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Concentration and divergence of sediment in an erosional landscape

Jonathan D. Phillips [a,b,*], Daniel A. Marion [a,c], Kathleen G. Kilcoyne [a]

[a] Earth Surface Systems Program, Department of Geography, University of Kentucky, Lexington, KY 40506-0027, USA
[b] Department of Geography, Planning, and Environment, East Carolina University, Greenville, NC, USA
[c] Formerly: Southern Research Station, USDA Forest Service, Hot Springs, AR, USA

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ABSTRACT

In an eroding landscape, the erosional source area (A_e) may be larger or smaller than the depositional or storage area (A_d). This corresponds to areal concentration ($A_e/A_d > 1$) or divergence ($A_e/A_d < 1$) of sediment. We investigated this in an area of the Ouachita Mountains for three different time periods: before the early 1800s (pre-European settlement), early 1800s to 1990s, and post 1990s. Pre-1800, the forest was mainly undisturbed and soil loss was dominated by slow erosion and mass wasting from ridge tops. In the latter period establishment of all-terrain vehicle (ATV) trails created a small area of rapid, concentrated, persistent erosion. In the middle period, logging operations resulted in short-lived erosion hotspots scattered throughout the landscape. For the pre-1800s period, we estimated A_e/A_d based on the spatial distribution of alluvial, colluvial, and upland potential source area soils. $A_e/A_d = 0.81$, and <1 even when alluvial soils are not included. For the most recent era, field studies documented the eroding surface area of trails, as well as the area of near-trail sediment deposits and of deposition in smaller stream channels. $A_e/A_d = 6.60$, indicating concentration. In the intermediate era, conditions were more similar to the pre-European condition, as harvested areas and temporary unpaved roads recover quickly to pre-disturbance conditions and use of permanent roads was far lower before the ATV trails. The strongly dissected, steep topography, humid subtropical climate, limited potential for agriculture, and the nature of the ATV trail erosion all play roles in creating the sediment divergence in earlier eras and sediment concentration more recently. This suggests a need for more case studies to develop more general principles or guidelines to predict sediment concentration and divergence.

1. Introduction

Erosion and sediment transport redistribute sediment. Some eroded material is exported from the landscape, such as sediment yield from the outlet of a drainage basin, or aeolian transport to the ocean or an adjacent landscape. Variable but significant amounts of sediment, however, are redistributed within the landscape. Further, the potential for redistribution varies with the mode of erosion and transport (e.g., water vs. wind vs. mass movements), and sediment caliber. The finest materials, for instance, can potentially be transported anywhere that flowing water can go or that dust can blow. Transport of large boulders, by contrast, may be restricted to local slopes. This paper explores the redistribution and storage of eroded sediment in a landscape in the Ouachita Mountains of western Arkansas, with particular attention to the extent to which eroded material becomes concentrated or diverges. In the former case, the area of storage or deposition (A_d) is less than the eroding source area (A_e), while divergence occurs where eroding material is spread to a broader area than its eroding source ($A_e/A_d < 1$).

The study area, the Wolf Pen Gap (WPG) ATV (all terrain vehicle) trail complex within the Board Camp Creek watershed (Fig. 1), has undergone three distinct episodes of erosion in the historic era. Before European settlement, the area experienced very low denudation due to a dense forest cover and negligible land disturbance. Between the early 1830s and the late twentieth century, the area underwent some episodes of logging, a few small mining operations, and perhaps scattered agriculture. Erosion rates increased, but erosion was scattered in both space and time (see Section 2.2). In the 1990s, the trail complex for off-highway vehicles, principally all-terrain vehicles, was established. This initiated an era of rapid erosion on the trails, with the remainder of the forested landscape experiencing minimal denudation. The area is thus well suited for this study because of this historical variation. It is also conducive because the area's geology and soils make the recognition of colluvial soils much more straightforward than is normally the case, as described below.

We hypothesize that under natural conditions (defined here as minimal human disturbance), sediment flux is dominantly divergent. The

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* Corresponding author at: Earth Surface Systems Program, Department of Geography, University of Kentucky, Lexington, KY 40506-0027, USA.
E-mail address: jdp@uky.edu (J.D. Phillips).

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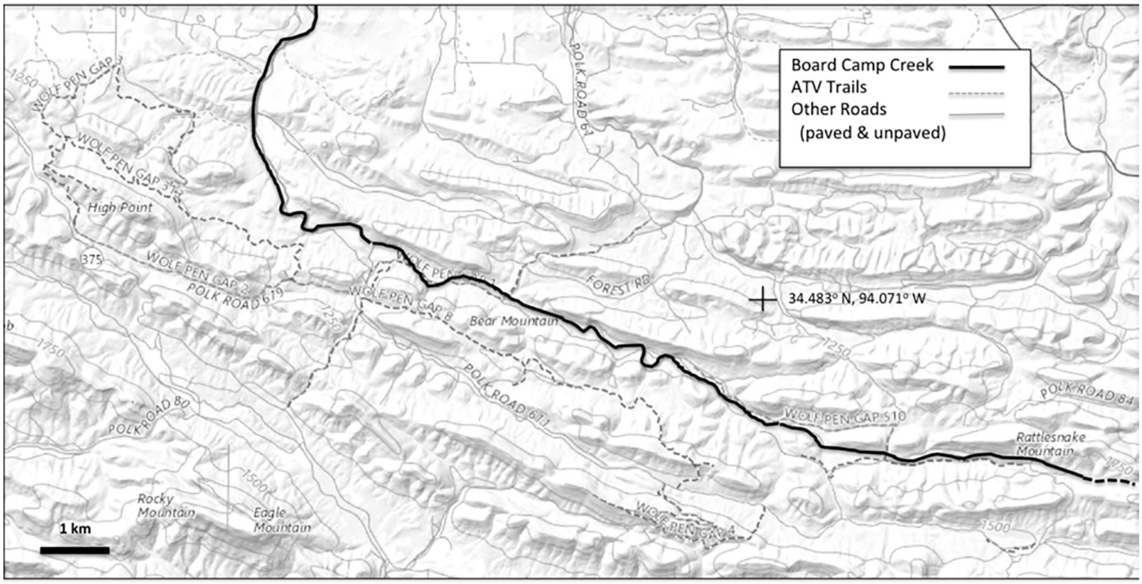

Fig. 1. Study area, showing trail sections and stream sample sites (circles) sampled for fine sediment deposition. Base image from U.S. Geological Survey National Map (https://nationalmap.gov/).

reasoning is that erosion hot spots would be rare, small, short lived, and widely dispersed over the landscape, and areas characterized by persistent, if slow, soil removal (ridgetops and upper slopes) are relatively minor in total area but present throughout the landscape. Mass wasting and water erosion gradually distributes this material to midslopes, toeslopes, hollows (unchannelled valleys), and stream valleys, resulting in divergence as eroded sediments are spread over an area larger than their source.

