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Reach-scale geomorphic differences between headwater streams draining mountaintop mined and unmined catchments

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A B S T R A C T

Mountaintop surface mining (MTM) is a controversial coal extraction method commonly practiced in the central and southern Appalachian Mountains, USA, that drastically reengineers previously steep, forested landscapes and alters sediment and water delivery processes to and along headwater channels draining mined areas. Although sediment delivery and hydrologic response from MTM operations remain highly variable and poorly resolved, the inherent close coupling between hillslopes and headwater channels is expected to result in geomorphic differences in stream channels draining MTM landscapes relative to unmined landscapes. Dedicated geomorphic studies are severely lacking in comparison to extensive research on water quality impacts of MTM. This study reports moderate geomorphic differences between headwater (catchment area <~6 km^2) stream channels draining MTM and unmined catchments in tributaries of the Mud River in southern West Virginia. Univariate and multivariate analyses indicate that MTM streams are characterized by deeper maximum channel depths, smaller width-to-depth ratios, increased bedrock exposure along the streambed, and increased frequency of very fine silt and sand deposition relative to channels draining unmined catchments. Geomorphic differences are most pronounced for streams draining the smallest catchment areas (<3.5 km^2). Collectively, geomorphic differences provide evidence for relatively rapid channel adjustment of accelerated bedrock incision attributed to potential increased hydraulic driving forces and altered sediment regimes in MTM channels, notably sustained delivery of very fine sediment and potentially reduced coarse sediment delivery. More rapid delivery and transfer of water in addition to excess delivery of very fine sediments to and through headwater channels will have consequences to flooding and water quality in the short term and landscape evolution processes over longer time scales. Given the extent of MTM operations in this region, additional studies are urgently needed to more rigorously evaluate geomorphic response to mining at the reach and at the network scales.

1. Introduction

Mountaintop surface mining (MTM) is a controversial coal extraction method that represents the largest land conversion activity in the central Appalachian Mountain region in the eastern USA (Townsend et al., 2009). Mountaintop mining activities have been described elsewhere (e.g., Palmer et al., 2010; Miller and Zégre, 2014); however, briefly, the method removes up to ~300 vertical meters of forest, soils, and intact bedrock to expose coal seams in the upper reaches of catchments through the use of explosives and heavy earth-moving machinery, radically reengineering the rugged mountainous terrain to a modified land surface topography composed of contoured mine spoil. In addition, MTM activities include valley fill (VF) construction in which excess overburden mining material is deposited into valleys adjacent to mined areas, which often results in burial of headwater streams located within the valleys (EPA, 2011). The dramatic transformation to compacted, unconsolidated mine spoil, limited soil structure, modified vegetative cover, and buried headwater streams by VFs result in a landscape with highly altered hydrologic and sediment transport processes (Palmer et al., 2010; Wickham et al., 2013) and newly mobilized chemical constituents as a consequence of exposed coal and bedrock material (Griffith et al., 2012). The method began in the 1970s and increased rapidly in the 1990s. Currently, ~6% of the central and southern Appalachian region has experienced MTM activities (EPA, 2011), accounting for the greatest amount of earth movement than any other process in the region (Hooke, 1999).

The consequences of landscape scale disturbances associated with MTM have received increasing research attention. Mountaintop mining has been studied extensively in terms of water quality and aquatic ecosystem impacts (e.g., Merricks et al., 2007; Petty et al., 2010; Lindberg et al., 2011; Merriam et al., 2011; Bernhardt et al., 2012; Griffith et al., 2012; Pond, 2012). Substantial effort has been made to quantify changes to altered hydrologic regimes in MTM sites (reviewed by Miller and Zégre, 2014). In addition, differences in terrestrial landforms between MTM and unmined landscapes have been evaluated (Maxwell and Strager, 2013; Wickham et al., 2013).

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In contrast to this body of research, comparatively few studies have evaluated potential changes to stream channel morphology as a consequence of MTM activities. The MTM activities are limited to the uppermost regions of the catchment, which are characterized by strong coupling between headwater channels and the surrounding terrestrial environment thus rendering headwater streams as particularly sensitive to disturbance (Gomi et al., 2002; Benda et al., 2005; Meyer et al., 2007). Indeed, documented MTM-related impacts to water quality, aquatic biota, and streamflow regimes are largely a manifestation of the close coupling between stream channels and adjacent hillslopes, which results in shorter flow paths and more immediate delivery of terrestrial materials including water and sediment to the stream channel. Therefore, it follows that changes to the hydrologic and sediment regimes in MTM landscapes would have an effect on stream channel morphology that drain these landscapes. However, dedicated geomorphic research remains limited. Wiley (2001) and Touysinhthiphonexay and Gardner (1984) appear to be the only studies that evaluated reach-scale differences in channel morphology between mined and unmined catchments, with contrasting results. A third study conducted by Fox (2009) identified increased channel erosion rates in streams draining mined catchments through the use of isotopic tracers. Several ecological studies have incorporated some geomorphic parameters (e.g., streambed gradient, channel width, channel depth, and streambed grain size characterization) to evaluate aquatic ecosystem health (Fritz et al., 2010; Petty et al., 2010; Merriam et al., 2011) — although most geomorphic parameters were not included in the final statistical models. Other ecological studies have incorporated streambed sediment as part of their metrics associated with water quality (Hartman et al., 2005). Differences in channel morphology have been reported anecdotally in still other studies (Ritter and Gardner, 1993; Bonta, 2000).

The apparent lack of dedicated stream channel morphologic research may be attributed to the inherent challenge of conducting reach-scale, field-based research in these landscapes. Major limiting factors include (i) the substantial variability in catchment comparison study designs highlighted by Wiley (2001) and Wiley and Brogan (2003), (ii) the logistical challenge of long-term studies that track before and after mining effects, (iii) confounding land use impacts such as dispersed suburban and industrial development that limit the power to isolate potential geomorphic differences to MTM activities (Merriam et al., 2011), and (iv) access to MTM sites to carry out research. Despite the challenges, reach-scale field research is a necessary component to understanding impacts of MTM-related, landscape-scale disturbances. Headwater streams are the fundamental backbone of the river network supplying water, sediment, and nutrients downstream (MacDonald and Coe, 2007; Wipfli et al., 2007) and exerting influence on critical properties such as downstream flooding and water quality (Gomi et al., 2002; Alexander et al., 2007). Headwater streams are the primary conveyance mechanism to downstream networks; therefore changes to channels have important implications throughout the riverine network (Meyer et al., 2007).

The particular character of hydrologic response to MTM activities remains poorly resolved, but some consensus exists that a predominant response in small watersheds is augmented water delivery to the stream channel (Miller and Zégre, 2014), although water storage in VFs could diminish discharge to stream channels if the discharge point is a location different from the stream (Wunsch et al., 1996, 1999). Substantial variability exists among studies, which may be a consequence of variation in mining and reclamation methods, the legacy of subsurface mining, and local landscape conditions such as geology, topography, and climate (Miller and Zégre, 2014). However, in MTM landscapes with VF, research indicates that this augmented water delivery to headwater channels can manifest either as increased base flow (Messinger and Paybins, 2003; Zégre et al., 2014), increased peak flows (Messinger, 2003), or threshold response peak flows (Wiley and Brogan, 2003). Threshold response peak flows can be described as reduced peak flows that may be modulated by VFs until a critical threshold is reached beyond which point peak flow magnitudes are greater for a precipitation event of the same magnitude in an unmined catchment (Miller and Zégre, 2014).

