Both	8.06	425.8	0.048
8A	OHV	0.20	309.8	0.011
8B	OHV	0.04	203.6	0.109
8C	OHV	0.37	206.6	0.068
8outlaw	Illegal	0.11	172.2	0.102
243A	HWV	3.50	332.9	0.024
243B	HWV	3.43	383.7	0.022
243C	HWV	3.02	363.4	0.026
243D	HWV	2.40	290.5	0.025
243E	OHV	1.92	608.2	0.054
510A	Both	3.98	533.8	0.029
510B	Both	0.23	225.7	0.067
AdminA	Closed	1.61	334.1	0.030
AdminB	Closed	1.46	335.2	0.031
AdminC	Closed	0.12	167.4	0.049

[a] The number in the site codes refers to the Forest Service road or trail number.
[b] All use categories are those designated as of September 2011. OHV = open to OHV traffic only; HWV = open to highway-legal vehicles only, OHV use allowed prior to 2001; Both = open to both OHV and HWV; Closed = only administrative use currently allowed and is <6 times per year, OHV and HWV use allowed prior to 2008; Illegal = user-created OHV trail, no use since c. 2008.

2.3. In-channel field methods

Paired reaches were delineated at each site extending a minimum of 10 channel widths immediately up- and downstream from the crossing and incorporating at least three different hydraulic units up- and downstream. Hydraulic units were visually identified as riffles, runs (analogous to the 'glide' habitat type of Bisson et al., 1982), or pools, with additional units (e.g., step pools, boulder cascades) identified in some cases.

Multiple channel responses were assessed at each site (Table 2). The use of multiple responses to evaluate channel quality or stability using quantitative or qualitative feature conditions has a long history, and numerous methods and criteria have been proposed (Parrott et al., 1989 provided a succinct, if now a bit dated, summary). We chose responses that would potentially be altered by increases in either sediment or water delivered from the trail approach sections to the channel. Numerous channel bed and bank features were examined to determine whether a response was evident (Table 2). Some features were measured quantitatively (e.g., bankfull width:depth), whereas others were categorized qualitatively according to condition classes based on feature extent or frequency (e.g., mud coats) or by noting the presence of particular conditions (e.g., cutbanks, sediment plugs).

Environmental context is important for assessing whether observed differences might be unrelated to the stream crossing. Features were assessed separately within each hydraulic unit as individual features often exhibited marked variation between different units within the same study reach. Differences in bank material type or the presence of hillslope mass erosion were also noted so that these effects could be discounted.

While past work has recognized the importance of many of the features listed in Table 2 in the Ouachita Mountains (Taylor and Warren, 2001; Williams et al., 2002; Pugh et al., 2008), research supporting particular condition class breaks for individual features remains lacking. Therefore, we selected all class breaks conservatively so as to achieve two objectives: (i) condition categories could be perceived and differentiated consistently; and (ii) any upstream vs. downstream differences determined when using them were sufficient in magnitude to represent real differences in conditions.

A single difference rating was determined for each geomorphic response. The rating was determined by the change direction (increase or decrease) and qualified by the degree to which a feature differed or the number of features which differed for each response. Table 3 defines how qualifiers were determined for each response rating. For bank erosion and sediment deposition, all feature differences were considered in making a single, integrated rating. For channel geometry, the $\pm 50\%$ difference in bankfull width:depth corresponds to the variation limit we observed among the sites in these ratios between adjacent hydraulic units either upstream or downstream of crossings and thereby suggests that change beyond this level exceeds normal. A rating of 'none' was assigned to mud coats,

Table 2
Channel features and related measurements or observations used to evaluate geomorphic response occurrence at the OHV stream-crossing study sites; features were assessed separately within individual hydraulic types in each up- and downstream reach.

Location	Geomorphic response	Relevant channel or soil feature	Measurement, category, or observation made
In-channel	Channel geometry	Bankfull width:depth	Hydraulic depth and top width at bankfull elevation
	Bed-material size	Bed material composition	Proportions of bedrock, boulder, cobble, gravel, & smaller grain sizes
	Mud coats	Mud coats	Based on estimated percentage of silt/clay coatings on bedrock & coarse clasts: very few (<5%), few (5–25%), present (25–50%), present but only in backwater microsites, common (50–90%), extensive (>90%)
	Sediment deposition	Sediment deposition features	Presence of unstable lateral or mid-channel bars; distinct, mid-channel, relatively homogeneous, fine-sediment patches; or large (width > 0.5 × bankfull width), distinct, sediment 'slugs' that cause flow deflection or blockage (i.e., 'sediment plugs')
	Bank erosion	Bank shape	Convex, concave, straight, & combinations of these
		Bank vegetation cover	Fully (>75% cover), partially (25–75%), or unvegetated (<25%)
		Exposed roots	None, few or common
		Bank erosion features	Presence of overhangs, scarps, cutbanks, & bank failure surfaces (e.g., slump scars, friction cracks, etc.)
		Bank deposition features	Presence and material on channel shelves or insets, lateral bars
Out-channel	Soil loss	Soil profile truncation	Depth to bedrock in trail and adjacent undisturbed areas

bank erosion, and sediment deposition responses when no differences occurred, to channel geometry when bankfull width:depth change was <±25%, and to bed-material size when the statistical test was not significant (details on testing are given below).

When mud coatings, sediment deposition, or bank erosion responses were evident either at or downstream of a crossing, these were visually traced immediately upstream of the crossing and downstream beyond the downstream reach. The tracing continued downstream to at least the next stream junction or to the point where the geomorphic context changed such that no downstream-propagating effects could be distinguished confidently from changes in boundary conditions (whichever was encountered first).

Longitudinal and cross section surveys were conducted using a laser hypsometer/rangefinder and prism rod. Longitudinal profiles were measured along the channel study section, and along the trail approach areas on both sides of the crossing draining directly to the stream. Seven channel cross sections were surveyed at each site: one at the crossing itself and three each up- and downstream. Standard survey procedures were used (Harrelson et al., 1994), and all significant topographic breaks within the respective sections were included. The trail crossing location was mapped at the intersection with the stream channel centerline using differential global positioning system equipment.

