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HYDROLOGIC EFFECTS OF SURFACE COAL MINING IN APPALACHIA (U.S.)[1]

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ABSTRACT: Surface coal mining operations alter landscapes of the Appalachian Mountains, United States, by replacing bedrock with mine spoil, altering topography, removing native vegetation, and constructing mine soils with hydrologic properties that differ from those of native soils. Research has demonstrated hydrologic effects of mining and reclamation on Appalachian landscapes include increased peakflows at newly mined and reclaimed watersheds in response to strong storm events, increased subsurface void space, and increased base flows. We review these investigations with a focus on identifying changes to hydrologic flow paths caused by surface mining for coal in the Appalachian Mountains. We introduce two conceptual control points that govern hydrologic flow paths on mined lands, including the soil surface that partitions infiltration *vs.* surface runoff and a potential subsurface zone that partitions subsurface storm flow *vs.* deeper percolation. Investigations to improve knowledge of hydrologic pathways on reclaimed Appalachian mine sites are needed to identify effects of mining on hydrologic processes, aid development of reclamation methods to reduce hydrologic impacts, and direct environmental mitigation and public policy.

(KEY TERMS: surface mining; hydrologic impacts; hydrologic flow paths; mine hydrology.)

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INTRODUCTION

Surface mining for coal has been practiced for more than a century in the Appalachian Mountains of eastern United States (U.S.) (Abramson and Haskell, 2006). Surface mining reorganizes geologic materials and removes native biota and soil, and can have unintended effects on hydrologic flow paths and processes in the steep terrain of the Appalachian Mountains. Surface coal mining methods and regulations affecting those methods have changed over time. Notable changes occurred in response to the U.S. Surface Mining Control and Reclamation Act (SMCRA 1977) because of the reclamation practices that it requires. Under SMCRA, mine operators cover exposed rock highwalls, grade most mining areas to approximate original contour, and revegetate those areas after mining is complete. An unintended consequence of this law is the prevalence of soil compaction that occurred because of the heavy equipment used in reclamation operations (Thurman and Sencindiver, 1986; Haering *et al.*, 2004; Acton *et al.*, 2011). Soil compaction and associated reclamation operations inhibit water infiltration (Jorgensen and Gardner, 1987), reestablishment of native forest

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vegetation (Torbert and Burger, 1990; Conrad *et al.*, 2002; Burger and Evans, 2010), and natural succession (Ashby *et al.*, 1980; Groninger *et al.*, 2007), all of which have the potential to alter hydrologic flow paths and processes.

Other changes to surface mining that affect the hydrology of Appalachian mined areas have occurred in the modern era (post 1970s) because of increases in the operational scale of mining in the Appalachian region. New generations of mining equipment that can remove greater quantities of overburden and coal in this steep mountainous terrain have enabled larger mines, affecting surface geology, soils, and related hydrologic processes over extensive areas. The increased scale of surface mining in mountainous terrain often requires larger excess spoil disposal fills, such as valley fills (VFs), because of increased spoil volumes. This expanded scale of Appalachian mining operations (Haering *et al.*, 2004; Copeland, 2013) and use of VFs to store excess spoil (Shank, 2010) have implications for hillslope and headwater hydrology because of potential disruptions to premining hydrologic flow paths that may affect the timing and duration of storm-induced flows or flow regimes.

The Appalachian mining industry has changed over the past half century. Mines have grown larger while the U.S. coal industry has consolidated into fewer, larger firms (USEIA, 1993; Humphries and Sherlock, 2013). Environmental impact mitigation methods employed by industry have also changed. Acid drainage issues that were prevalent in the pre-SMCRA and early SMCRA eras (Herlihy *et al.*, 1990) are rarely an issue with contemporary mining operations today because of improved methods for acid spoil handling. Terrestrial ecosystems have been severely altered by Appalachian mining (Simmons *et al.*, 2008; Zipper *et al.*, 2011a; Wickham *et al.*, 2013), but new methods intended to restore forest vegetation on mine sites are being implemented (Burger *et al.*, 2005; Zipper *et al.*, 2011b). Major ions (e.g., SO_4^{2-}, HCO_3^-, Ca^{2+}, Mg^{2+}) and selenium are emerging water quality issues associated with coal mining (Pond *et al.*, 2008; Palmer *et al.*, 2010; Cormier *et al.*, 2013), but mining methods intended to reduce these pollutants in mine water discharge are being developed (Daniels *et al.*, 2013; Donovan and Ziemkiewicz, 2013; Quaranta *et al.*, 2013). However, we are aware of no published investigations focused on developing Appalachian mine reclamation methods intended for the explicit purpose of restoring pre-mining surface and groundwater flow paths on mine landscapes or mitigating hydrologic alterations caused by the mining process.