This study compares reach-scale channel morphology of small headwater streams (<~6 km^2) draining MTM and unmined catchments in West Virginia, USA. Hypothesized geomorphic differences between streams draining MTM and unmined catchments are based on the working premise that MTM activities augment water delivery to the stream channel, which is expected to increase overall hydraulic driving forces within the channel. In confined valleys such as the case in the MTM region of West Virginia, channel adjustment to increased driving forces can take the form of increased bank erosion, streambed incision, and streambed coarsening or steepening (Wohl, 2013; Knighton, 2014), which are documented responses to other land uses that have augmented water delivery, notably increased high flows from urbanization (Bledsoe and Watson, 2001; Paul and Meyer, 2001; Walsh et al., 2005). Therefore, streams draining MTM catchments are hypothesized to have larger, simplified channel dimensions relative to streams draining forested, unmined catchments (H_1). Streambed gradient is expected to be steeper and streambed material is expected to be either coarser or characterized by more exposed bedrock in streams in MTM catchments relative to streams in unmined catchments (H_2). Increased fine-grained sediment delivery to stream channels has been reported to occur in years immediately following conventional surface mining activity but declines with increased time since mining activity (Bonta, 2000; Fox, 2009). Therefore, fines are not expected in study sites in which mining and reclamation activities have been completed for at least four years.

1.1. Regional setting

This study was located within the upper Mud River catchment in southern West Virginia in the central Appalachian Mountains, USA (Fig. 1). The region is underlain by the Logan Plateau, which is composed of Paleozoic Pennsylvanian sedimentary rock sequences of sandstone, siltstone, and shale (Outerbridge, 1987). All study sites are locally underlain by sandstone; shale is located along ridge lines. The topography is rugged and highly dissected and characterized by narrow ridges and valleys, steep slopes of ~50%, and relief that ranges from 150 to 750 m (Outerbridge, 1987). Landslides and debris flows are common in this region (Wieczorek et al., 2009), and evidence of recent hillslope failures existed in some of the unmined sites (personal observation).

Six MTM and five unmined study reaches ($n = 11$) were selected along headwater tributaries draining into the upper Mud River (Table 1; Fig. 1). Surface mining activities have been active since at least the 1970s, but most MTM activities and valley fill construction at study sites occurred starting around 1990. Percent area surface mined ranged from 2.1 to 25.6% in MTM study sites (Table 1), and all MTM sites have been subject to subsurface mining. Study reaches are located high in the catchment to minimize confounding land use impacts. Drainage areas range from 0.9 to 6.2 km^2. Land cover is predominantly forest with the exception of 5_U (LeftFork$_U$), which is also characterized by low density residential land use. Effort was made to exclude direct impacts from adjacent roads. However, site 5_U (LeftFork$_U$) receives roadside runoff via two to three small culverts within the study reach, and site 6_M (BallardFork2$_M$) has unpaved recreational vehicle tracks crossing the channel upstream of the study site. All stream study sites were located in generally confined, steep valleys with the exception of site 6_M. Reclamation activities have been completed, including revegetation to grasses on the mined and VF areas at all sites.

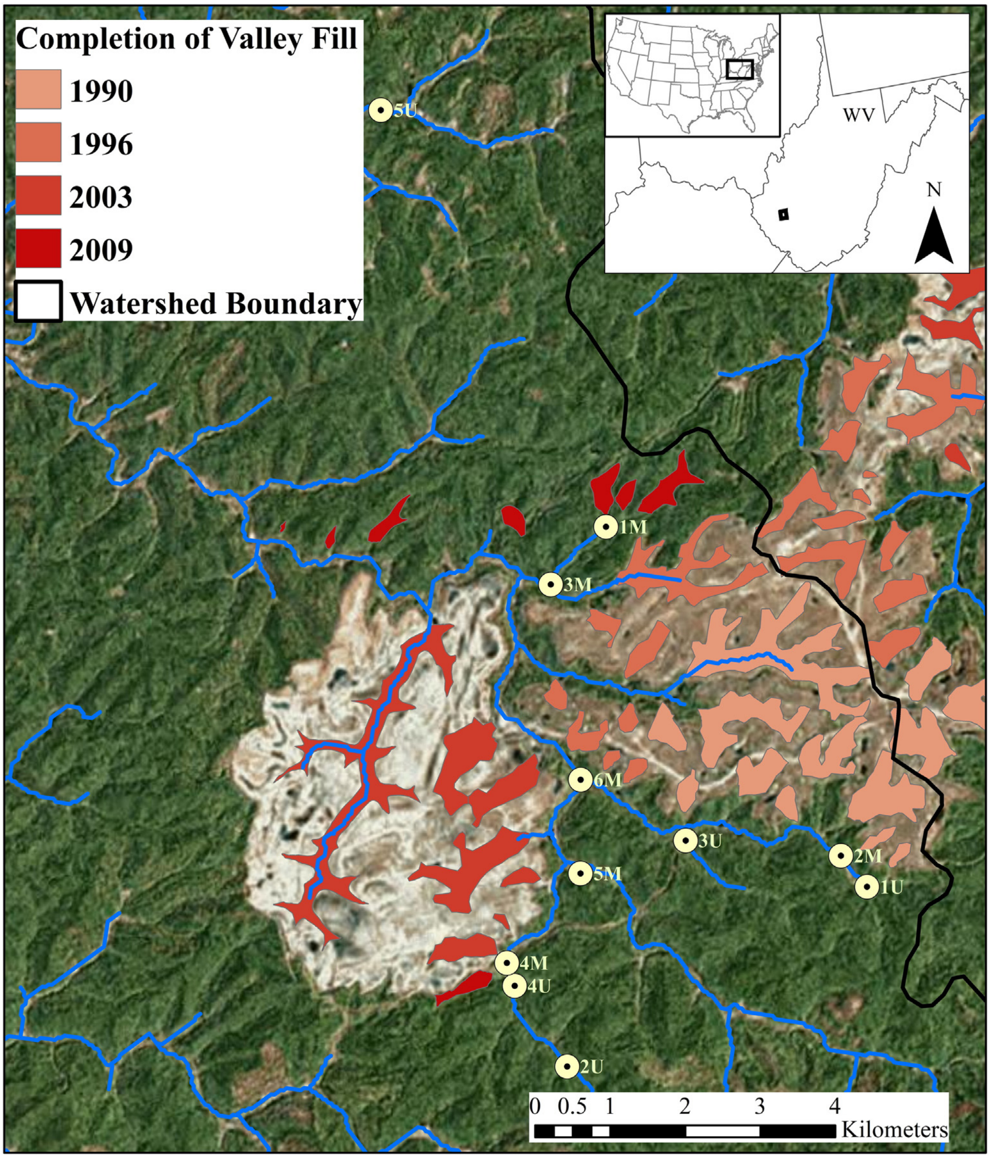

Fig. 1. Location map of MTM (M) and unmined (U) study sites. Site numbers correspond to site names in Table 1. Blue lines are a stream layer represented by high flow accumulation cells from the 10-m DEM. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Description of mountaintop mined (MTM) and unmined study sites[a].

