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

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ABSTRACT

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.