Here, we review literature on the hydrology of surface mine lands in Appalachia. We describe the region's hydrologic conditions without mining and their alteration by coal surface mining and reclamation. We then summarize the current scientific knowledge addressing effects of Appalachian surface mining and reclamation on hydrologic flow paths and processes on reclaimed mine lands. We introduce the idea of control points, which govern hydrologic flow paths in mined watersheds. We define control points as controlling features that exist on the mined landscape that are generally mine spoil/soil horizons or horizon interfaces in the post-mining engineered spoil or soil. We also quantitatively synthesize infiltration data from prior studies on mine lands and include discussion on how infiltration acts as an initial control point that partitions water into surface *vs.* subsurface flow paths. We discuss the potential fate and consequences of water that enters these two flow paths, effects of mining on storage and discharge, and conclude by describing research needs that are essential to improve knowledge of hydrologic processes and mitigation of hydrologic impacts.

THE APPALACHIAN COALFIELD

The Appalachian Coalfield extends from Pennsylvania and Ohio south to Alabama (Figure 1). Our focus is the central and northern Appalachian coalfield extending from eastern Tennessee northward. The Appalachian Coalfield is contained within the Appalachian Plateaus physiographic province (Fenneman, 1938), a predominantly forested landscape

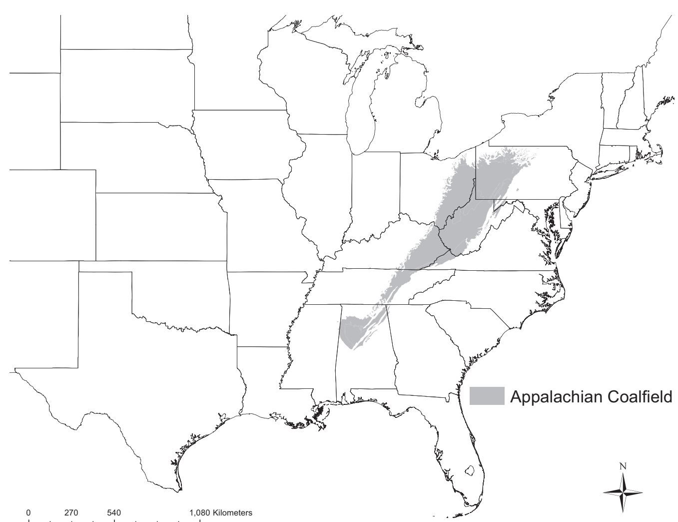

FIGURE 1. The Appalachian Coalfield in Eastern U.S. Source: USGS (http://pubs.usgs.gov/of/2012/1205/Downloads/Metadata/).

comprised of deciduous or mixed deciduous/coniferous forests that have been harvested repeatedly for timber over the last ~150 years. The climate is humid continental and is characterized by warm summers and cold winters with precipitation and high-intensity storm events throughout the year. In the northern end of the region, the mean annual temperature is 9.1°C with a mean of 112.8 cm of precipitation. In the southern end of the region, mean annual temperature is 12.8°C with a mean of 132.4 cm of precipitation (Frostburg, Maryland and Big Stone Gap, Virginia, respectively; NOAA 2015). As of 2011, >600,000 ha had been surface mined for coal in central and northern Appalachia since the passage of SMCRA (Zipper *et al.*, 2011b).