			Catchment scale			Reach scale							
Land use	Site number	Site	DA (km^2)	% Mined	Completion of valley fill	A (m^2)	w (m)	h_{Max} (m)	*W/D* (m/m)	S (m/m)	σ_{Bed} (m)	D_{10} (mm)	BR_{Prop}
MTM	1_M	$SugarTree1_M$	1.1	25.6	2009	6.9 (1.5)	7.6 (1.0)	1.4 (0.3)	8.8 (3.2)	0.020	0.71	1.6	0.15
	2_M	$BallardFork1_M$	1.2	5.4	1990	1.4 (0.6)	3.7 (1.0)	0.6 (0.1)	10.5 (3.7)	0.018	0.65	1.7	0.37
	3_M	$SugarTree2_M$	1.5	18.1	2009	4.9 (3.4)	7.2 (4.9)	1.2 (0.2)	10.4 (7.2)	0.022	0.79	7.0	0.16
	4_M	$LukeyFork1_M$	3.5	2.1	2009	1.2 (0.5)	3.7 (0.3)	1.5 (1.8)	12.4 (3.2)	0.010	0.39	1.8	0.27
	5_M	$LukeyFork2_M$	5.1	5.6	2003	3.3 (1.8)	7.2 (2.1)	0.9 (0.2)	17.9 (10.2)	0.010	0.41	1.7	0.01
	6_M	$BallardFork2_M$	6.2	14.5	1990	3.9 (1.3)	6.4 (2.0)	0.9 (0.1)	10.5 (3.7)	0.007	0.42	1.6	0.00
MTM overall			3.1	11.9		3.7 (2.6)	6.1 (2.7)	1.1 (0.6)	11.7 (6.1)	0.014 (0.006)	0.56 (0.18)	2.6 (2.2)	0.20 (0.14)
Unmined	1_U	$BallardFork1_U$	0.9	0.0		4.4 (4.7)	7.9 (4.7)	0.7 (0.4)	19.7 (5.3)	0.039	1.38	1.8	0.00
	2_U	$LukeyFork1_U$	1.2	0.0		1.2 (0.5)	4 (1.3)	0.4 (0.1)	13.4 (3.9)	0.018	0.43	1.8	0.00
	3_U	$BallardForkTrib2_U$	1.4	0.0		3.5 (1.3)	7.5 (2.6)	0.8 (0.3)	24.5 (28.7)	0.016	0.49	1.7	0.02
	4_U	$LukeyFork2_U$	2.7	0.0		2.6 (0.8)	6.5 (1.3)	0.8 (0.3)	17.0 (4.9)	0.012	0.40	3.6	0.00
	5_U	$LeftFork_U$	5.3	0.0		2.8 (0.9)	4.9 (0.5)	0.8 (0.2)	9.5 (3.1)	0.007	0.30	4.6	0.05
Unmined overall			2.3	0.0		2.9 (2.0)	5.9 (2.5)	0.7 (0.3)	15.2 (11.9)	0.018 (0.013)	0.60 (0.44)	2.7 (1.4)	0.00 (0.00)

[a] DA, drainage area, % mined, percent of catchment mined, completion of valley fill, approximate year of completed valley fill construction within the catchment, A, channel cross-sectional area, w, width, h_{max}, maximum depth, *W/D*, width-to-depth ratio, S, streambed gradient, σ_{Bed}, standard deviation of the channel thalweg elevation, D_{10}, diameter of 10th percentile grain size, and proportion BR, proportion of streambed that is bedrock. Values are means (standard deviation) unless specified. Overall mean and standard deviation values are calculated across all MTM and unmined sites, respectively.

2. Materials and methods

2.1. Reach surveys

Geomorphic field data were collected for all study reaches in summer 2012 during low flow conditions. Each stream reach was ~100 m long, generally representing 13–27 times bankfull channel width. A longitudinal profile of the channel thalweg and four cross sections along each reach were surveyed using either a laser level and stadia rod or a laser theodolite and prism rod. Four additional bankfull channel widths were measured with a field tape to capture reach-scale variability in channel width. Streambed substrate was characterized by measuring the intermediate axis of 400 randomly selected clasts along each reach (Wolman, 1954; Kondolf, 1997). The sample size included all geomorphic units within the entire bankfull channel to avoid bias and allow for comparison with other studies (Bunte et al., 2009). The D_{10}, D_{50}, and D_{90} (representing grain size diameter of the 10th, 50th, and 90th percentile of substrate) were computed from the 400 clast count using Gradistat software (Blott and Pye, 2001). Exposed bedrock that did not include a veneer of sediment grains was included in the clast count. Proportion of clast count that was bedrock (BR) was computed by dividing the bedrock counts by the total clast count and served as a proxy for proportion of the channel with exposed bedrock. Drainage area was derived using GIS and a 10 m or finer digital elevation model (DEM) for all sites. Mining extent within these catchments was mapped using data from Bernhardt et al. (2012).

Width-to-depth ratio (W/D; which describes reach-scale channel geometry) and standard deviation of channel thalweg elevation (σ_{Bed}; a measure of streambed variability as a proxy for complexity) were calculated from cross sections and the longitudinal profile. Variables that estimate reach-scale hydraulic conditions include streambed slope (S) and shear stress (τ). Streambed slope was calculated from the longitudinal profile. Shear stress was calculated using

$$\tau = \gamma RS$$

where γ is the specific weight of water (9.81 N/m^3), and R is hydraulic radius, which is cross-sectional area/wetted perimeter at bankfull.

2.2. Data analysis

Field-measured and -derived metrics included channel bankfull cross-sectional area (A), width (w), maximum depth (h_{max}), width-to-depth ratio (W/D), standard deviation of bed elevation (σ_{Bed}), streambed gradient (S), shear stress (τ), proportion of bedrock (BR), D_{10}, D_{50}, and D_{90}. The field-measured and -derived metrics were selected a priori as potentially useful for identifying differences between MTM and unmined stream reach groups based on the specific hypotheses. When possible, variables were transformed (ln(x) or square root(x)) to meet assumptions of normality. Student t-test and Mann–Whitney U test, two types of sample comparisons, were conducted to identify statistical differences between the two groups. Longitudinal trends were also assessed by plotting variables against drainage area.

Following univariate statistical comparisons, a subset of five variables (h_{max}, W/D, σ_{Bed}, BR, and D_{10}) was included in nonmetric multidimensional scaling (NMDS) to identify potential geomorphic differences between MTM and unmined streams. The multivariate analysis is common in ecological studies, including studies that identify differences in biological communities based on geomorphic variables (e.g., Walters et al., 2003; Saintilan, 2004; Virtanen et al., 2010) and is increasingly included in dedicated geomorphic studies (e.g., Merriam et al., 2011; Sutfin et al., 2014; Varanka et al., 2014). Variables were excluded from NMDS if the MTM and unmined groups plotted very similarly in the boxplots or if variables followed similar longitudinal trends when plotted against drainage area. The variable σ_{Bed} was included as the sole metric to describe streambed complexity. The relatively small number of study sites ($n = 11$) limits the ability to carry out multivariate hypotheses testing. However, as an exploratory ordination method, NMDS is useful for visually describing the structure of communities, in this case MTM or unmined streams, and distinguishing communities from each other based on environmental variables, in this case channel geomorphic metrics. The NMDS analysis was chosen because it has no assumptions of data normality or linearity. All statistical analyses were performed in R (version 3.1.1; R Team, 2012); NMDS was performed using the *vegan* package (Oksanen, 2011). Specifically, the *metaMDS* function was used with the Bray–Curtis dissimilarity measure. Dimensions were limited to two because of the small number of geomorphic variables. Minimum stress, a measure of goodness-of-fit, for two dimensions was computed from 20 random starting configurations. Vectors, which are the geomorphic variables, were fitted onto the ordination using the *envfit* function and are indicated as arrows; individual vector significance was evaluated with 999 permutations. The length of the arrow represents the correlation between the geomorphic variable and the linear ordination. Correlations among geomorphic variables were completed using Spearman's coefficient, and all included variables were below a threshold correlation coefficient (r_s-value) of $\pm$ 0.8.

3. Results

Univariate statistical differences in geomorphic metrics that represent channel dimension and complexity were limited between streams draining MTM and unmined catchments (Fig. 2). Notably, no statistical differences existed in channel dimensions (A, w, W/D) or streambed variability (σ_{Bed}) with the exception of significantly ($p < 0.1$) larger maximum channel depths in MTM streams relative to unmined streams. The MTM stream sites had significantly higher proportions of exposed bedrock along the streambed and were characterized by smaller-sized fines (e.g., smaller D_{10}) (Figs. 2 and 3). In addition, excluding 6_M, MTM sites had a narrower range of smaller diameter fine streambed sediments relative to unmined streams (0.2 vs 2.9 mm, Table 1).