2.4. Channel geometry

Channel geometry variables were determined using the survey data. The energy slope was estimated from the longitudinal profile using the slope of the stage necessary to just inundate the channel bed (see Fig. 2A). While local slopes could conceivably be modified by geomorphic changes associated with trail impacts, slope was included mainly because it is a necessary component for estimating shear stress and stream power, and is a possible explanation for upstream-downstream variation in other factors. Channel dimensions were computed from cross-sections surveyed within riffles to standardize for variations among different hydraulic units. The highest-gradient riffles in each up- and downstream reach and closest to the crossing were chosen because these were expected to best manifest any geometry changes due to increased water or sediment delivery from the trail.

All channel dimensions were referenced to the bankfull elevation (Dunne and Leopold, 1978) for the cross-sections being compared. As reliable bankfull-elevation indicators were often absent or inconsistently expressed at the crossing sites, we estimated the bankfull elevation using a combination of morphologic evidence recorded on the cross-section surveys, along with estimates of bankfull discharge obtained from regional models (see Appendix A for details).

2.5. Bed-material size

Change in bed-material size has been used previously to assess channel response to environmental disturbances (e.g., Potyondy and Hardy, 1994; Bevenger and King, 1995; Wohl and Cenderelli, 2000). For this paper, only one type of bed-material size change was considered: a general shift in grain size between up- and downstream reaches. Clast size was measured within the same hydraulic type in both up- and downstream reaches. Size was determined from pebble counts of approximately 350 to 450 per reach to achieve reasonable precision (Rice and Church, 1996). Clast size was measured at numerous transects across the units using a template or ruler and standard procedures (Bunte and Abt, 2001). A change in either the mean or median bed-material size was tested, depending on whether normality could be confidently assumed for the grain size distribution of each sampled facie. As size might either increase (coarsen) or decrease (fine) due to increased water or sediment inputs, respectively, each crossing site pair was tested individually rather than pooling all samples together and testing for one type of size change. To control for the experiment-wise error in making multiple comparisons this way, a Bonferroni correction was applied

Table 3
Rules used to determine rating qualifier assigned to increase or decrease difference in geomorphic response indicators between upstream and downstream reaches at OHV stream-crossing study sites; see Table 2 for features and classes used in ratings.

Rating qualifier	Difference required for qualifier				
	Mud coats	Bank erosion	Bankfull width:depth	Sediment deposition	Bed-material size
Slight	1 class (e.g., few to present)	1 class for single feature	≥±25.1 and <±50%	Not used	Not used
(Unqualifed)	2 classes (e.g., few to common)	2 classes for single feature or 2 features	≥±50 and <±100%	1 feature (not including sediment plug)	Significant at experiment-wise rejection level = 0.05
Large	≥3 classes (e.g., few to extensive)	Any combination of class or features ≥3	≥±100%	≥2 features or sediment plug	Not used

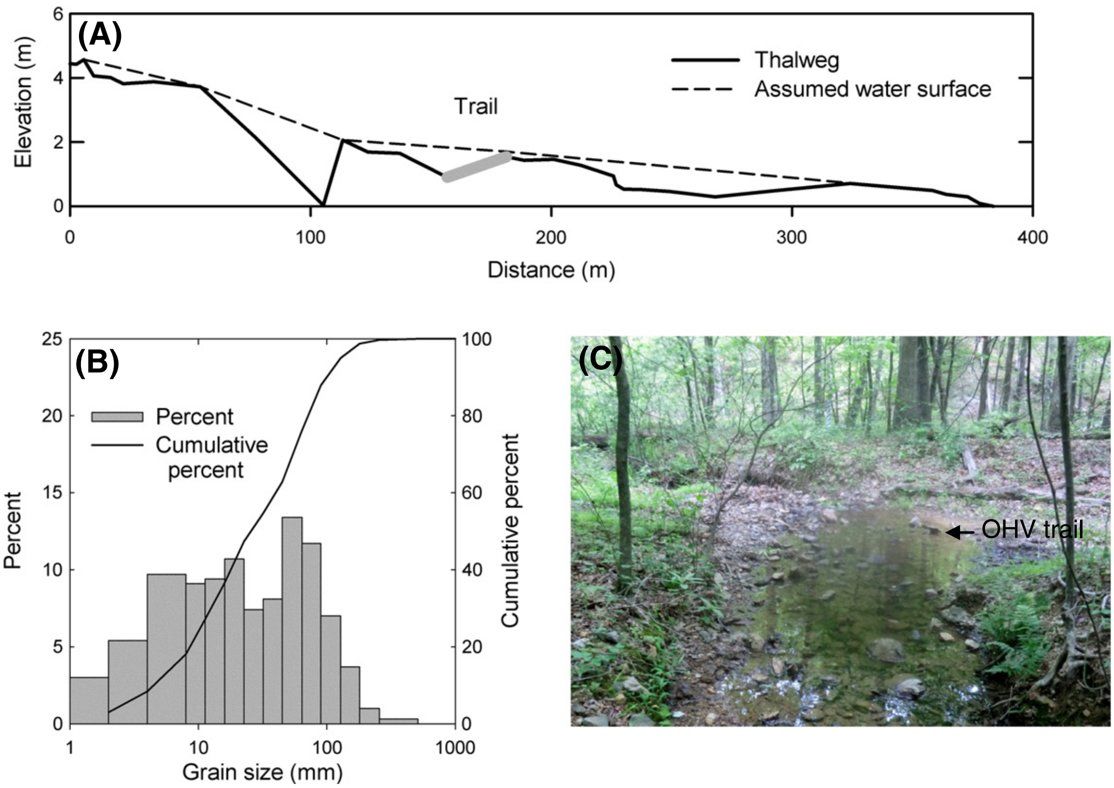

Fig. 2. Examples of typical channel characteristics within the study reaches: (A) channel profile and method used to estimate water-surface slope; (B) grain size distribution within a sampled reach; and (C) bank erosion and hydraulic type variation (site 243B).

resulting in rejection levels of 0.005 and 0.010 for the individual *t*- and Mann–Whitney tests, respectively. See Appendix B for details.