In recent decades following the establishment of the ATV trails, erosion is strongly dominated by the local source of the trails. While some sediment reaching streams may be widely dispersed, colluvial storage of eroded sediment is likely to be concentrated in topographically controlled depositional hotspots. Thus we hypothesize that sediment flux in this situation is convergent, despite the relatively small eroding area.

Though our hypotheses are specific to the WPG area, the reasoning applies in a general sense to other locations that have undergone a transition from a slow, spatially dispersed erosion regime to one with rapid rates of removal from spatially localized hotspots.

1.1. Conceptual framework

When sediment is eroded and transported by water, the transport distance may be minimal, complete (i.e., removal from the drainage basin), or anywhere in between. Minimal transport occurs when the eroded material is deposited immediately adjacent to the site of erosion, and complete transport occurs when sediment is exported. With respect to water erosion, a broad distinction is made among the following:

(1) Detachment and mixing: Particle detachment by raindrop impact, for example, and soil mixing by bioturbation result in transport a very short distance from the original site, but at the plot or pedon scale or larger, the sediment remains in place (Morgan, 2005).
(2) Colluvium: Though definitions of colluvium vary, here we use the simplest and broadest—material that is removed by erosion or mass wasting and redeposited before it reaches a fluvial channel.
(3) Alluvium: Sediment stored within stream channels or on floodplains.
(4) Yield: Sediment exported from the drainage basin.

This is highly simplified. Colluvial storage, for example, may occur near the site of erosion, or some distance downslope. Some colluvial storage is long-term, as reflected by pedogenesis in colluvial parent materials, while some is transitory, with episodic remobilization. Likewise, alluvial storage may occur at or near where sediment is delivered to channels, at the watershed outlet in deltas, or anywhere in between. Alluvium also varies in residence time, from frequently mobile bed material to long-term storage in alluvial terrace soils, and is also subject to remobilization (Phillips and Marion, 2019).

Clay particles, once detached, fine silt, and particulate organic matter have very slow settling velocities in water. Thus they are capable of being transported anywhere that water can flow, and will generally be deposited only when flow is ponded or impeded, or as stage levels fall. Sizes larger than silt are less often transported in suspension, and particles larger than sand are rarely transported in suspension. The larger particles are entrained less often, and transport distances are shorter. The largest clasts, cobbles and boulders, cannot generally be transported by water except in channels, and thus move on hillslopes only via gravity-driven mass movements.

Convergence or concentration occurs when material eroded from a broader area is concentrated in a smaller area. This is the case in many U.S. rural landscapes, for instance, where numerous small ponds sequester sediment eroded from agricultural watersheds (Renwick et al., 2005). At a more local scale, colluvial deposits from erosion of crop fields is typically concentrated in smaller areas of colluvial or cumulic soil, rill fans, and field-edge deposits at lower field boundaries (e.g., Slattery et al., 2002). In karst landscapes, sinkholes may serve to concentrate solids eroded from surrounding land (Hart and Schurger, 2005).

Divergence exists where sediment eroded from a smaller area is spread over a larger area. For example, erosion from a specific gully, construction site, or other disturbed land may result in sediment distribution (particularly of finer material) by surface runoff or fluvial processes over broad areas of colluvial and alluvial deposition. In some mountain environments, the total area of colluvial soils or those that include transported material on lower and mid-slopes may exceed the total upslope source area, with $A_e/A_d < 1$ (e.g., Phillips et al., 2005).

In many cases, however, concentration or divergence is not as straightforward or evident as in the examples above. Further, the same landscape may vary at different times due to land use, climate, or other environmental changes, or due to the effects of large events such as floods. The concentration/divergence question is relevant for four main reasons. First, it is relevant to studies of sediment connectivity, extending the concept to within-hillslope connectivity in addition to connectivity within fluvial systems and between hillslopes and channels (Baartman et al., 2013; Fryirs, 2013). Comparing the magnitude of erosional source areas and depositional areas is obviously directly related to their connectivity. Consideration of the extent to which sediment flux spatially concentrates vs. dispersing sediment moves connectivity beyond the usual connected-or-not binary. Second, concentration/divergence links surficial sediment flux to regolith and soil formation; directly linking source areas to zones of depositional additions to soil and regolith. In many high-relief areas a key distinction is between soils from primarily in situ weathered regolith or from predominantly colluvial parent material. Also, in areas characterized by aeolian silt or loess caps, the presence or absence and thickness of these surficial materials is a key discriminant among soil types and is associated primarily with post-depositional redistribution. Because soil survey and mapping depend on extrapolating scattered field measurements using soil-landscape relationships (Hudson, 1992), understanding patterns of sediment convergence and divergence could greatly improve soil inventories. Third, the convergence or diffusion of eroded sediment is relevant to the targeting of sediment control or rehabilitation efforts focused on the offsite impacts of soil loss and targeting of erosion control, since deposition sites are often used to identify erosion source areas (Rickson, 2014; Richardson et al., 2019). Finally, where contaminated sediments or sediment-associated pollutants are of concern, there is a need to know if and how these are dispersed or concentrated in the landscape (Franz et al., 2013; Biswas et al., 2018).