Comparisons between individual sites with similar drainage area identified distinct differences in grain size distribution and streambed substrate composition. With the exception of the largest catchments (e.g., >5.1 km^2), all MTM streams had a markedly higher proportion of bedrock (0.15–0.37) relative to unmined catchments (0–0.05) (Fig. 4). Further, with the exception of one paired comparison, a greater proportion of the grain sizes of MTM sites was characterized by finer, smaller diameter grains (up to ~10 mm diameter) relative to grain size distributions in streams at unmined sites (Fig. 4).

Longitudinal trends were apparent in the hydraulic channel condition variables slope and shear stress. Slope and shear stress decreased with increasing drainage area similarly for MTM and for unmined groups (Fig. 5). Maximum channel depth demonstrated no significant relationship with drainage area for MTM or unmined groups. Apparent trends in W/D ratio for MTM and unmined groups were driven by single individual sites and, therefore, were disregarded. No relationship was found between proportion of bedrock and drainage area in unmined streams. In MTM streams, proportion of bedrock decreased with drainage area.

The NMDS ordination with fitted geomorphological vectors identified some obvious dissimilarity between MTM and unmined stream reaches that were particularly apparent for those streams draining the smallest catchments (Fig. 6). The two-dimensional ordination minimized stress to 0.08 for the 11 reaches. Stress values of <0.1 are considered to be a good ordination with no real risk of drawing false inferences (McCune and Grace, 2002). Three of the five variables (W/D, BR, and D_{10}) were statistically significant (Table 2). Although a Mann–Whitney test indicated that maximum channel depth was significantly different between MTM and unmined streams (Fig. 2), this variable was not significant when considered in the multivariate analysis. Separation between MTM and unmined stream reaches was dominated by

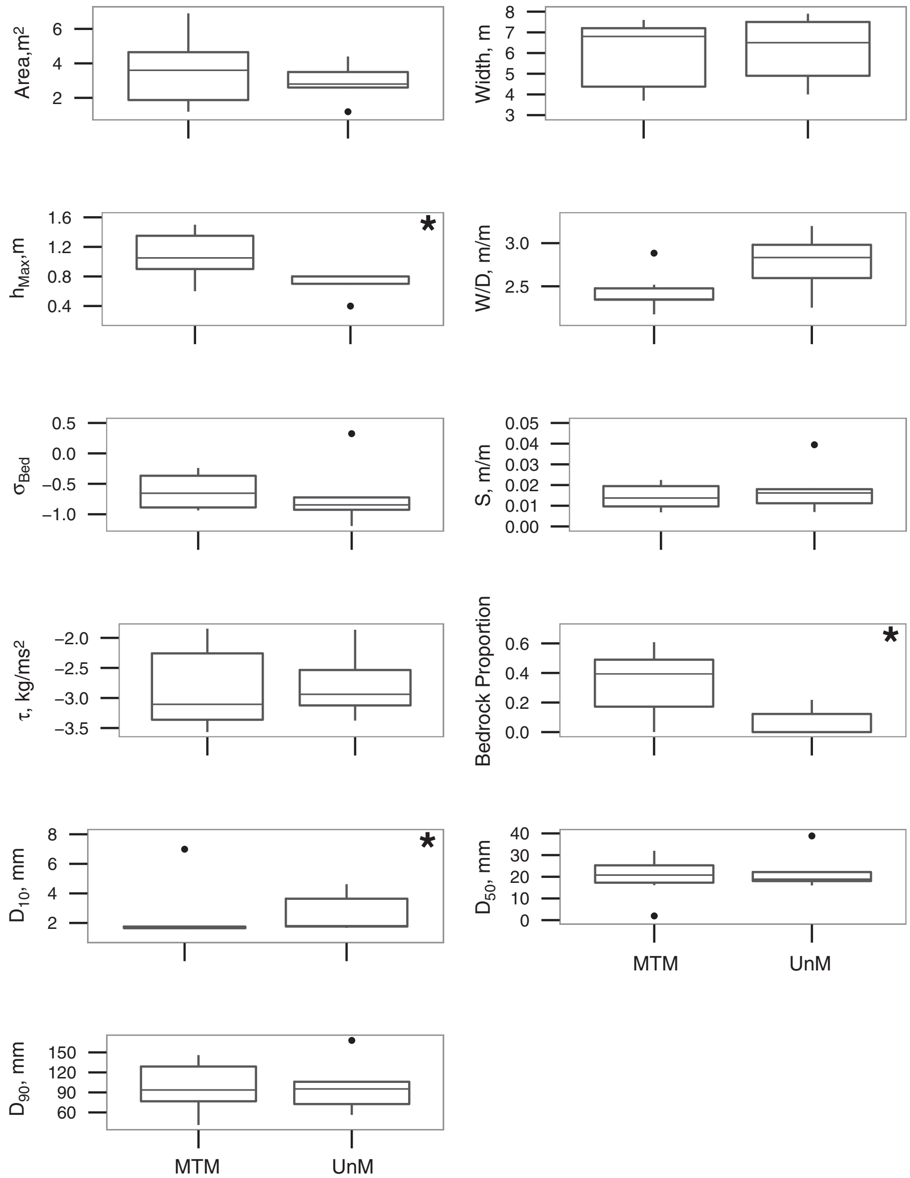

Fig. 2. Boxplots of 11 geomorphic variables (A, w, h_{max}, W/D, σ_{Bed}, S, τ, BR, D_{10}, $D_{50,}$ and D_{90}) for the six MTM and five unmined (UnM) stream sites. W/D, σ_{Bed}, and τ were natural log transformed; BR was square root transformed. Box center lines indicate the median, box ends are the 25th and 75th percentiles; lines extend to the 5th and 95th percentiles. * Indicates significant ($p < 0.10$) difference between MTM and unmined stream sites based on either two-sample t-test or Mann–Whitney test.

proportion of bedrock and W/D along the primary horizontal axis, NMDS1. Separation between the two stream groups was less distinct along the vertical axis, NMDS2, but was characterized by the D_{10} grain size. In general, the MTM sites were characterized by smaller W/D and more exposed bedrock relative to unmined sites. Geomorphic differences were most distinct in the smallest channels with drainage area of <3.5 km^2.

4. Discussion

A combination of two sample tests and NMDS indicates moderate geomorphic differences between MTM and unmined streams. Notably, MTM streams were characterized by greater maximum depths, smaller W/D, more exposed bedrock, and increased frequency of fine sediment. The particular character of geomorphic differences was somewhat unexpected and did not necessarily align with the hypotheses that MTM streams would have larger, simplified morphology (H_1) with steeper slopes and coarser substrate (H_2). However, results provide evidence for relatively rapid channel adjustment to geomorphic conditions that suggest increased hydraulic driving forces and changes in the character of sediment delivery to the stream channel that is attributed to increased fine sediment supply and decreased coarse sediment supply. Dedicated studies are needed to validate assertions of altered hydrologic and sediment regimes.