3. Results

3.1. Soil truncation

Significant soil removal is obvious at all sites except one (Table 4). The one exception (8outlaw) is an illegal, user-created trail where use was stopped after a short time. The effects of trail construction and subsequent erosion have exposed bedrock at all of the other 14 crossing sites. Trail surfaces at virtually all of these sites were a combination of exposed bedrock and bedrock with a thin veneer (≤5 cm) of soil or sediment (Table 4). Even the exception (AdminC) had only 10 cm of unconsolidated material overlying bedrock. Adjacent forest soils all had significantly thicker soils overlying bedrock, with mean thickness of about 40 cm. Overall, results indicate ~30 to 45 cm of soil truncation associated with the OHV trails at the approved crossing sites.

During runoff and erosion events, sediment from the trail surfaces must be supply-limited because of the extensive exposed bedrock along trail surfaces, particularly where the exposed bedrock is predominantly chert, novaculite, or sandstone. Shale, by contrast, weathers rapidly and is more erodible, though still much less so than soil. Widening of trails and erosion surfaces is limited in places by the tendency of the

Table 4
Depth to bedrock for trail and adjacent forest areas at OHV stream-crossing study sites; determination of soil types is based on a combination of soil maps and field observations; full taxonomic descriptions were not made.

	Depth to bedrock (cm)				Lithology	Soil type (series)
		Forest				
Site	Trail	Minimum	Maximum	Mean		
2A	<2	24	95	45.2	Weathered shale	Bengal, Bismarck, Ceda
8A	0–3	29	52	37.7	Sandstone	Clebit, Nashoba
8B	0	29	75	43.3	Weathered shale, chert	Bengal, Bismarck, Avant
8C	0	22	35	28.8	Shale	Bismarck
8outlaw[a]						Bengal, Bismarck, Yanush
243A	0–5	21	83	44.0	Weathered shale, sandstone, quartz	Bengal, Bismarck, Clebit, Ceda
243B	0–5	21	89	47.8	Chert, sandstone, weathered shale	Avant, Bismarck, Yanush, Ceda
234C	0–3	24	49	47.3	Weathered shale	Bismarck, Ceda
243D	0–3	10	41	30.0	Chert, weathered shale	Avant, Bismarck, Ceda
243E	<2	29	90	37.7	Sandstone	Clebit, Nashoba, Ceda
510A	<2	26	120	49.2	Weathered shale; weathered sandstone	Bengal, Clebit, Ceda
510B	0–5	12	117	33.9	Sandstone, chert	Clebit, Avant
AdminA	0–5	20	66	46.8	Sandstone, weathered shale	Nashoba, Bengal, Bismarck, Clebit
AdminB	<2	21	73	38.3	Weathered sandstone	Clebit, Nashoba, Ceda
AdminC	10	14	117	41.2	Chert	Yanush, Avant

[a] Truncation was minimal at this site and was not assessed.

trails to become entrenched between embankments or hillslopes, and by vegetation growth or berm development along the trail margins. Further, surface runoff depths are limited by the relatively short trail lengths between the crossing and the first uphill flow-relief structure (e.g., a dip or outlet to the forest floor). Nonetheless, while extensive bedrock exposure suggests some sediment exhaustion effects on the trail approaches, field evidence indicates ongoing weathering of the exposed rock and continued loosening of material by OHV traffic.

The large variability in forest-soil thickness and soil type shown in Table 4 was not unexpected. Studies of soil geomorphology and spatial variability in the Ouachitas have shown very high degrees of spatial variation in soil morphology over short distances and small areas, attributable to lithological variations and local biomechanical effects of individual trees (Phillips and Marion, 2005; Phillips et al., 2005).

3.2. General channel characteristics

The streams where the crossing sites occur are all steep, predominantly bedrock-controlled, low-order streams (Fig. 2C). Bedrock outcrops, or bedrock with a thin veneer of alluvium, are common in the channels. Sediment is mostly in the coarse-gravel to small-cobble sizes, but ranges from sands and finer to boulders (Fig. 2B). Channel longitudinal profiles are approximately straight overall, likely caused by the relatively short reach lengths evaluated (Table 1). Within-reach bed elevations are highly variable (Fig. 2A), reflecting the high diversity of hydraulic types and, in some cases, in-channel sediment deposits that occur within the sample reaches. Mean channel gradients upstream of the crossings are all high, ranging from 0.011 to 0.109 (Table 1). A rough inverse correlation exists between slope and drainage area (Table 1). The watersheds are all small, with only one site having a drainage area >4 km^2, and six being <1 km^2. Estimated bankfull discharges range from 0.25 to 6.91 cms.

3.3. Channel responses

Table 5 summarizes the in-channel response ratings for all crossing sites. In the findings and discussion below, we focus on those responses that represent the most clearly discernible downstream changes (i.e., 'slight' differences are excluded). Downstream decreases in bank erosion were observed at two sites (AdminA, AdminC), both of which have been closed to regular traffic and show signs of recovering from impacts (discussed below). One other site (243C) showed evidence of a decrease in sediment deposition downstream because mid-channel bars were present upstream but absent downstream. These decreases cannot be readily explained by possible increases in trail runoff or sediment, therefore they too are not discussed as responses. They do illustrate the fact that local variations (as in all fluvial systems) may either obscure or reinforce any apparent trends observed. The responses not excluded are tallied in the last column of Table 5 and hereafter, unless specifically noted otherwise, are what is meant by a 'response.' This distinction is made to increase the likelihood that the up- vs. downstream differences identified are sufficient in magnitude to demonstrate compelling evidence that channel responses have occurred.

Of the five in-channel response types evaluated (Table 2), upstream vs. downstream comparisons reveal that 14 of the 15 crossing sites exhibit one or more responses (Table 5). Seventy-three percent of the sites exhibit two or more responses, with one site (8B) exhibiting all five. Only one of the closed sites (AdminA) showed no responses.

3.4. Bankfull width:depth and bank erosion

Eighty percent of the 15 sites exhibit downstream width:depth changes that are ±50% or greater, with 33% of the sites exceeding ±100% (Fig. 3A). Of the 80%, the majority (seven sites) exhibit downstream increases in width:depth, as do all five sites that exhibit changes ≥100%.

Increased bankfull discharges do not seem to explain where width:depth changes occur. Only two sites (8B and 243E) provide morphologic evidence that bankfull discharge increases more than 5% downstream (Fig. 3C). Of these, 8B has a decrease in width:depth of about 70%, while no change occurs at 243E. Bankfull discharge changes <±5% are likely below what can be reliably detected using morphologic evidence and would also seem too small to produce substantial changes in the dimensions of these coarse-bed channels. One site (8A) could not be evaluated for a discharge change as none of the three downstream cross sections was large enough to contain the estimated bankfull discharge. However, even at less than bankfull discharge, the width:depth change downstream was over 350% (Fig. 3A).