2. Study area

2.1. Environmental context

The WPG Trail Complex is in the Ouachita Mountains near Mena, Arkansas (Fig. 1). The Ouachita Mountains are approximately parallel ridges, oriented generally east-west, with typical peak elevations in the study area of about 500 to 700 m. The humid subtropical climate features hot summers, relatively mild winters, and year-round precipitation. Mean annual precipitation is about 1350 mm, nearly all rain.

The WPG area is 95% forested, with a mixture of pines (mainly shortleaf pine, *Pinus echinata*) and hardwoods. Non-forested areas include roads and trails, scattered campsites and parking areas, and some clearings maintained with herbaceous plant cover for wildlife habitat.

The geology of the Ouachita Mountains is complex. The Paleozoic sedimentary rocks have undergone extensive tectonic deformation, with steeply dipping and contorted strata common (Stone and Bush, 1984). Geological formations are composed of various combinations of relatively weak and readily weathered shales, hard and highly resistant cherts and novaculites, and sandstones of intermediate and highly variable resistance. Along with variations in original bedding and intergradations among these lithologies, deformation results in formations that are lithologically and structurally variable in both the vertical and horizontal dimensions. The harder rocks (sandstone, novaculite, chert) are often strongly jointed or fractured, and often occur in strata <15 cm thick, with intervening layers of shale. Thus, though individual clasts are minimally weathered, exposure of these rocks near the surface typically produces an abundance of cobble-sized material.

Study area soils are predominantly Typic Hapludults on ridgetops and sideslopes, with some Dystrudepts in thin-soil areas. Some Paleudalfs are also found on upland sites. Valley bottom soils are Typic Udifluvents or Ultic Hapludalfs (Olson, 2003). Soils are thin except in valley bottoms, generally <1 m over weathered or unweathered bedrock, with common rock outcrops. Rock fragment contents of 70% or more are not uncommon, and nearly all soils have rock fragment content >30%.

2.2. ATV trails

During fieldwork for this project (2012–2018), nearly 80 km of trails were open to off-highway vehicles within the WPG Trail Complex. These include dedicated ATV trails, and unpaved roads for multipurpose use or where highway-legal vehicles only are permitted. As of June 2011, the complex included about 1600 water diversion bars, and nearly 35,000 m^2 of lead-off ditches (small ditches that convey runoff from unpaved road surfaces to streams). These features are common on forest roads. However, they are not considered suitable for ATV trails, and have been recommended for reconstruction and removal, respectively, at WPG (Stinchfield et al., 2011). The complex is open year-round, though since 2011 the entire complex or individual trails are sometimes closed to ATV use in wet weather. Trails range from unpaved roads included in the county and Forest Service road systems, to repurposed logging roads, to trails specially constructed or renovated for ATV use. A few sections have been restricted to only highway-legal vehicles since 2001, though ATV use was previously allowed and still occurs illegally. ATV (as opposed to other vehicles) use is dominant. A number of erosion and sediment control structures (mainly sediment traps) were constructed between 2012 and 2018, and culverts were installed at some stream crossings that were previously fords. Some severely eroded trails have been closed, and some steep eroded segments have been armored with porous pavers. Some new trail segments have been constructed, and a more systematic program for wet-weather trail closures has been implemented.

2.3. Land use history

The exact date of European- and African-American settlement and land use change in the study is uncertain, but occurred in the early nineteenth century (though some exploration and possibly isolated settlement may have occurred earlier). The U.S. acquired the area now known as Polk County in 1803 via the Louisiana Purchase, and the Arkansas Territory was established in 1819, by which time several settlements existed in the county. Statehood occurred in 1836, and land grants to military veterans in 1837 initiated a surge in settlement. The area was described as an uncharted wilderness in 1812, though Native Americans were present by the early Holocene, and the first recorded European explorer (Hernando DeSoto) arrived in 1541. Ouachita National Forest, the first in the U.S., was established in 1907. The land purchased included forests, and also submarginal farms that were either seeded to pine or allowed to re-vegetate naturally (USDA Forest Service, 1937).

Land use information and logging records specific to the WPG area are not available. However, harvesting occurred within the area before and after establishment of the national forest. No logging has occurred since establishment of the WPG Trail Complex.

3. Methods

In this study we make use of three major data sources. First is extensive fieldwork associated with a series of studies of ATV trail erosion, geomorphic impacts of the ATV trails on streams, sediment connectivity, and the fate of fine sediments eroded from the trails (Marion et al., 2014a, 2019; Phillips and Marion, 2019; Phillips et al., 2020). In addition to data from this work that has already been published, we also used some previously unpublished data associated with this work. Second, we used digital soil data and maps from the U.S. Department of Agriculture Web Soil Survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). The third major data source is a ~ 1 m (3 ft) horizontal resolution digital elevation model (DEM) derived from LiDAR and obtained from the U.S. Geological Survey (https://nationalmap.gov/).

3.1. Pre-1800s

Our assessment of sediment redistribution before major land disturbances by logging, agriculture, and unpaved roads and trails is based on soil geography. This depends on the assumption that gross soil morphology at the landscape scale reflects long-term environments of pedogenesis rather than more recent local changes. We realize that there are certainly exceptions to the latter, and have used soil profile truncation, for instance, as evidence of recent and contemporary erosion and deposition (Marion et al., 2019; Phillips et al., 2020).

Soils mapped in the study area can be divided into three general categories: residual, colluvial, and alluvial (Olson, 2003). Residual soils formed primarily from in situ weathering of underlying bedrock. Colluvial soils formed primarily in transported material on hillslopes. Alluvial soils formed in water-deposited sediment in floodplains and fluvial terraces. Because of the lithological variations in the Ouachita Mountains and the tendency for sandstone, chert, and novaculite to outcrop on ridgetops and upper slopes, colluvial soils are relatively easily and confidently recognized based on lithological contrasts and a prevalence of non-oriented rock fragments. Using the digital soil data, derived from field soil mapping at the 1:24,000 scale, we determined the total area of residual (upland), colluvial, and alluvial soils.