Deeper maximum channel depths, smaller W/D, and increased exposure of bedrock suggest that the MTM streams have rapidly adjusted channel dimensions by incising into bedrock rather than widening through lateral bank erosion or steepening. While increased bank erosion has been identified in MTM streams (Fox, 2009), personal field observations identified that most of the upper Mud River MTM streams contained engineered structures to provide bank stabilization and streambed grade control, including large boulders installed along banks below bankfull and wood or boulder steps along the streambed (Fig. 7). The presence of these engineering structures may constrain lateral erosion and bed incision that would be detectable at the reach scale, which may account for the lack of statistical difference in mean channel width, depth, and streambed gradient between the two stream groups in the univariate analysis. The engineered structures were not sufficient

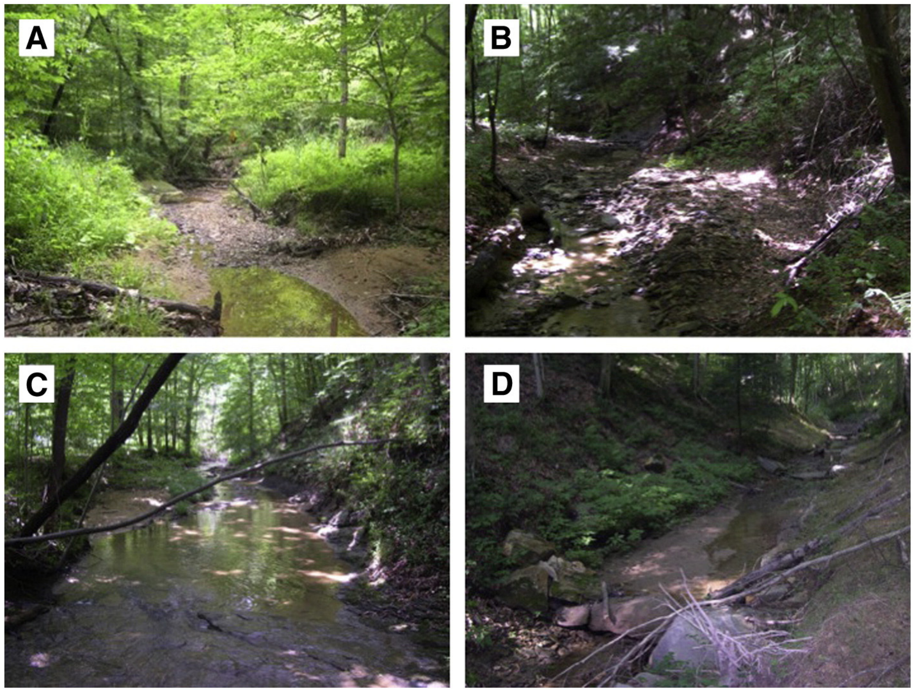

Fig. 3. Unmined and mountaintop mined (MTM) stream reaches. Unmined reaches 2_U and 1_U are characterized by coarser and more abundant sediment (A and B). MTM streams 2_M and 1_M have increased bedrock exposure and increased frequency of very fine sediments (C and D).

though to eliminate local scour that resulted in greater maximum depths or reach-scale incision that resulted in more exposed bedrock and smaller *W*/*D* in MTM streams.

The distribution of D_{10} within MTM and unmined sites (Fig. 2) and the grain size distributions across sites (Fig. 4) indicate a marked increased frequency of very fine substrate in the MTM sites relative to unmined sites. Terrestrial surface erosion is expected to diminish from elevated levels following completion of reclamation activities of surface mined sites (Bonta, 2000; Fox, 2009). Another study in southern West Virginia that compared residentially developed catchments with active and completed MTM catchments identified greater percentages of finer-grained sediments (clay, silt, sand, and gravel) and smaller percentages of coarser sediments (cobble, boulder) and of bedrock in the MTM streams; however, timing and completion of MTM activities were not reported, and therefore drawing inference on the relationship between sediment delivery rates and timing of mining activities is difficult (Merriam et al., 2011). In the Mud River study sites, VF construction and reclamation activities were completed by 2009 at all MTM study sites, and detention pond structures were located at the base of each VF in these sites. Although the overall mean D_{10} was similar between MTM and unmined sites (Table 1), the increased frequency of fines in five of the six MTM sites (Fig. 4) suggests that at least fine substrates are being delivered from upstream sources (including the sediment ponds) in volumes that facilitate deposition within these reaches as veneers over bedrock or behind grade control structures (Fig. 3). In contrast, fine sand and silt veneers were markedly absent in all unmined streams. The dramatic increased frequency of fine-grained substrate in the MTM site draining the largest catchment area (6_M), which included distinct sand bars and deposition that draped the streambed at depths of 20–30 cm, may also be attributed to additional land use activities,

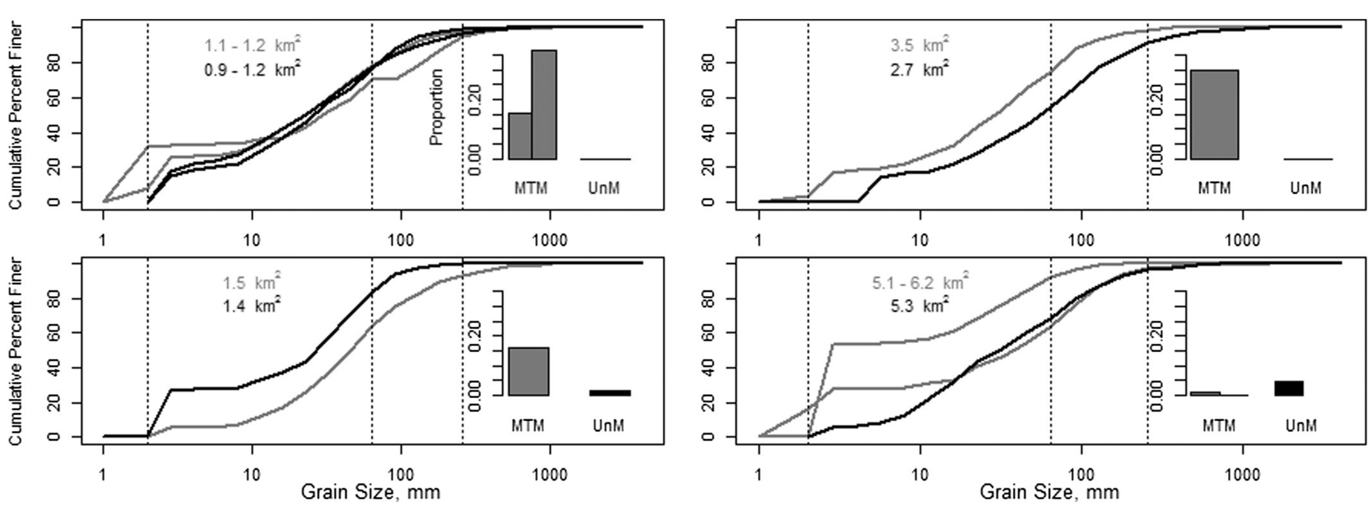

Fig. 4. Grain size distribution and proportion of bedrock for MTM (gray) and unmined (black) study sites grouped by drainage area. Drainage area values for individual study sites are identified by inset text within each plot. Dashed vertical lines demarcate breaks from left to right between sand (<2 mm), gravel (2–64 mm), cobble (64–28 mm), and boulder (>128 mm) substrate classes.