Natural Landscapes

The geologic structure of the Appalachian Coalfield is generally comprised of flat lying to gently sloping sedimentary rock strata, predominantly clastics (sandstones, siltstones, and shales) of Pennsylvanian geologic age in the southern range and of Permian age in the north (Seaber *et al.*, 1988). The region is elevated relative to adjacent terrain and serves as a headwater source area. The dominant topographic formation process has been dissection (Fenneman, 1938). Current terrain ranges from steeply dissected remnants of an ancient plateau, generally capped with resistant sandstones in central Appalachia (Tennessee, Virginia, eastern Kentucky, and southern West Virginia) to gentler slopes and rounded hills further north (western Pennsylvania, northern West Virginia, and southeastern Ohio). Soils on side slopes are generally young and thin, often <1 m in steeper terrains. Soils on ridges and in coves are generally older and deeper than on side slopes. The upper strata of sedimentary rocks have been affected by earth-surface environmental processes, such as oxidation and leaching, and are said to have been “weathered” (Haering *et al.*, 2004; Zipper *et al.*, 2013). Weathered rocks, typically brownish in color due to Fe oxidation and 10-20 m in thickness, are underlain by rock materials that are said to be “unweathered,” although they are affected in their upper segments by groundwater movement enabled by the fracturing and jointing that resulted from geologic uplift and stress relief (Borchers and Wyrick, 1981).

Throughout the region, most groundwater flows occur near the surface, in the upper fracture systems of bedrock and in colluvium on slopes (Seaber *et al.*, 1988; Harlow and LeCain, 1991). Primary permeability varies among geologic units, with certain sandstones and coal seams having sufficient permeability to enable lateral movement of groundwater (Harlow and LeCain, 1991; Minns, 1993; Callaghan *et al.*, 1998). However, finer grained clastics (siltstones and shales) and tight grained sandstones, predominant rock types within the geologic column throughout much of the region, typically have low primary permeabilities. Fractures have enhanced the secondary permeability of near-surface materials and allow for some movement of groundwater into deeper geologic zones. Such groundwater flows are most active in the upper 100-200 m (Seabers *et al.*, 1988) where surface coal mining occurs. Groundwater discharge may emerge on slopes as springs often where geologic units transmitting lateral flows outcrop, or along valley floors where water that has been transmitted through surficial material including near-surface bedrock and colluvium, and through deeper geologic units emerging as streams (Callaghan *et al.*, 1998) (Figure 2).

In native forests in this region, response to precipitation is consistent in many ways, with forested areas often featuring significant topographic relief. Runoff is generally minimal in such settings for a variety of reasons. First, intact forests intercept precipitation and lead to evapotranspiration (ET) from overstory and understory vegetation and from litter layers on the forest floor (Davie, 2008), as well as slow the rate of precipitation that reaches the forest floor. Second, intact forests improve soil surface characteristics, such as soil organic matter in the upper soil horizons that promote infiltration of precipitation. As a result, infiltration is generally substantial in this setting and there is little surface runoff. In rare cases where precipitation does not evapotranspire or infiltrate it becomes available for runoff or overland flow. This can happen in two ways, including infiltration excess overland flow and saturation excess overland flow. The former occurs when the infiltration capacity of the soil is exceeded and the latter occurs when the soil voids are filled with water. In humid climates, saturation overland flow is typically dominant (Smith and Goodrich, 2005; Davie, 2008).

Precipitation that infiltrates during storm events moves through the ground in a variety of ways. The two main categories are subsurface storm flow and groundwater flow. Groundwater flow is the slow movement of water through the deep saturated zone that occurs both during and between storms (Toth, 1963; Freeze and Cherry, 1979). Subsurface storm flow is rapid lateral movement of infiltrating precipitation in the rooting zone or relatively shallow soil caused by the water table rising into a surface layer of higher conductivity or presence of a relatively shallow low-permeability layer (bedrock is a common example in mountainous terrain) (Weiler *et al.*, 2005). This flow path is referred to by a variety of