Many soil mapping units contain multiple series, with the typical percentage of each indicated in associated attribute data. We first categorized all soil series mapped in the WPG area as upland (residual), colluvial, or alluvial. Then the total area of each map unit was multiplied by the estimated proportion of colluvial and alluvial soil types to estimate the total area within that map unit. These were then summed for the study area, with the remainder assumed to be upland, residual soils.

3.2. Early nineteenth to late twentieth century

Little direct information exists for the era of logging and agriculture before the ATV trails. We inferred general trends from twentieth century studies in the region of erosion and sediment yield from forested and logged watersheds, and landscape evidence of land disturbance and geomorphic change such as old logging roads and alluvial terraces (see Section 4.2).

3.3. ATV trails

In recent decades the WPG trail network is by far the major erosion source. In previous work we measured soil loss from trails using sediment traps and soil profile truncation (Marion et al., 2019), inventoried soil erosion features and assessed their sediment connectivity with drainageways (Phillips et al., 2020), examined geomorphic effects on streams (Marion et al., 2014a; Phillips and Marion, 2019), and measured fine sediment accumulations. These consisted of clay, silt, sand, and fine gravel (<8 mm diameter) in trailside settings and small streams (Phillips et al., 2020). Methods are described in the citations above.

From these data we determined the total area of eroding trails and the area of measurable concentrations of trailside fine sediment accumulations derived from trail erosion. These estimates were based on extrapolating the storage areas per unit length of trail along the 26.5 km of trail where measurements were made to the entire trail network. We also measured fine sediment accumulations in 33 study reaches in four types of small stream channels, and extrapolated these to the total length of these channel types within the WPG area, as described by Phillips et al. (2020). Sediment storage in larger streams is based on alluvial soil map units, as little in-channel storage was found by Phillips and Marion (2019).

3.4. DEM analysis

The 1 m horizontal resolution DEM was analyzed using RiverTools™ (Rivix, Inc.). Shaded relief and 3D surface maps were produced for terrain visualization. The stream network was extracted using a D8 flow algorithm. This was pruned by flow path link order so that the lowest-order basins in the derived network have a minimum drainage area of 2550 m^2 (0.256 ha) and a mean of 45,962 m^2 (4.6 ha). This corresponds well to channel networks observed in the field. This differs somewhat from the network extraction thresholds used in earlier work (Guarneri, 2013; Phillips et al., 2020). However, the previous work was based on a DEM with a 10 m horizontal resolution.

A topographic wetness index was calculated for each pixel based on

$$\mathrm{TI} = \ln(A/S) \tag{1}$$

where A is the contributing area for the pixel and S the local slope. Steeper slopes with smaller contributing areas produce lower TI values, and vice-versa. Higher values indicate areas more likely to experience flow convergence and wetter conditions, and lower TI values are associated with runoff-shedding pixels.

4. Results

4.1. Soil geography

Two colluvial soils are mapped in the WPG area, the Bengal and Yanush series. Bengal (Typic Hapludults in the U.S. Soil Taxonomy) has upper layers (A and Bt horizons) that are stony loam or clay loam in texture, with sandstone fragments. This is the colluvial material. The underlying soil (2Bt and 2C horizons) is a clay texture derived from weathering of shale, with some shale fragments but no sandstone. The Yanush series is a Typic Paleudalf formed entirely in colluvial material, as indicated by a profile that contains 20 to 70% chert and novaculite fragments in a silt loam or silty clay loam matrix, overlying shale or shale interbedded with sandstone and chert. They occur downslope of upper slope and ridgetop chert and novaculite outcrops.

Two alluvial soil series occur in the area along the valley bottoms of Board Camp and Gap creeks, and sporadically along other valley bottoms. Ceda (Typic Udifluvents) is a minimally developed soil with abundant gravel and cobbles (35 to 70%) in a loamy matrix, and an A-C profile. Kenn soils are better developed (Ultic Hapludalfs), with argillic horizons. They tend to have fewer rock fragments in the upper solum, but very high stone content (up to 85%) in 2C horizons. Other soil series found in the study area are upland, residual types.

The general spatial distribution of colluvial and alluvial soils is shown in Fig. 2. Alluvial soils are, as expected, concentrated in valley bottoms. Map units containing some colluvial soils, however, are ubiquitous.

The relative proportions of upland, colluvial, and alluvial soils are shown in Table 1.

If the non-colluvial upland soils are considered the erosional source area, the ratio of eroding area to depositional area (colluvial plus alluvial soils) is 0.81, indicating an expansion ratio of 1.23.

4.2. Nineteenth and twentieth century legacies

The most likely changes after 1800 are associated with timber harvesting. Two small abandoned novaculite mine sites occur within the WPG area, but no extensive land disturbance occurred, and there was no other industry or commercial land development. Agriculture does not appear to be a significant factor, either. No historical record exists of any farm sites within the study area, and we observed no field