Similarly, downstream changes in water-surface slope do not correlate to width:depth differences. Four sites have slope changes greater than ±50% (Fig. 3B). Two of the four sites show no substantial change in downstream width:depth (AdminA and 243D). The other two sites do have width:depth changes greater than ±50%, but they exhibit opposite responses. Whereas both have increased slope downstream, the downstream width:depth increases at site 243C, but decreases at site 510A.

The OHV crossings themselves significantly widen the channel by locally obliterating the banks, with widths typically double those of the cross section immediately upstream. Differences in width (crossing vs. upstream) range from 0.26 to 15.11 m (mean 5.67 m; standard deviation 5.16 m). In relative terms, the crossing sites are 1.15 to 5.45 times wider than the upstream section (mean 2.36; standard deviation 1.34).

A third of the sites (five) have increases or large increases in downstream bank erosion (Table 5). No correlation is apparent between downstream bank erosion response and downstream width:depth change. Of the five sites with notable increases in bank erosion downstream, two show increases in width:depth downstream (243C and 8A), two sites show decreases (510A and 8B), and one shows a slight decrease (243A). The one site that exhibits decreased bank erosion downstream (AdminC) has a large increase in width:depth. Of all nine sites judged as displaying some kind of change (i.e., >50% increase or decrease) for bank erosion and for width:depth, just over half (five) display contrasting changes.

3.5. Bed-material size

Fourteen of the 15 crossing sites were used to test whether a general shift occurs in bed-material size immediately downstream (Table 6). Site 8C was excluded because no common hydraulic types occur in both up- and downstream reaches. At two of the 15 sites, riffle hydraulic types were not available in both reaches and either a pool or run type was used.

The size and distribution characteristics of bed material are similar at most sites. Grain sizes range from fine gravels and smaller to cobbles with D_{95} sizes typically between 100 and 250 mm. Most sample segments have mean grain sizes between 15 and 40 mm (Table 6). Seventy-nine percent (11) of segments exhibit poorly sorted bed-material sizes (coefficients of 1.0 to 2.0: Folk and Ward, 1957), which is typical of mountain gravel-bed streams (Bunte and Abt, 2001); while the remainder rate as very poorly sorted (2.0 to 4.0). The size distributions of a slight majority of segments are skewed toward the fine side (skewness <−0.1; Folk and Ward, 1957); the others have symmetric distributions. Nine of the samples sites were judged to have both up- and downstream size distributions close enough to normal for parametric statistical testing; at the other five sites, either one or both samples varied substantially from a normal distribution.

Eight of the 14 tested crossing sites (57%) exhibit very significant differences in bed-material size between up- and downstream reaches (Table 6). Five of the eight sites have finer grain sizes downstream, while three have coarser sizes. One additional site (243E) would also have been judged different if the individual rejection level for t tests had been 0.01.

Table 5
Summary of difference ratings in geomorphic response indicators downstream (DS) of OHV stream-crossing sites, compared to upstream (US); basis for rating is given in parentheses.

Site	Mud coats	Bank erosion	Bankfull width:depth	Sediment deposition	Bed-material size[a]	Total number of differences[b]
2A	Large increase (US very few; DS common)	Slight increase (US—no undercut banks; DS undercut banks)	Slight decrease (−47%)	None	NSD	1
8A	None	Large increase (US stable convex banks; DS undercut convex & concave banks and cutbank)	Large increase (356%)	Increase (DS increased fine deposition)	NSD	3
8B	Increase (US present; DS extensive)	Increase (US no erosion; DS erosion scarp & exposed roots)	Decrease (−69%)	Large increase (DS sediment plug)	Decrease	5
8C	Large increase (US few; DS extensive)	Slight increase (US stable convex banks; DS undercut convex banks & exposed roots)	Increase (92%)	Large increase (DS increased fine deposition; sediment plug)	N/A	3
8outlaw	None	None	Large increase (439%)	Large increase (DS large sediment plug)	Decrease	3
243A	None	Increase (US convex or bedrock banks with some exposed roots; DS concave banks with erosion scarps)	Slight decrease (−34%)	None	Decrease	2
243B	Slight increase (US few; DS present)	None	Large increase (186%)	None	Increase	2
243C	Slight increase (US few; DS present)	Increase (US no erosion; DS many exposed roots)	Increase (56%)	Decrease (US mid-channel bars present)	NSD	2
243D	Increase (US present; DS extensive)	None	None (−1%)	None	Increase	2
243E	Increase (US present; DS extensive)	Slight increase (DS exposed roots & undercuts more common)	None (1%)	None	Possible increase	1
510A	Large increase (US few; DS extensive)	Increase (US none; DS exposed roots & erosion scarp)	Decrease (−65%)	None	NSD	3
510B	Increase (US few; DS common)	None	Large increase (154%)	Large increase (DS Fine sediment plug)	Decrease	4
AdminA	Slight decrease (US common; DS present)	Slight decrease (US exposed roots more common)	None (16%)	None	NSD	0
AdminB	None	Slight increase (DS exposed roots more common & concave bank present	Slight increase (32%)	None	Increase	1
AdminC	Slight increase (US present; DS common)	Decrease (US active cutbank present	Large increase (145%)	Large increase (DS large fine & coarse sediment plug)	Decrease	3

[a] NSD = no significant difference at experiment-wise rejection level = 0.05.
[b] Number does not include 'Slight' differences for all response types, or 'Decrease' difference for bank erosion and sediment deposition.

3.6. Mud coatings and sediment plugs

Significant increases in mud coatings on downstream clasts and bedrock occurs at seven sites (Table 5). These sites are typically associated with pools, which are favorable sites for fine sediment accumulations. Five of the seven (2A, 510A, 510B, 8C, 243E) have large (relative to the size of the channel) pools downstream of the crossing. In four cases, the pools are incised and likely predate the trail; at 8C the pool is a backwater feature associated with a sediment plug downstream. However, two sites show a substantial increase in mud coatings with no large pools downstream. At one of these (8B), the mud coats are primarily associated with a low gradient sediment plug. At the other (243D) the thick, extensive mud coatings may be caused by a combination of clay-rich shale-derived soil and extensive disturbance at the crossing. Site 243D has the second highest length of trail within the channel of all sites, and the greatest increase in width at the crossing relative to upstream of any site. Two sites have large pools downstream of the crossing, but no major increase in mud coatings, though one of these (243B) does show a small increase. The other (243A) is situated so that the crossing site occupies thin, coarse-grained soils unlikely to produce much fine sediment and downstream mud coats.