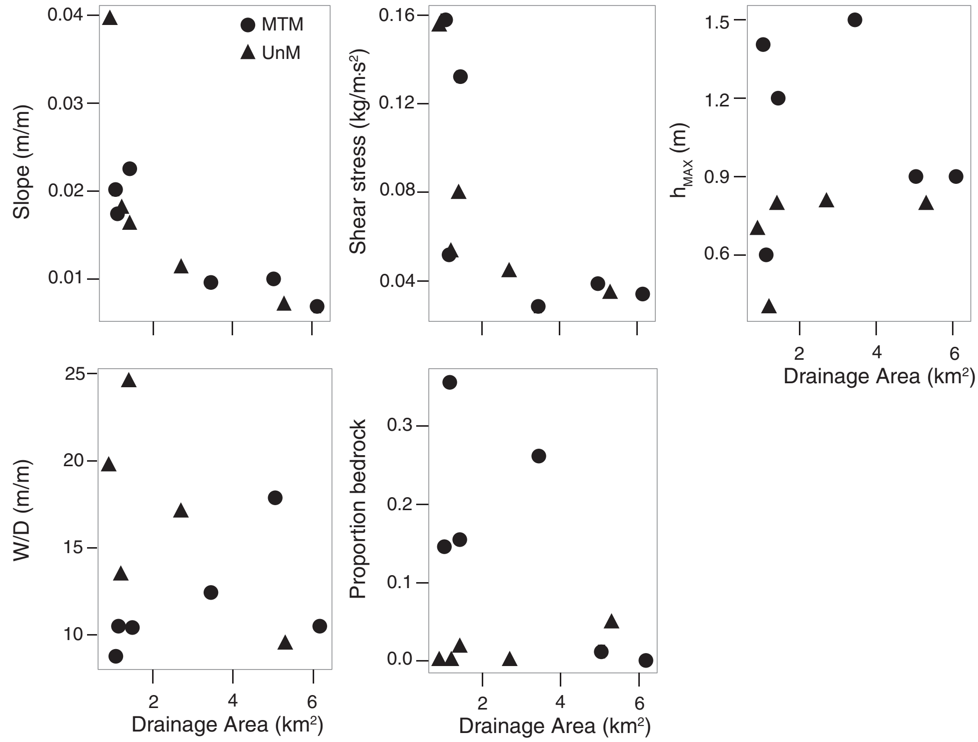

Fig. 5. Scatter plots of S, τ, h_{Max}, W/D, and BR versus drainage area.

notably all-terrain recreational vehicle tracks and dirt roads, occurring along and upstream of this reach.

The increased frequency of very fine sediment in MTM relative to unmined streams suggests a potential mechanism for increased bedrock incision. Recent laboratory experiments identified suspended sediment as a major driver in bedrock incision rates in steep mountain channels, particularly during flood events (Scheingross et al., 2014). During high flows, increased sediment supply provides ample interaction between the suspended particle and streambed to support erosion rates that are similar to or exceed erosion rates under a purely bedload regime (Scheingross et al., 2014). The diminished capacity of very fine particles to cause fluvial abrasion relative to suspended coarser grains is counteracted by the increased sediment supply.

The MTM streams potentially may be receiving less coarse sediment delivery or hydraulics may be sufficient to remove the coarse sediment supply, both of which would further contribute to accelerated bedrock incision rates. The region is mapped as a high landslide and debris flow incidence zone (Wieczorek et al., 2009), and headwater channels in this area experience chronic input of colluvium from adjacent hillslopes that serves as unconsolidated streambed material over a near surface bedrock layer. Recent scars of small-scale hillslope failure, direct deposition of colluvium at the base of failure scars and increased frequency of sediment bars as transient sediment storage features were evident in the smallest unmined stream sites but absent in the comparable MTM sites (Fig. 3). In MTM streams, input of hillslope material may be decreased as a consequence of MTM-associated earthmoving activity that compacts terrestrial surfaces and reduces slopes (Maxwell and Strager, 2013), which could limit hillslope failure rates. Therefore, increased hydraulic driving forces, either through larger streamflow magnitudes or sustained/augmented base flow, may be sufficient to mobilize and remove coarse sediment in MTM streams, which may not be resupplied by hillslope colluvial input thus resulting in bedrock exposure. Quantitative studies on sediment input to streams are necessary to support these field observations. Fox (2009) identified continued surface erosion on mined areas through rilling despite revegetation. In addition, relatively high frequencies of slope failures of backfilled mine spoil have been documented on older mines (pre-

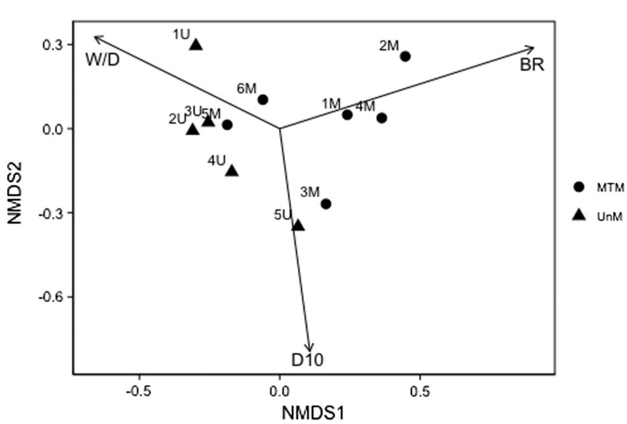

Fig. 6. Nonmetric dimensional scaling (NMDS) for the first two axes of geomorphic variables. Only variables significant at $p < 0.1$ are shown. Site names are labeled for each point. NMDS1 is dominated by W/D and BR. NMDS2 is dominated by D_{10}.

Table 2
Pearson correlation coefficients for NMDS ordinations among geomorphic variables and squared correlation coefficient (R^2) as the goodness-of-fit statistic between geomorphic variables and ordination scores; significance of correlation evaluated with 999 permutation tests[a].

	NMDS1	NMDS2	R^2
BR	0.95	0.30	0.90***
D_{10}	0.13	−0.99	0.64**
W/D	−0.90	0.44	0.54*
h_{Max}	0.91	−0.41	0.34
σ_{Bed}	−0.15	0.99	0.26

[a] Statistical significance codes: ***$p < 0.001$, **$p < 0.05$, *$p < 0.1$.

Fig. 7. Engineered structures in mountaintop mined (MTM) streams including boulders for bank stabilization (A) and log steps for streambed grade control (B).

1990s) (Bell et al., 1989) as well as larger scale valley fill instabilities (Michael et al., 2010).

Geomorphic differences are more distinct in the smaller channels with drainage area of <3.5 km^2 and differences become less distinct with increasing drainage area (Fig. 6). This finding generally agrees with Touysinhthiphonexay and Gardner (1984) – who reported that abrupt changes in channel morphology and substrate material are evident in first-order streams when a critical threshold of mined area has been exceeded – but that geomorphic change is dampened with increasing drainage area. In their study that compared streams draining catchments with conventional strip mining and streams in unmined catchments in central Pennsylvania, Touysinhthiphonexay and Gardner (1984) identified a critical threshold of 0.45 km^2 or 50% of the catchment mined at which point channel cross-sectional area and size of transported substrate blocks increased, although slight increases in channel dimension and block size were detected at catchments with 10% of its area mined. They attributed the changes to increased hydraulic driving forces during infrequent high magnitude events, which were amplified in the mined sites. In the Mud River study sites, mining intensity ranged from 2.1 to 25.6% and mined area ranged from 0.7 to 0.89 km^2, although only the site with the largest drainage area (6_M, 6.2 km^2) exceeded 0.45 km^2 of mined area. Therefore an absence of greater geomorphic differences between MTM and unmined sites may be attributed to the low intensity of mining at these sites relative to those in central Pennsylvania. Alternatively, discrepancies in morphologic differences between the studies could be a result of differences in surface mining activities, which leads to differences in the character of altered sediment and hydrologic regimes.

Notably, VF ages of 2_M and 6_M are older (1990) relative to the other four MTM sites (2003–2009) (Table 1) and therefore differences may exist in VF construction among the different sites that could influence both hydrologic and sediment regimes to downstream channels. Information on specific VF construction methods could not be obtained for the sites in this study. However, neither site (drainage areas 1.2 and 6.2 km^2, respectively) appears geomorphically distinct from the other MTM sites of comparable drainage area (Figs. 4 and 6). In addition, excess fine sediment in the 6_M site is more likely a result of the immediate geomorphic and land use conditions within the valley. Therefore at least in the relative short term, geomorphic influences of potential differences among VF construction are not apparent.