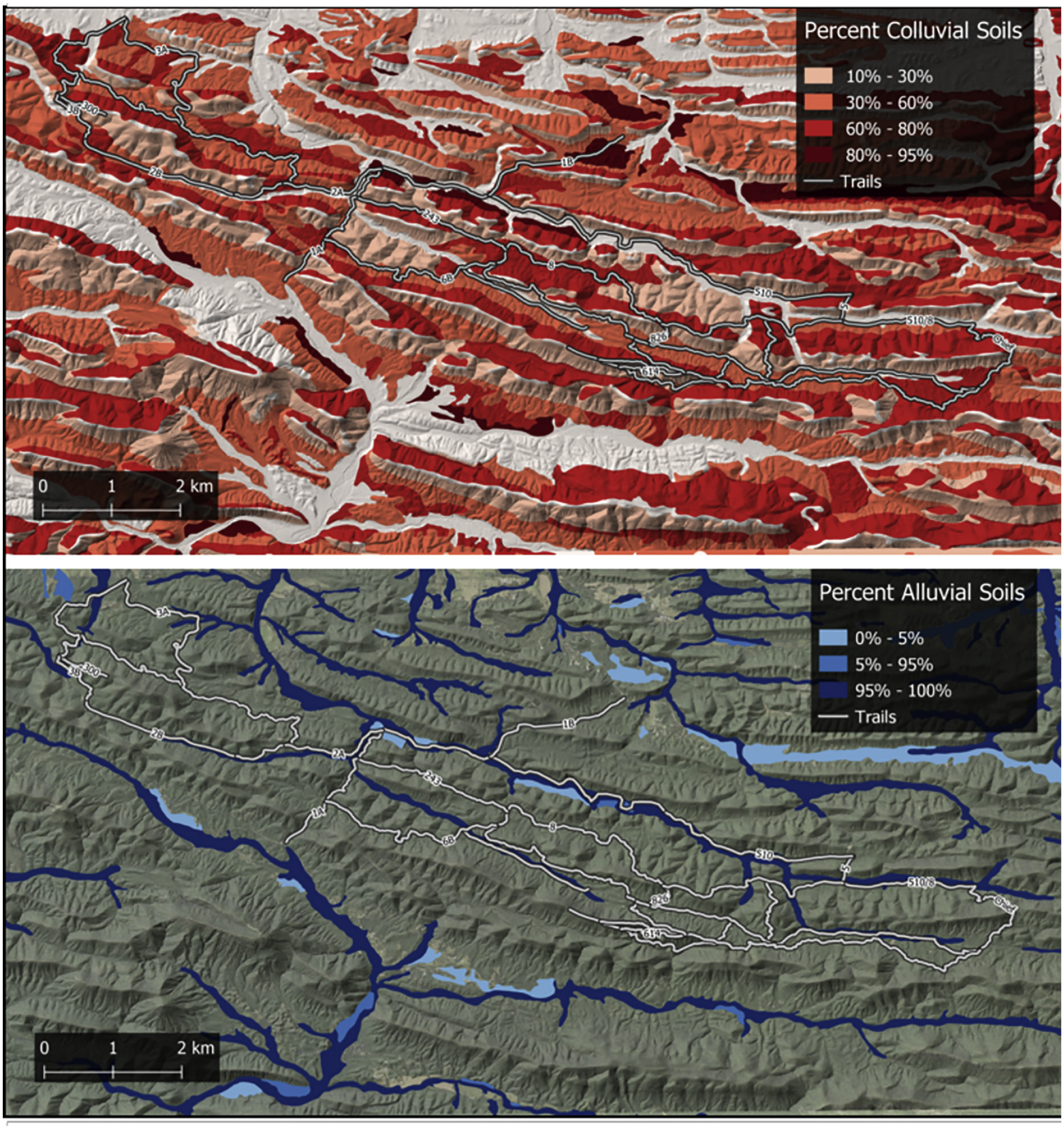

Fig. 2. The percentage of colluvial (Bengal and Yanush series; top) and alluvial (Ceda and Kenn series) in soil mapping units.

evidence, such as relic furrows or the objects such as abandoned farm implements or building ruins typically found in agricultural areas abandoned in the 1800s or 1900s. The forest service's historical overview of the Ouachita National Forest published 7 years after the national forest was established indicates that, in general, farms were rare in the steep uplands such as those that dominate the WPG area, though logging did occur (USDA Forest Service, 1937).

Modern soil surveys rank soil types according to a seven-category agriculture-focused land capability classification system, with class I indicating the most favorable soils and class VII soils having very severe limitations making them unsuitable for cultivation (Table 2). The system also assigns subclasses related to the most severe limiting factors, such as stone content, erosion susceptibility, waterlogging, etc. The GIS analysis of soils in the study area shows that >95% of the soils are in class VII, due mainly to very high stone contents and occurrence on steep slopes. No class I soils are mapped (Table 2). This supports the idea that there was little or no cultivation with the WPG area.

Logging did occur. No specific records exist of timber harvesting or sales before or after establishment of the national forest, but logging

Table 1
Upland, colluvial, and alluvial soils.

	Area (ha)	Area (%)
Total study area	1873	100.0
Upland soils	841	44.9
Colluvial soils	847	45.2
Alluvial soils	185	9.9

Table 2
Area of soils by land capability class (LCC) in the study area.[a]

LCC	Description	Area (ha)	Area (%)[a]
I	Few limitations that restrict their use	0	0
II	Moderate limitations that restrict choice of plants or require moderate conservation practices	13.1	0.8
III	Severe limitations that restrict choice of plants or require conservation practices	0	0
IV	Very severe limitations that restrict choice of plants or require conservation practices	38.0	2.4
V	Subject to little or no erosion but have other limitations, impractical to remove, that restrict their use	0	0
VI	Severe limitations that make them generally unsuitable for cultivation	24.6	1.5
VII	Very severe limitations that make them generally unsuitable for cultivation	1539.0	95.3

[a] Percent of classified soils; 258.3 ha of the study area are unclassified or non-soil.

was common throughout the region. In the field, sawn stumps from twentieth century harvesting can be found, along with field evidence of old logging roads (Fig. 3).


Fig. 3. Examples of abandoned logging roads in the Wolf Pen Gap area.

No hydrological or geomorphological studies of timber harvesting effects were conducted until the late twentieth century. These studies generally show relatively high erosion rates from unpaved forest roads and trails, low rates from logged areas, and negligible soil loss from undisturbed forests (Table 3). Some of these studies are based on sediment yield in streams rather than direct measurements of soil loss. These will underestimate erosion to the extent that eroded material is stored as colluvium before reaching streams. However, the yield-based studies were conducted in small, steep headwater basins with drainage areas <0.05 km^2. Field conditions in these study sites suggest minimal colluvial storage (see discussion by Marion et al., 2019, p. 3–4).

As is common in the humid subtropical southern USA, vegetation in the Ouachitas recovers rapidly after even clear-cut logging, unless specifically repressed by management activities. Runoff and sediment yields are elevated for the first year post-harvest, but within three years have declined to pre-harvest levels (Miller, 1984; Marion et al., 2014b). With the exception of the highly used trails in the WPG trail complex, studies in the Ouachitas show that erosion rates from unpaved roads declines over time (Table 3), and logging roads, once disused, revegetate rapidly.