Stream-bed disturbance by vehicles crossing the channel would seem to be the major source of the downstream fines and mud coats. During our field work, we observed scores of vehicles crossing streams and noted that when surface flow was present each crossing produced a plume of readily suspended, fine sediment from the channel bed. High turbidity conditions would persist for several minutes after each crossing with the sediment plume moving downstream. The displacement distance downstream varied depending on channel conditions, but much of the suspended sediment often got trapped in secondary currents or behind obstructions, which increased deposition near the crossing site.

Five sites have large, valley-bottom-filling sediment plugs downstream of the crossing (Table 5). Sediment-plug occurrence seems to be controlled by channel size (discussed later) and the local longitudinal profile. At the five sites (8B, 8C, 8outlaw, 510B, AdminC) the channel profiles downstream of the crossing are relatively straight (i.e., not convex or concave) and lack significant pools. The only other site with a profile of this type, AdminA, has some evidence that a sediment plug may have once been present in the form of remnant channel and channel margin bars. The presence of pools is significant because the higher shear stress and stream power at high flows in pools allows coarse clasts to be moved through the reach more effectively (Keller, 1971; Lisle, 1979; Thompson and Wohl, 2009), reducing the likelihood that coarse deposition may partially block the channel, initiating a sediment plug.

3.7. Upstream, downstream propagation

In all cases where mud coatings, sediment deposition, or bank erosion responses occur (80% of total sites), propagation of OHV impacts downstream from the immediate vicinity of the crossings clearly occurs, particularly with respect to fine sediment accumulations. Downstream changes were observed at least 100 to 200 m downstream in all cases, sometimes continuing into receiving streams. However, in essentially all cases the study streams join larger streams within about 200 m or less, or are joined by tributaries, or encounter different geomorphic boundary conditions (e.g., transitions from confined to unconfined valley settings or a

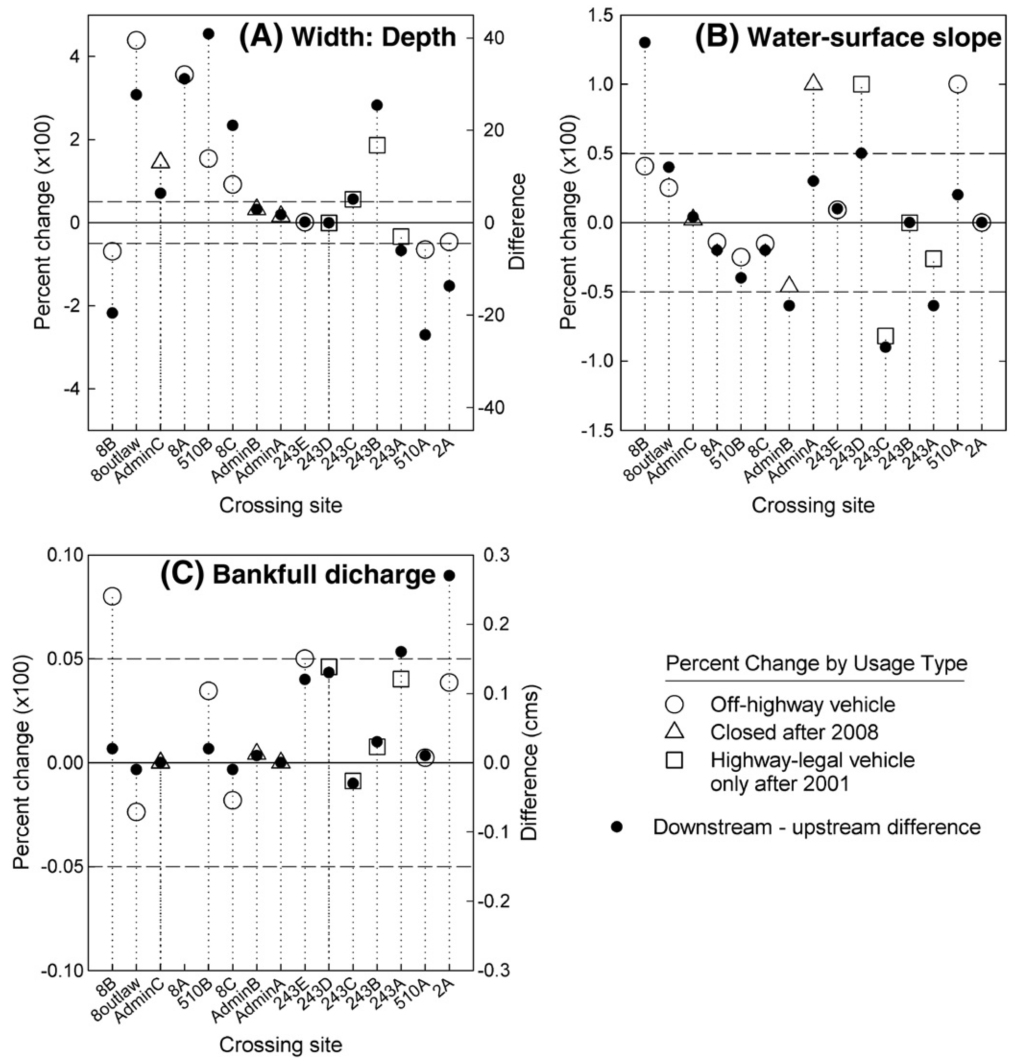

Fig. 3. Downstream differences and percent change in (A) bankfull width:depth, (B) water-surface slope, and (C) bankfull discharge for paired hydraulic types up- and downstream of OHV crossings. Crossing study sites are listed in ascending order by channel size (as indexed using drainage area).

Table 6
Mean or median bed-material diameters (mm) within the same hydraulic units up- and downstream of OHV stream-crossing sites and results of statistical difference testing.