Observed morphologic differences in the smaller headwater MTM channels have differential consequences to headwater channels and to the downstream network over short and longer time scales. In the short term (10^1 years), potential heightened hydraulic driving forces attributed by increased bedrock incision suggest more rapid delivery of water to the downstream network. Increased water delivery may be through increased peak flows (Messinger, 2003; Wiley and Brogan, 2003; Phillips, 2004) or through increased duration and magnitude of mean or base flows (Messinger and Paybins, 2003; Zégre et al., 2014), though further study is necessary at these sites to determine the particular nature of the altered hydrology. Regardless of the character of augmented water delivery, given the high frequency of headwater streams in any river network (60–80% of most channel networks; Benda et al., 2005), the cumulative effect of altered hydrologic regimes in this portion of the network has important consequences for river processes that affect aquatic ecosystems and water resources at reach and network scales (Gomi et al., 2002; Alexander et al., 2007). Over longer time scales (e.g., 10^{3-4} years), accelerated bedrock incision in headwater channels could have consequences on denudation rates and the evolution of mountainous landscapes subject to MTM that could affect the geologic lifespan of topography in mined areas (Egholm et al., 2013). Finally, increased turbidity and sedimentation by fines poses a major threat to water quality issues and ecosystem health in river systems (Henley et al., 2000; Bilotta and Brazier, 2008; Kemp et al., 2011). Sustained delivery of excess fine sediments for at least four years following reclamation activities identified in these study sites further contributes to this ongoing water quality problem.

5. Conclusions

Mountaintop mining activities in the central and southern Appalachian Mountain region, USA have resulted in a severe reengineering of the topographical landscape, changing sediment and hydrological processes in headwater catchments. Altered processes are expected to influence channel morphology of the headwater streams draining mined areas; however, dedicated geomorphic studies are limited and results have been variable, potentially in part from geomorphic variability among the few existing studies and inconsistencies in the character, extent, and timing of mining activities among studies. In this study, comparisons between headwater stream channels draining unmined catchments and catchments with completed MTM activities within at least four years indicate moderate differences in reach-scale geomorphic characteristics. Channels draining MTM catchments had deeper maximum depths, smaller *W/D* ratios, increased proportion of exposed bedrock, and increased frequency of very fine sediment. Results suggest relatively rapid adjustment to augmented water delivery, increased fine sediment delivery, and potentially decreased coarse sediment delivery through accelerated bedrock incision. Given the extent of MTM operations in this region, an understanding of sediment, hydrologic, and geomorphic response to this land use becomes increasingly necessary, particularly because of the high frequency of headwater streams draining MTM areas and the potential consequences to flooding and water quality in the short term and landscape evolution over longer time scales.