Some low-order valleys and hillslope hollows within the study area contain apparent debris flow deposits. These could be associated with landscape destabilization from logging, but the origin and dates of the debris flow features are unknown. A more likely impact of logging is stream incision due to increased runoff. The presence of alluvial terraces along some stream reaches provides evidence of incision episodes (Fig. 4). However, these terraces have not been dated and may or may not be associated with forestry activities.

4.3. Water erosion from ATV trails

In the study of fine sediment accumulations (FSA) from ATV trail erosion of Phillips et al. (2020), sediment volumes were measured by determining the surface area of FSA accumulations and multiplying these by mean depths. These surface areas were taken from that data set, and extrapolated to the entire study area. Results are shown in Table 4. Note that about 27% of the stream sediment measurements were in streams not affected by ATV trails (i.e., no trails within the watershed of the sampled reach).

The total surface area of unpaved roads and trails in the WPG complex is 19.88 ha, computed as 79.52 km in total length, by 2.50 m mean width reported by Marion et al. (2019), the entire area of which is eroding. The measured surface area of trailside fine sediment accumulations is 7475 m^2 (0.75 ha) along 26.3 km of sample trail length. Extrapolated to the entire network, this amounts to 2.26 ha.

Surface areas of fine sediment storage in sampled streams averages 1.41 m^2 m^{-1} of channel length in the smallest perennial headwater streams, and 1.04 in larger headwater streams. Storage rates of 0.55 and 0.46 m^2 m^{-1}, respectively, were found in two classes of upper valley streams. Extrapolated to the total length of each stream type, the area of stream storage is estimated as about 0.75 ha.

Table 3
Measured erosion and sediment yield rates from forest areas of the Ouachita Mountains, Arkansas and Oklahoma.

Mean erosion rate (tonne ha^{-1} yr^{-1})	Environmental setting	Notes	Source
75–210	Off-highway vehicle trails	Estimates based on soil truncation & sediment traps	Marion et al., 2019
55	Unpaved forest roads	4 segments monitored for 17 months	Miller et al., 1985
91	Unpaved forest roads	4 segments monitored for 12 months; newly constructed	Vowell, 1985
79	Unpaved forest roads	3.5 year study of newly constructed roads; rate decreased over time	Turton and Vowell, 2000
6.5 to 7.6	Unpaved forest roads	6 month study of 25 year old roads	Busteed, 2004
0.282	Clear cut	Sediment yield from 3 small basins, first year after harvest	Miller, 1984
<0.035	Clear cut	Sediment yield from 3 small basins, 2–4 years post-harvest	Miller, 1984
≤0.2	Clear cut	Cesium-137 estimates at two sites	McIntyre et al., 1987
0.0022 to 6.1	Undisturbed forest	Universal soil loss equation, lowest to highest factor values (with average factor values, 0.18)	Dissmeyer and Stump, 1978
0.016	Undisturbed forest	Sediment yield over 9 years from storm runoff in 3 headwater basins <0.7 ha	Lawson, 1985 Rogerson, 1985
0.018	Undisturbed forest	Sediment yield over 4 years from storm runoff in 3 headwater basins <4.2 ha	Miller et al., 1985
0.036	Undisturbed forest	Sediment yield over 3 to 4 years from 9 headwater basins <4.9 ha	Miller et al., 1988; Miller, 1984

The total eroding trail area is about 8.8 times larger than the area of trailside fine sediment accumulations, and >25 times than the total estimated area of small stream storage (ratio = 25.60). However, the concentration is even greater when only trail-influenced streams are considered (ratio = 42.30). The concentration ratio overall (eroding trail area/total trailside and small stream depositional areas) is 6.60.

The area of mapped alluvial soils is more than nine times the eroding trail area (ratio = 0.11). However, these alluvial deposits represent long-term inputs from all sources, and previous studies of ATV trail effects on larger stream channels indicates minimal and highly localized effects (Marion et al., 2014a; Phillips and Marion, 2019).

While our studies of sediment accumulation focused on fine sediment, trail erosion includes coarse sediment. These gravel and cobble size clasts are transported by water during high runoff events, dry ravel rock creep, and wheel ravel. Wheel action physically abrades trail surfaces, as well as dislodges and moves sediment from the wheel tracks to trail edges and centerline, and preferentially downslope. Dry ravel moves coarse fragments downslope, where they may accumulate at topographic lows (Fig. 5). Wheel ravel, in addition to detaching particles for dry ravel and fluvial transport, may concentrate rock fragments at trail edges and center ridges (Fig. 6).

Fig. 4. Examples of alluvial terraces along Board Camp Creek, possibly indicating post-logging incision.

4.4. Topographic analysis

The 18.73 km^2 study area is strongly dissected, with complex topography. Drainage density of perennial streams is 19.94 km km^{-2}, indicating a drainage area of 939 m^2 (0.09 ha) for each linear meter of stream channel.

Total relief within the study area is 406 m (285 to 691 masl). Local relief between adjacent ridgetops and valley bottoms is typically 120 to 215 m. Local (pixel-scale) gradients, expressed as rise/run, vary enormously, from 0 to 0.8440 (mean = 0.1296; standard deviation = 0.0876). Local drainage areas vary from 0.0001 ha (1 m^2) to 4114 ha. The mean of 6.45 ha and standard deviation of 159.2 are strongly affected by high drainage areas associated with pixels on the lower reaches of Board Camp and Gap creeks in the study area. The median drainage area per pixel is about 0.0004 ha (4 m^2).

The topographic index is spatially complex, as shown by the comparison of surface plots of the topography and topographic wetness index in Fig. 7. As expected, there is a broad correlation between the TI and elevation, slope, and location relative to the channel network. However, this pattern is overlain with variation associated with local (within hillslopes, valleys, etc.) variability.

Table 4
Areas of eroding trails and fine sediment accumulations (FSA). H1 and H2 streams are low-order, headwater channels. H1 channels are steeper and have longer, steeper valley side slopes than H2. UV1, UV2 are larger, upper-valley channels, with drainage areas ≤3 or > 3 km^2, respectively. Full explanation of the classification is given by Phillips et al. (2020).