Site[a]	Hydraulic unit	Mean or median diameter		Test used[b]	Probability under H_0
		Upstream	Downstream		
2A	Riffle	46.3	41.8	T	0.229
8A	Riffle	15.7	16.2	T	0.735
8B	Riffle	25.1	15.4	T	<0.0001 [c]
8Outlaw	Riffle	18.7	16.7	MW	<0.0001 [c]
243A	Riffle	38.3	24.1	T	<0.0001 [c]
243B	Riffle	29.4	54.4	T	<0.0001 [c]
243C	Riffle	21.7	20.9	T	0.582
243D	Pool	22.4	31.4	MW	0.005 [c]
243E	Riffle	22.6	28.2	T	0.009
510A	Riffle	44.8	38.2	T	0.093
510B	Riffle	20.7	7.9	MW	<0.0001 [c]
AdminA	Riffle	30.9	32.6	T	0.506
AdminB	Run	12.2	21.8	MW	<0.0001 [c]
AdminC	Riffle	40.4	29.6	MW	0.0003 [c]

[a] Comparable hydraulic units were not available at site 8C.
[b] Test types: T = *t*-test using mean diameter; MW = Mann–Whitney using median diameter.
[c] Significantly different at an overall (experiment-wise) rejection level of 0.05.

significant hillslope mass movement input). Thus geomorphic changes farther downstream are difficult to conclusively demonstrate without further, detailed studies (e.g., tagging and tracing trail sediment).

With the exception of possible upstream migration of knickpoints initiated by local erosion near crossings, upstream impacts are limited to the immediate vicinity of the crossings. Mud coatings and fine sediment deposition were frequently observed immediately upstream of crossings, but only for a very short distance (<2 m). Upstream impacts of the OHV trails are likely constrained by the steep channel slopes, which limit any backwater effects of the pools that often develop at the crossing sites. Exceptions to this pattern are instances where headcut erosion triggered by responses at or downstream of the crossing has translated upstream. This appears to have occurred at two sites (AdminB and C) at least.

4. Discussion and interpretations

4.1. Runoff vs. sediment impacts

The presence and use of the OHV trails have the potential to contribute increased runoff and sediment at, and immediately downstream of, the stream crossings. Increased bank erosion and width:depth change are channel responses that could result from either runoff or sediment increases. However, other combinations of downstream responses might indicate if either runoff or sediment increases are the predominant forcing factor. If increased water delivery is predominant, then bed coarsening along with a lack of sediment plugs or increased mud coatings and fine-sediment deposition might be expected. The reverse might be true if increased sediment delivery is predominant, with bed fining and increases in the sediment-deposition responses.

Little evidence exist that increased runoff from the trail approach sections either occurs in the absence of increased sediment delivery or in sufficient amounts to remove any sediment increases. Two sites (243B and AdminB) do exhibit bed coarsening without also showing substantial increases in sediment deposition (Table 5). However, neither of these two sites shows definite evidence of increased bankfull discharge (Fig. 3C). Two additional sites (243D and 243E) also exhibit bed coarsening, but also have significant sediment deposition responses (Table 5). Moreover, 243E is one of the two sites that do indicate an increase in downstream discharge (Fig. 3C).

Some evidence exist that sediment delivery in excess of what can be removed by any flow additions from the trails is occurring. Two sites (510B and 8B) have increased mud coatings and sediment plugs and decreased bed-material size (Table 5). Site 8B is one of the sites where bankfull discharge appears to increase downstream (Fig. 3C), so the evidence is even more compelling at this site. One additional site (8C) also has both increased mud coatings and a sediment plug, but bed-material size change could not be determined because of the lack of comparable hydraulic units in both reaches. Still two more sites (8outlaw and AdminC) have both sediment plugs and decreased bed-material size, but did not exhibit increased mud coatings.

These findings indicate that sediment sources are not being exhausted over time. Increased runoff from the trail approach sections should be relatively constant over time. If sediment supplies were diminishing, then it would seem likely that more than 13% of the sites would exhibit responses indicative of increased runoff. The fact that 33% of the sites show clear evidence of increased sediment delivery despite the constant additional runoff contributions indicates that sediment supplies are either renewed by weathering on the trail surfaces or are being derived from nontrail sources.

4.2. Effects of channel size and OHV-use status

Channel size is clearly related to the occurrence of pronounced sediment deposition responses and, to a lesser degree, to width:depth and bed-material size responses. Here, channel size is a relative term used to distinguish hillslope channels with basin areas <0.4 km^2 from valley bottom channels with areas >1.5 km^2 (no sites fall between these size limits). All of the small-channel sites (six or 40% of total sites) have sediment plugs or increased fine-sediment deposition, and all sites that exhibit these responses (100%) are small channels (Table 7). Moreover, all small channels show substantial changes (either >50% or <−50%) in width:depth. However, unlike sediment deposition responses, width:depth changes also occur at three of the large-channel sites. Four of the sites where downstream fining occurs are small channels, and all four sites where coarsening occurs (and site 243E) are large channels. Site 243A is an exception, being a large channel that exhibits bed fining instead of coarsening. The correlation between increased sediment deposits and channel size may suggest a threshold: in small channels, the interactions between streamflow competence, channel dimensions, and sediment volumes displaced in response to an OHV crossing produce deposition, width:depth changes, and bed fining; whereas in larger channels, other responses are produced. In contrast, mud coatings and bank erosion changes all occur at about the same frequencies in both large and small channels.

The correlation is limited between the current OHV-use status of the crossings and severity of impacts other than for mud coatings and other sediment accumulations. Increases in downstream mud coatings occur at sites where OHV use is currently allowed at over five times the frequency compared to where it is not (40 and 7%, respectively; Table 8). Sediment deposition increases occur twice as frequently (27 and 13%, respectively) at current OHV-use sites. As noted previously, recent and frequent stream-bed disturbance by vehicle crossings seems a likely cause of the downstream fines and mud coats. In contrast, notable changes in bank erosion and width:depth occur in roughly equal numbers in the two usage classes (Tables 1 and 3). At the two active OHV-use crossings where marked bed-material size changes occurs (sites 510B and 8B), both exhibit bed fining. However, a similar number of sites (three) exhibit fining at sites where OHV use is not currently allowed. The finding that all sites except one (AdminA) display one or more substantial responses (Table 5), yet more recent OHV use does not seem to increase the response frequency or severity, lends support to earlier studies (Foltz, 2006; Meadows et al., 2008; Olive and Marion, 2009) that found the occurrence or absence of OHV use, rather than the intensity, is often a major determinant of impacts.