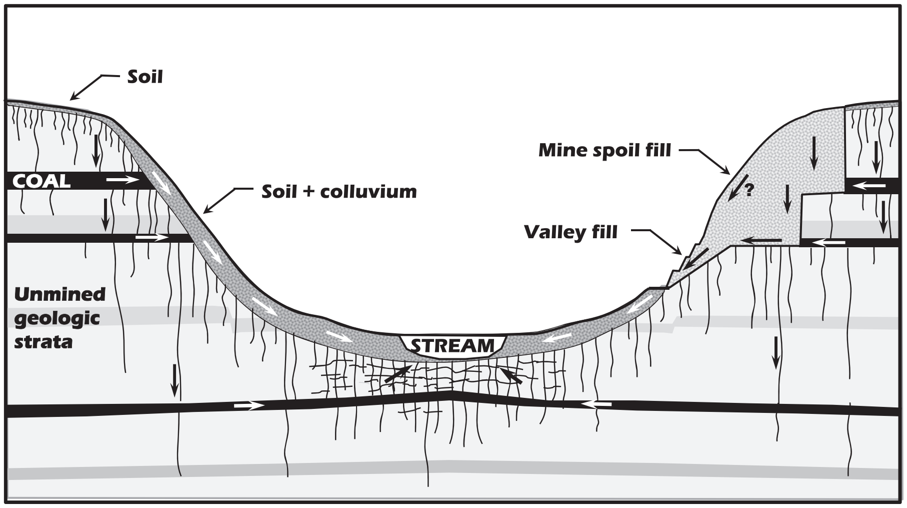

FIGURE 2. Conceptual Model of Appalachian Region Hydrology Undisturbed (left) and after Modification by a Contour Surface Mine with Valley Fill (right). Natural hydrology representation is based on Seaber *et al.* (1988), Harlow and LeCain (1991), and other studies. Hydrologic flow paths within geologic strata, as illustrated, assume those strata dip toward the valley. Hydrologic flow paths within the mine spoil fill, other than discharge from the toe, are not well known. Drawing is not to scale.

synonymous terms, including interflow and throughflow. It is now accepted that most such flow is saturated or nearly saturated. This flow can occur through the soil matrix but also through macropores, soil pipes, and rock fractures. Where there are depressions in the bedrock or other low-permeability layers that direct inflow, the "fill and spill" theory proposes that significant subsurface storm flow will occur only after enough precipitation has occurred to fill those depressions (Meerveld and McDonnell, 2006).

Mining Disturbances

Surface mining for coal requires removal of the geologic materials overlying the coal seam (overburden). The overburden, which includes the soil if it is not removed and segregated, is typically blasted with explosives, converting it to variously sized fragments called mine spoil. Where multiple coal seams are present and accessible, the intervening rock material (interburden) is treated similarly. Mine spoils are transported and placed for reconstruction of previously mined terrain. During this process, the land surface, native geology, and hydrologic structure are altered. Mine pits are refilled producing mine spoil fills with higher pore and void volumes than the original geologic structure (Diodato and Parizek, 1994; Hawkins, 2004). Most mine spoil fills are sufficiently porous and permeable to act as unconfined aquifers, and are underlain by flat benches or buried plateaus that act as a lower aquifer confining bed (Wunsch *et al.*, 1999). Mine spoil volumes typically exceed those of the pre-mining native rock because of fragmentation by explosives. Hence, mine operators must manage higher spoil volumes than are needed to recontour the land, leading to construction of structures called excess spoil disposal fills which do not conform to the land's original contours. VFs are excess spoil disposal fills constructed as wedge shaped piles or tiered lifts placed in valleys, covering ephemeral, intermittent, or perennial streams (Evans *et al.*, 2014). In response to increased regulatory restrictions on VFs (USEPA, 2013), excess spoil disposal fills in upland locations above perennial streams are being used more commonly in recent years in the Appalachian region.