	Measured area (ha)	Extrapolated area (ha)
Eroding ATV trails	9.60	19.88
Trailside FSA	0.75	2.26
FSA H1 streams	0.06	0.38
FSA H2 streams	0.05	0.30
FSA UV1 streams	<0.01	0.02
FSA UV2 streams	<0.01	0.03
Total H1, H2, UV1, UV2	0.13	0.75
Total trail-influenced streams	0.08	0.47

Fig. 5. Downhill concentration of rock fragments due to dry ravel.

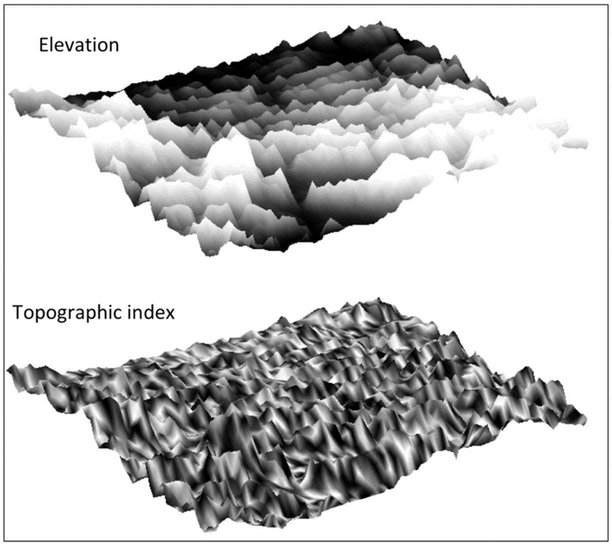

Fig. 7. Vertically exaggerated surface plots of the elevation (top), with topographic index shading superimposed (bottom). Higher values of the TI indicate likely areas of moisture convergence and wetness. In both plots lighter shade = higher values.

5. Discussion

5.1. Changes in erosion and sediment flux

Before the 1800s, erosion rates in the minimally disturbed forest were likely very low. Some evidence exists that native Americans periodically burned some areas for habitat manipulation purposes (Fowler and Konopik, 2007; Hedrick et al., 2007). However, due to rapid vegetation recovery and the fire-adapted nature of the vegetation (Hedrick et al., 2007) this is unlikely to have produced much erosion. It is possible, but unlikely, that some cultivation by native Americans may have occurred. However, no archaeological evidence of settlement on slopes of the WPG area has been found, and the same environmental factors that made it unattractive for post-1800 immigrants to farm would have applied.

For the reasons above, the relative abundance of upland residual, colluvial, and alluvial soils provides a reasonable index of sediment divergence or concentration at the landscape scale. This shows divergence, with colluvial and alluvial soil areas >1.2 times that of the upland source areas. Both colluvium and alluvium may be remobilized and redistributed, but the soil geography indicates the prevailing long-term trends.

The WPG area is particularly well suited to recognition of colluvial soils due to the lithological variations in parent material. Layers including clasts of novaculite, chert, and sandstones that outcrop upslope but are not present in the underlying rock are a reliable indicator of a colluvial source. Such indicators are not always present. In the central Kentucky soil landscape analyzed by Phillips (2018), for example, such lithological contrasts are absent. Though colluvial deposition occurs in that landscape, there is no clear stratigraphic indicator thereof, and no colluvial or cumulic soil types are mapped.

Fig. 6. Cobble and gravel sorting by wheel ravel.

This situation likely changed only slightly after the area became part of the USA. Crop agriculture was minimal, if present at all. Logging likely provided relatively short-lived pulses of erosion and sediment flux, with increases likely after the early twentieth century as mechanized logging and road building became more extensive. Fine grained sediment produced during this period was probably largely transported through the fluvial system if it reached streams, based on contemporary patterns (Phillips and Marion, 2019; Phillips et al., 2020). Geomorphic impacts are likely where logging roads crossed streams, but were most likely highly localized (Marion et al., 2014a).

The situation changed dramatically after establishment of the WPG trail complex in the early 1990s. The ATV trails are used more extensively than other forest roads, and unlike logging roads or skid trails, are not subject to revegetation and recovery after a short period of use (though contemporary trails are now sometimes closed during wet-weather conditions, or seasonally). ATV trails in WPG that have been closed do show significant recovery within a few years (Marion et al., 2019; Phillips et al., 2020), but active trails are eroded to or near the underlying bedrock. The (conservative) erosion rates estimated by Marion et al. (2019) range from those comparable to newly constructed forest roads to about three times those rates (Table 3).

With respect to trailside areas of fine sediment accumulation (FSA), the eroding area is nearly nine times larger than the depositional area. Because trail erosion features are mainly strongly connected to channels (Phillips et al., 2020), channels are the main colluvial storage areas. Compared to the pre-1800 condition, erosion rates have not only increased by orders of magnitude, but are now highly concentrated. The gradual movement of material from ridges and upper slopes to lower slopes, indicating sediment divergence, continues. However, these rates are dwarfed by trail erosion, where colluvial storage indicates strong concentration tendencies, though fine sediments are apparently readily transported and dispersed once in the fluvial system.

5.2. Divergence and concentration

Results support our hypotheses—that under the minimally disturbed pre-1800 erosion regime, sediment flux is divergent. The colluvial soil area is slightly larger than that of upland residual soils (which are not all necessarily erosional sources). The total colluvial plus alluvial area yields an A_e/A_d ratio of 0.81. By contrast, the rapidly eroding but spatially localized trail erosion is associated with concentrated sediment flux. The eroding source area is nearly nine times larger than the trailside FSA accumulations, and 6.6 times the total trailside FSA area plus the FSA in trail-effected stream segments.