The three sites where all vehicle use has been greatly reduced since 2008 (AdminA, AdminB, and AdminC) show possible signs of recovery. The lack of marked downstream increases in mud coatings and bank erosion at all three sites (Table 5) suggests that the contemporary impacts of these closed-trail crossings are less severe than several of the sites on trail 243 that, though closed to ATV use since 2001, continue to exhibit clear increases. The downstream coarsening of bed material at AdminB could plausibly be a legacy effect of past trail use, and the more significant impacts at AdminC (sediment plugs and a migrating knickpoint) are almost certainly legacy effects of trail use. Overall, these results suggest that trail closure may result in a rapid remediation of some impacts, while others are likely to be more persistent. This is

Table 7
Frequency of downstream sediment deposition and bankfull width:depth response ratings with channel size at OHV stream-crossing sites (total = 15).

Channel response	Downstream change[a]	Channel size[b]	
		Large	Small
Sediment deposition	Increase or Large increase	0	6
	Other	9	0
Bankfull width:depth	Decrease or Large decrease	1	1
	Increase or Large increase	2	5
	Other	6	0

[a] Change categories use groupings of respective difference ratings listed in Table 4 for each of the two channel responses. For Sediment deposition: Other = number of sites with rating of None, Slight increase, Slight decrease, or Decrease in Table 4. For Bankfull width:depth: Other = number of sites with rating of None, Slight increase, or Slight decrease in Table 4.
[b] Channel size categories use basin area for each site as an index of size: Small = <0.4 km^2; Large = >1.5 km^2 (no sites have areas ≥0.4 and ≤1.5 km^2).

Table 8
Frequency of downstream mud coatings and sediment deposition response ratings with current OHV-use designation at OHV stream-crossing sites (total = 15).

Channel response	Downstream change[a]	OHV-use designation[b]	
		Closed	Open
Mud coatings	Increase or Large increase	1	6
	Other	7	1
Sediment deposition	Increase or Large increase	2	4
	Other	6	3

[a] Change categories use groupings of respective difference ratings listed in Table 4 for each of the two channel responses. For both responses, Other = number of sites with rating of None, Slight increase, Slight decrease, or Decrease in Table 4.
[b] OHV-use designation as of August 2013: Closed = Highway-legal vehicle only (HWV), closed, or illegal (see Table 1); Open = OHV use only or OHV + HWV.

speculative, however, as it is based on evidence from only three sites in close proximity and needs further investigation.

4.3. Contingency

The locally variable nature of the fluvial response within a relatively small study area with no major variations in geology or land use indicates that few generalizations about OHV impacts are likely to be applicable at all sites. While at least one of the channel responses is evident at every site, only one site exhibited all response types (Table 5). Sites located on the same stream and relatively short distances apart often exhibit very different responses (e.g., 243A and 243B, 8A and 510B). The presence or absence, magnitude, and relative importance of individual responses are strongly contingent on the local details of channel and valley geomorphology. The apparent influence of relative channel size has already been noted. Based on our observations, we speculate that factors such as the supply of rock fragments from adjacent valley-side hillslopes, bedrock constraints on channel erosion and migration, and local alluvial storage sites independent of the OHV trails may also affect local channel response. Vegetation also plays a key, locally variable role, e.g., in stabilizing channel bars and increasing channel resistance where large roots are exposed across the channel.

Local factors that complicate responses to stream crossings can also make it more challenging to attribute causation. At 8A, the trail placement at a preexisting morphological transition made interpretation of OHV impacts more difficult. Local factors can also result in upstream–downstream contrasts independent of OHV impacts. At 243B, for example, downstream increases in coarse sediment size are at least partly caused by local hillslope inputs, and at 510A some changes are attributable to tributary inputs downstream of the crossing, though these inputs are likely also affected by the tributary stream's close proximity to the OHV trail.

4.4. Validity of methods used

While one could define different criteria for determining change than are used here, we seriously doubt that greatly different judgments regarding upstream–downstream differences would result if credible criteria were used. In many cases, the features used in the present study (Table 2) are either present or not, and we think it unlikely that experienced observers would have significant disagreements about their existence. The condition class breaks used here are more debatable. We purposely chose class breaks that were few enough in number to be easily distinguished and different enough in magnitude to represent real differences. Any bias we introduced was toward discounting any difference our observations did not indicate was substantial (>'slight' in Table 5) or which we thought could be explained by context factors that made the upstream–downstream comparison questionable. One could certainly define class breaks that would increase the number of differences shown in the last column of Table 5, but the overall conclusion that the stream crossings do show signs of impacts would be essentially unchanged. To define class breaks that would reduce the number of differences in a substantial way would require stipulating ranges or feature changes that we think would not be credible among our peers. Therefore, we think that anything short of radical changes in the criteria used here would produce similar overall results.

5. Conclusions

Analysis of trail stream crossings (fords) at 15 sites in the WPGTC clearly shows geomorphic impacts resulting from OHV use. All of the sites designated for OHV use over different periods since c. 1992 (14 sites) exhibit soil loss of ~30 to 45 cm within the trail segments on either side of the crossings as compared to surrounding undisturbed forest soils. Upstream vs. downstream comparisons of channel reaches at the crossings reveal that 93% of the sites (14) have notable downstream impacts. These include channel erosion and widening, deposition of large sediment plugs, increased mud coatings on substrate surfaces, and changes in bed-material size. However, while every site but one shows at least one of these channel impacts, only one site shows all of them. Sediment impacts seem to predominate over runoff impacts from the trails, which supports the contention that sediment sources on the trails are renewed over time. Small channels (basin areas <0.4 km^2) show some consistency in their responses, exhibiting sediment plugs, width:depth changes, and bed fining frequently; whereas large channels show more variable responses. Where OHV use is currently allowed, downstream increases in mud coatings and sediment deposition features are more common, whereas the other responses considered seem uncorrelated to recent OHV use. This suggests that the occurrence of past OHV traffic is more important than the recentness of OHV usage—at least with respect to stream impacts, as opposed to degradation of trail surfaces themselves.