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References

Alexander, R.B., Boyer, E.W., Smith, R.A., Schwarz, G.E., Moore, R.B., 2007. The role of headwater streams in downstream water quality. J. Am. Water Resour. Assoc. 43, 41–59.
Bell, J.C., Daniels, W.L., Zipper, C.E., 1989. The practice of "approximate original contour" in the Central Appalachians. I. Slope stability and erosion potential. Landsc. Urban Plan. 18, 127–138.
Benda, L., Hassan, M.A., Church, M., May, C.L., 2005. Geomorphology of steepland headwaters: the transition from hillslopes to channels. J. Am. Water Resour. Assoc. 41, 835–851.
Bernhardt, E.S., Lutz, B.D., King, R.S., Fay, J.P., Carter, C.E., Helton, A.M., Campagna, D., Amos, J., 2012. How many mountains can we mine? Assessing the regional degradation of Central Appalachian rivers by surface coal mining. Environ. Sci. Technol. 46, 8115–8122.
Bilotta, G., Brazier, R., 2008. Understanding the influence of suspended solids on water quality and aquatic biota. Water Res. 42, 2849–2861.
Bledsoe, B.P., Watson, C.C., 2001. Effects of urbanization on channel instability. J. Am. Water Resour. Assoc. 47, 255–270.
Blott, S.J., Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf. Process. Landf. 26, 1237–1248.
Bonta, J.V., 2000. Impact of coal surface mining and reclamation on suspended sediment in three Ohio watersheds. J. Am. Water Resour. Assoc. 36, 869–887.
Bunte, K., Abt, S.R., Potyondy, J.P., Swingle, K.W., 2009. Comparison of three pebble count protocols (EMAP, PIBO, and SFT) in two mountain gravel bed streams. J. Am. Water Resour. Assoc. 45, 1209–1227.
Egholm, D.L., Knudsen, M.F., Sandiford, M., 2013. Lifespan of mountain ranges scaled by feedbacks between landsliding and erosion by rivers. Nature 498 (7455), 475–478.
EPA, 2011. The Effects of Mountaintop Mines and Valley Fills on Aquatic Ecosystems of the Central Appalachian Coalfields. Office of Research and Development, National Center for Environmental Assessment, Washington, DC (EPA/600/R-09/138 F).
Fox, J.F., 2009. Identification of sediment sources in forested watersheds with surface coal mining disturbance using carbon and nitrogen isotopes. J. Am. Water Resour. Assoc. 45, 1273–1289.
Fritz, K.M., Fulton, S., Johnson, B.R., Barton, C.D., Jack, J.D., Word, D.A., Burke, R.A., 2010. Structural and functional characteristics of natural and constructed channels draining a reclaimed mountaintop removal and valley fill coal mine. J. N. Am. Benthol. Soc. 29.
Gomi, T., Sidle, R.C., Richardson, J.S., 2002. Understanding processes and downstream linkages of headwater systems: headwaters differ from downstream reaches by their close coupling to hillslope processes, more temporal and spatial variation, and their need for different means of protection from land use. Bioscience 52, 905–916.
Griffith, M.B., Norton, S.B., Alexander, L.C., Pollard, A.I., LeDuc, S.D., 2012. The effects of mountaintop mines and valley fills on the physicochemical quality of stream ecosystems in the central Appalachians: a review. Sci. Total Environ. 417, 1–12.
Hartman, K.J., Kaller, M.D., Howell, J.W., Sweka, J.A., 2005. How much do valley fills influence headwater streams? Hydrobiologia 532, 91–102.
Henley, W., Patterson, M., Neves, R., Lemly, A.D., 2000. Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. Rev. Fish. Sci. 8, 125–139.
Hooke, R., 1999. Spatial distribution of human geomorphic activity in the United States: comparison with rivers. Earth Surf. Process. Landf. 24, 687–692.
Kemp, P., Sear, D., Collins, A., Naden, P., Jones, I., 2011. The impacts of fine sediment on riverine fish. Hydrol. Process. 25, 1800–1821.
Knighton, D., 2014. Fluvial Forms and Processes: A New Perspective. Routledge.
Kondolf, G.M., 1997. Application of the pebble count: notes on purpose, method, and variants. J. Am. Water Resour. Assoc. 33, 79–87.
Lindberg, T.T., Bernhardt, E.S., Bier, R., Helton, A.M., Merola, R.B., Vengosh, A., Di Giulio, R.T., 2011. Cumulative impacts of mountaintop mining on an Appalachian watershed. Proc. Natl. Acad. Sci. U. S. A. 108, 20929–20934.
MacDonald, L.H., Coe, D., 2007. Influence of headwater streams on downstream reaches in forested areas. For. Sci. 53, 148–168.
Maxwell, A.E., Strager, M.P., 2013. Assessing landform alterations induced by mountaintop mining. Nat. Sci. 5, 229–237.
McCune, B., Grace, J.B., 2002. Analysis of Ecological Communities. MjM, Gleneden Beach, OR.
Merriam, E.R., Petty, J.T., Merovich Jr., G.T., Fulton, J.B., Strager, M.P., 2011. Additive effects of mining and residential development on stream conditions in a central Appalachian watershed. J. N. Am. Benthol. Soc. 30, 399–418.
Merricks, T.C., Cherry, D.S., Zipper, C.E., Currie, R.J., Valenti, T.W., 2007. Coal-mine hollow fill and settling pond influences on headwater streams in southern West Virginia, USA. Environ. Monit. Assess. 129, 359–378.
Messinger, T., 2003. Comparison of Storm Response of Streams in Small, Unmined and Valley-Filled Watersheds, 1999–2001, Ballard Fork, West Virginia. US Department of the Interior, US Geological Survey.
Messinger, T., Paybins, K.S., 2003. Relations Between Precipitation and Daily and Monthly Mean Flows in Gaged, Unmined and Valley-Filled Watersheds, Ballard Fork, West Virginia, 1999–2001. US Department of the Interior, US Geological Survey.
Meyer, J.L., Strayer, D.L., Wallace, J.B., Eggert, S.L., Helfman, G.S., Leonard, N.E., 2007. The contribution of headwater streams to biodiversity in river networks. J. Am. Water Resour. Assoc. 43, 86–103.
Michael, P.R., Superfesky, M.J., Uranowski, L.J., 2010. Challenges to applying geomorphic and stream reclamation methodologies to mountaintop mining and excess spoil fill construction in steep-slope topography (eg Central Appalachia). In: Barnhisel, R.I. (Ed.), 2010 National Meeting of the American Society of Mining and Reclamation, Pittsburgh, PA June 5–11, 2010. 27, pp. 98–115.
Miller, A.J., Zégre, N.P., 2014. Mountaintop removal mining and catchment hydrology. Water 6, 472–499.
Oksanen, J., 2011. Multivariate analysis of ecological communities. R: Vegan Tutorial. R Package Version 1.
Outerbridge, W.F., 1987. The Logan Plateau, A Young Physiographic Region in West Virginia, Kentucky, Virginia, and Tennessee. US Government Printing Office.
Palmer, M.A., Bernhardt, E.S., Schlesinger, W.H., Eshleman, K.N., Foufoula-Georgiou, E., Hendryx, M.S., Lemly, A.D., Likens, G.E., Loucks, O.L., Power, M.E., White, P.S., Wilcock, P.R., 2010. Mountaintop mining consequences. Science 327, 148–149.
Paul, M.J., Meyer, J.L., 2001. Streams in the urban landscape. Annu. Rev. Ecol. Syst. 333–365.
Petty, J.T., Fulton, J.B., Strager, M.P., Merovich Jr., G.T., Stiles, J.M., Ziemkiewicz, P.F., 2010. Landscape indicators and thresholds of stream ecological impairment in an intensively mined Appalachian watershed. J. N. Am. Benthol. Soc. 29, 1292–1309.
Phillips, J.D., 2004. Impacts of surface mine valley fills on headwater floods in eastern Kentucky. Environ. Geol. 45, 367–380.
Pond, G.J., 2012. Biodiversity loss in Appalachian headwater streams (Kentucky, USA): Plecoptera and Trichoptera communities. Hydrobiologia 679, 97–117.
R Team, 2012. R: A Language and Environment for Statistical Computing.
Ritter, J.B., Gardner, T.W., 1993. Hydrologic evolution of drainage basins disturbed by surface mining, central Pennsylvania. Geol. Soc. Am. Bull. 105, 101–115.
Saintilan, N., 2004. Relationships between estuarine geomorphology, wetland extent and fish landings in New South Wales estuaries. Estuar. Coast. Shelf Sci. 61, 591–601.
Scheingross, J.S., Brun, F., Lo, D.Y., Omerdin, K., Lamb, M.P., 2014. Experimental evidence for fluvial bedrock incision by suspended bedload sediment. Geology. http://dx.doi.org/10.1130/G35432.1.
Sutfin, N.A., Shaw, J.R., Wohl, E.E., Cooper, D.J., 2014. A geomorphic classification of ephemeral channels in a mountainous, arid region, southwestern Arizona, USA. Geomorphology 221, 164–175.
Touysinhthiphonexay, K.C., Gardner, T.W., 1984. Threshold response of small streams to surface coal mining, bituminous coal fields, Central Pennsylvania. Earth Surf. Process. Landf. 9, 43–58.
Townsend, P.A., Helmers, D.P., Kingdon, C.C., McNeil, B.E., de Beurs, K.M., Eshleman, K.N., 2009. Changes in the extent of surface mining and reclamation in the Central Appalachians detected using a 1976–2006 Landsat time series. Remote Sens. Environ. 113, 62–72.
Varanka, S., Hjort, J., Luoto, M., 2014. Geomorphological factors predict water quality in boreal rivers. Earth Surf. Process. Landf. http://dx.doi.org/10.1002/esp.3601.
Virtanen, R., Luoto, M., Rämä, T., Mikkola, K., Hjort, J., Grytnes, J.A., Birks, H.J.B., 2010. Recent vegetation changes at the high latitude tree line ecotone are controlled by geomorphological disturbance, productivity and diversity. Glob. Ecol. Biogeogr. 19, 810–821.
Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan, R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. J. N. Am. Benthol. Soc. 24, 706–723.
Walters, D., Leigh, D., Freeman, M., Freeman, B., Pringle, C., 2003. Geomorphology and fish assemblages in a Piedmont river basin, USA. Freshw. Biol. 48, 1950–1970.
Wickham, J., Wood, P.B., Nicholson, M.C., Jenkins, W., Druckenbrod, D., Suter, G.W., Strager, M.P., Mazzarella, C., Galloway, W., Amos, J., 2013. The overlooked terrestrial impacts of mountaintop mining. Bioscience 63, 335–348.
Wieczorek, G.F., Eaton, L., Morgan, B.A., Wooten, R., Morrissey, M., 2009. An Examination of Selected Historical Rainfall-Induced Debris-Flow Events Within the Central and Southern Appalachian Mountains of the Eastern United States.
Wiley, J.B., 2001. Reconnaissance of Stream geomorphology, Low Streamflow, and Stream Temperature in the Mountaintop Coal-Mining Region, Southern West Virginia, 1999–2000. US Department of the Interior, US Geological Survey.
Wiley, J.B., Brogan, F.D., 2003. Comparison of Peak Discharges Among Sites With and Without Valley Fills for the July 8–9, 2001, Flood in the Headwaters of Clear Fork, Coal River Basin, Mountaintop Coal-Mining Region, Southern West Virginia.
Wipfli, M.S., Richardson, J.S., Naiman, R.J., 2007. Ecological linkages between headwaters and downstream ecosystems: transport of organic matter, invertebrates, and wood down headwater channels. J. Am. Water Resour. Assoc. 43, 72–85.
Wohl, E., 2013. Mountain Rivers Revisited. John Wiley & Sons.
Wolman, M.G., 1954. A Method of Sampling Coarse River-Bed Material. American Geophysical Union.
Wunsch, D.R., Dinger, J.S., Taylor, P.B., Carey, D.I., Graham, C.D.R., 1996. Hydrogeology, Hydrogeochemistry, and Spoil Settlement at a Large Mine-Spoil Area in Eastern Kentucky: Star Fire Tract. Kentucky Geological Survey Lexington, KY, USA.
Wunsch, D.R., Dinger, J.S., Graham, C.D.R., 1999. Predicting ground-water movement in large mine spoil areas in the Appalachian Plateau. Int. J. Coal Geol. 41, 73–106.
Zégre, N.P., Miller, A.J., Maxwell, A., Lamont, S.J., 2014. Multiscale analysis of hydrology in a mountaintop mine impacted watershed. J. Am. Water Resour. Assoc.