Our results may apply more generally to other locations that have undergone a transition from a slow, spatially dispersed erosion regime to one with rapid rates of removal from spatially localized hotspots, but local and regional factors strongly influence geomorphic process in the WPG area. Our hypotheses were based on extensive field observations in the study area. Starting from more general considerations, however, we might well have come up with quite different expectations. That is, one could reason that rapidly eroding, locally concentrated source areas would lead to divergence, as the sediment is deposited in, e.g., fan-type lower slope deposits and spread over floodplains. Similarly, it might be expected that slow soil loss from extensive or widely dispersed sources—at least the colluvial portion—would be concentrated in topographically-controlled depositional hotspots, resulting in concentration.

One reason trail erosion in WPG tends to concentrate sediment has to do with the nature of trail erosion. Though the trails represent just a tiny fraction of the land area, the entire surface of the trails has been eroding. In many cases local runoff flows along the trail until it reaches a natural topographic low point. GIS analysis shows 480 locations where trails intersect the stream network, for example, and many more crossings of unchannelled valleys exist. Flow along trails to these low points may be facilitated by the formation of coarse sediment ridges at trail edges due to wheel ravel (Fig. 6). These dips in the trail surface are where wing ditches are typically constructed, or where concentrated flow features (rills or gullies) form. This phenomenon is recognized in the siting of sediment traps in such settings. Marion et al. (2019) measured trail contributing areas of 24 to 336 m^2 for 30 traps, with a mean of 88. FSAs in these dip locations are generally <10 m^2 in surface area, and less in sediment traps. Coarse sediment may also accumulate in these locations due to dry ravel. In streams, fine sediment deposits are relatively small, and localized in pools or behind woody debris.

The upland denudational regime under natural conditions is characterized by ubiquitous, though relatively slow, removal from ridgetops and upper slopes. Local slope failures such as slumps, landslides, and debris flows occur in other locations in the Ouachita Mountains (Phillips and Marion, 2005; Phillips et al., 2005; Regmi and Walter, 2020). However, rock and soil creep from upper slope and ridge sources is ubiquitous (Phillips and Marion, 2005; Phillips et al., 2005), and this is reflected in the spatial extent of colluvial soils (e.g., Fig. 2). In a setting more dominated by water erosion or localized mass wasting, the situation might well be different. Further, an analysis of sediment volumes or mass, rather than depositional surface area, would almost certainly show a greater degree of concentration in valleys.

The topography of the study area also plays a role. The terrain is strongly fluvially dissected, with high drainage density. Local spatial variation in the topographic wetness index is high. This results in many, widely dispersed sites for both local sediment storage and sediment delivery to channels, which is not typical of all landscapes.

We therefore recommend additional studies of concentration and divergence in landscapes with different dominant denudational processes, and variable topographic and environmental settings. Other regions where lithological or other parent material contrasts make recognition of colluvium or colluvial soils relatively straightforward would be logical starting points. However, this kind of work (identification of colluvial or cumulic soils) can be accomplished in other settings, such as the coastal plain agricultural landscapes studied by Phillips et al. (1999). However, in such settings extensive field work is required, and without extensive resources must be restricted to a local scale.

5.3. Implications

A strong scientific urge exists to quantify, and to measure things simply because one can. Does the sediment convergence/divergence concept and A_e/A_d ratio have any value added beyond the data and information needed to calculate it? As outlined in Section 1.1, we think so.

One of the advantages identified was moving beyond a binary linked-or-not view of sediment connectivity. In the Ouachitas and other mountainous areas, the existence of connectivity of upper and lower slopes is easily determined. However, the relative proportion of source and colluvial deposition areas is not obvious without explicit consideration. The observed divergence on slopes has important implications with respect to the apparent dominance of sheet and ephemeral rills and creep processes in the natural or semi-natural setting, as opposed to concentrated-flow processes such as gully erosion and debris flows.

Another identified advantage of the convergence/divergence perspective is the linkage of erosion, transport, and deposition processes with soil and regolith stratigraphy. Our results, while not making any significant advances in process understanding, demonstrate a method of assessing potential source and deposition areas using soil data, and of the direct use of soil-stratigraphy to identify or infer processes.

A third potential advantage is in targeting of soil erosion and sediment control resources. Assuming that some conservation or protection is necessary or desired, a divergence-dominated system suggests that control might be best focused on the smaller erosional source area. A convergent situation—such as the eroding WPG trail system—indicates targeting of zones of concentrated impacts. In this case, our findings reaffirm the current USFS strategy of focusing on sediment traps and rock aprons at dips in the trail surface as opposed to efforts to control detachment over the entire eroding surface area.

Finally, we identified the issue of contaminated sediments as a possible advantage of the A_e/A_d approach. Again, where this is an issue, results would indicate the likely efficacy of erosion or contaminant control at the source vs. sediment control, mitigation, or cleanup at the concentration sites. *If* metals or toxic chemicals, for instance, had been identified as an issue at WPG (they have not), our results would provide a reasonable starting point for spatially targeting control or mitigation.

6. Conclusions

In erosional landscapes the erosional source area may be larger or smaller than the depositional area, corresponding to either areal concentration or divergence of sediment. In the Wolf Pen Gap area of the Ouachita Mountains, before the early ninteenth century the forest was largely undisturbed, and soil loss was dominated by slow erosion and mass wasting from ridge tops throughout the study area, deposited on mid- and lower slopes as colluvium. Based on the spatial distribution of alluvial, colluvial, and upland potential source area soils, we estimate $A_e/A_d = 0.81$, and <1 even when only colluvial soils are considered, indicating divergence. Because agricultural land uses were minimal or absent, between the early 1800s and 1990s conditions were somewhat similar to the pre-European condition. Logged areas and temporary unpaved roads recovered quickly to pre-disturbance conditions, and use of permanent roads was far lower before the ATV trails. After establishment of ATV trails in the 1990s, the trails became local sources of rapid, persistent erosion, and the regime shifted to sediment convergence, with $A_e/A_d = 6.60$.

This study is but a starting point for examining concentration/divergence, as the results are linked to the strongly dissected, steep topography, humid subtropical climate, limited potential for agriculture, and the nature of the ATV trail erosion. This suggests a need for more case studies to develop more general principles or guidelines to predict sediment concentration and divergence.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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