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Appendix A. Bankfull elevation determination

The bankfull elevation occurs at the topographic break between the channel bank and the adjacent active floodplain (Dunne and Leopold, 1978). The elevation of a well-developed floodplain is the best morphologic indicator for identifying the bankfull elevation in Ouachita Mountains streams (USDA Forest Service, Rocky Mountain Research Station, 2003), but floodplains are often absent or inconsistently expressed at the crossing sites, which occur within channels having mixed bedrock-alluvial sections. Therefore, we estimated the bankfull elevation using a combination of morphologic evidence from topographic benches or flats recorded on the cross section surveys and estimates of bankfull discharge obtained from regional models.

A 3-step process was used to define the bankfull elevation for the cross sections compared at each crossing site. First, an initial estimate was computed of the 1.1- and 3.0-year floods at each site. Past studies have shown that the bankfull discharge predominantly has a 1.0- to 3.0-year return period (e.g., Dury, 1973; Williams, 1978; Petit and Pauquet, 1997). For sites with drainage areas <0.40 km^2, these flood discharges were estimated using an existing regional flood-frequency model (Marion, 2004). For sites with larger drainage areas, the same frequency floods were estimated using models of peak discharge as a function of drainage area that were developed using unpublished annual-series data from Forest Service gauging stations within the Ouachita Mountains. Second, all three upstream cross sections at each site were analyzed to determine the discharge that corresponded to possible bankfull features observed on each cross section. Cross-sectional dimensions and discharge were computed using the WinXSPro application (Hardy et al., 2005). Discharge was computed using the Manning equation with a mean roughness value estimated using Jarrett's (1984) model. Third, the discharges from the second step were then compared to those from the first to insure they fell within the discharge range for 1.0- to 3.0-year floods and to insure that the discharges used at each site were not unrealistically different from those up- or downstream, or with similar drainage areas. Based on these comparisons and the judged quality of the bankfull features at each cross section, a representative discharge was selected based upon one or more of the three cross section estimates.

The second and third steps were then applied to the selected downstream cross section. As increased discharge is possible at the downstream cross section, a higher discharge was accepted if the bankfull features were judged as being trustworthy and the increase was deemed reasonable. Where bankfull features were uncertain or produced discharges that were less than those upstream, the selected upstream discharge was used. Cross-sectional dimensions were then determined based upon the elevations that produced the selected bankfull discharges at the up- and downstream cross sections being compared.

Appendix B. Bed-material size sampling and testing

Both types of bed-material size change are potentially possible at OHV stream crossings. Increased delivery of smaller grains (say, <16 mm) from the trail area could cause the downstream reach substrate to decrease in size (i.e., cause fining of the bed). Conversely, increased surface runoff delivery to the stream from the trail area, especially where trail sediment might be exhausted, could create relatively deeper, more erosive flows and cause the downstream substrate to increase in size (coarsening of the bed). As either change seemed plausible, each crossing site pair was tested individually.

The same hydraulic units (generally riffles) were sampled up- and downstream of the crossings to minimize hydraulic differences between sample locations. The hydraulic units used for grain size sampling were different from those used for other morphological and hydraulic comparisons to avoid affecting those other comparisons.

Pebble counts were accomplished by sampling at 0.2-m intervals along several transects across individual hydraulic units. A tape was stretched across the channel, and bed clasts intersecting the tape line were picked up and measured along the median axis (Bunte and Abt, 2001). The number and spacing of transects were based on channel width and length of the sampled unit to ensure sufficient samples. Where material less than fine gravel size (2–4 mm) was encountered, the diameter was recorded as <4 mm because of the difficulty in consistently picking up these grains. The nature of the sampling procedure is biased against fine gravel and smaller size particles, but any such bias is consistent within and between the sample sites. Further, as this bias is inherent to the method, our results are comparable to those using the same pebble-counting procedures.

Two-sample statistical tests were used to determine if a shift in bed-material size occurred downstream of a trail crossing. Grain size distributions for each sample facie were evaluated to determine if they were sufficiently close to a normal (Gaussian) distribution to warrant using parametric statistical methods. All grain sizes were transformed logarithmically into φ-units, as is common in evaluating grain sizes from coarse-bed streams (Bunte and Abt, 2001). Schleyer (1987) goodness-of-fit and D'Agostino normality tests (Gilbert, 1987) were computed, as well as the sorting, skewness, and kurtosis statistics (after Folk and Ward, 1957) for evaluating normality. The mean grain size was computed using Folk and Ward's (1957) equation, while the median was determined by linear interpolation of the 50th percentile from the grain size distribution. Cumulative probabilities used in the goodness-of-fit test were computed from a function provided by Gilbert (1987). For sites where both the up- and downstream size distributions seemed reasonably close to normal, a *t*-test was used to test whether the mean grain sizes were different; otherwise, the Mann–Whitney nonparametric test was used to test whether the median values differed. A large-sample approximation and correction for the number of ties was used with all Mann–Whitney tests (Daniel, 1978). As each test was applied when appropriate based on the respective test assumptions and the sample sizes used for each test (350–450) were roughly equivalent, the results using the two tests are comparable.

The testing of each site in this way creates the same issue as occurs in analysis of variance wherein multiple comparisons of sample subsets increases the chance of type I error (i.e., the null hypothesis being rejected when the null is in fact true). An overall (i.e., experiment-wise) type I error rate can be maintained by using a Bonferroni correction to the individual site (i.e., the comparison-wise) significance level based on the number of sample sites tested (Mason et al., 1989). Wohl et al. (1996) used the same correction to perform multiple comparisons of variance and distribution differences between grain size distributions determined by different operators. However, the division of sites in the present study into two groups based on their different frequency distributions effectively creates a testing design consisting of two independent experiments. As the two groups represent different statistical populations, testing within one group should not affect the chance of type I error when testing within the other group; thus the corrected comparison-wise significance level only considers the number of samples within each group (normal = 9, nonnormal = 5). To maintain the same overall rejection level of 0.05 for both groups, then, the comparison-wise rejection levels used were 0.005 (after rounding) for the individual *t*-tests and 0.010 for the Mann–Whitney tests. This approach is conservative in that it keeps the probability of rejecting the null when it is true very low and accepts the possibility of somewhat higher errors in not rejecting the null when it is false.

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