Appalachian mining operations reconstruct the landscape to mimic the pre-mining land contours to the extent that is possible while managing the excess spoil. However, significant changes to the landscape are a reality of surface mining. Steep but geotechnically stable slopes for excess spoil disposal fills are encouraged by regulatory policies as a means of minimizing the mining disturbance footprint. Reclaimed landforms often include structures that capture and channelize water including roadways and storage areas for vehicles, ponds, and channels intended to retain water (Merricks *et al.*, 2007), narrow benches on steep slopes intended to slow water movement (Quaranta *et al.*, 2013), and rock-lined channels on steep slopes intended to transmit water rapidly to the slope base (Fritz *et al.*, 2010).

Mine site surfaces may be constructed from salvaged native soils, but soil substitutes constructed from rock fragments are more common in Appalachia (Daniels and Amos, 1985; Sencindiver and Ammons,

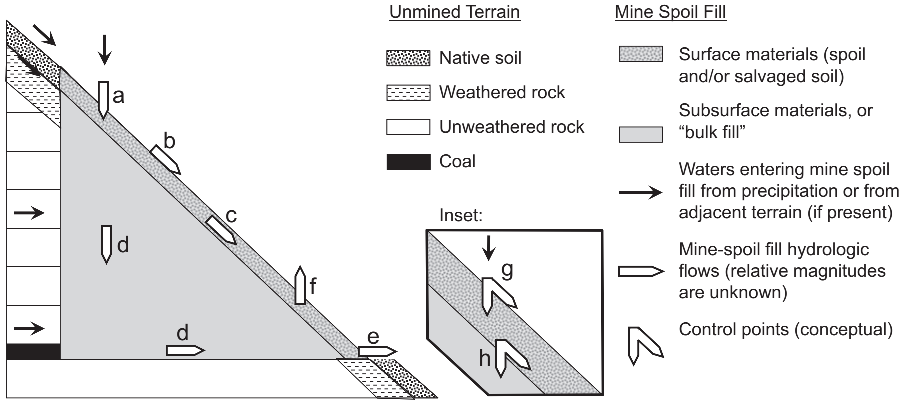

FIGURE 3. Conceptual Representation of a Mine Spoil Fill Placed within Unmined Terrain, with Hydrologic Flow Paths. Terms used to describe mine spoil fill flow paths are as follows: a = infiltration; b = runoff or surface flows; c = subsurface storm flow; d = deep-fill flows; e = discharge; f = evapotranspiration. The inset represents the surface of the mine spoil fill, magnified, with the conceptual control points introduced by this article: g = surface; h = subsurface. The near-surface materials on the mine spoil fill may be applied separately from the subsurface materials; or the mine spoil may be placed as a single operation such that the near-surface materials are identical to those comprising the bulk-fill. The occurrence of c (near-surface flows) as a flow path that is distinct from d (deep-fill flows) has not been demonstrated to occur universally on Appalachian mine sites.

2000; Simmons *et al.*, 2008; Zipper *et al.*, 2011a). Salvaged soil and/or spoil materials placed on the mine site surface are commonly called "mine soils" because they support plant communities and form soil-like properties over time. When constructed from rock spoils, these mine soils contain no pedogenic organic matter upon initial placement, but organic matter accumulates on the surface once vegetation becomes established. Mine soils form surface horizons in response to incorporation of organic materials (Haering *et al.*, 2004), often within five years after construction (Ciolkosz *et al.*, 1985; Roberts *et al.*, 1988a; Sencindiver and Ammons, 2000). Illuviation of clays, organic materials, and other materials also occurs, as in natural soils, but the times required for these processes to form subsurface horizons similar to those of natural soils are far longer (Ciolkosz *et al.*, 1985; Sencindiver and Ammons, 2000). Appalachian mine soils constructed from rock spoils typically differ from native soils in certain respects (Daniels and Amos, 1985) including the lack of soil structure at depth or presence of compacted layers that may lead to hydrologic properties in subsurface horizons, such as reduced porosity, that restrict water movement (Thurman and Sencindiver, 1986; Skousen *et al.*, 1998; Haering *et al.*, 2004).

HYDROLOGIC FLOW PATHS ON MINE SITES

Sources of water entering the mined watershed include water from precipitation, surface water draining from upslope areas, and groundwater from adjacent terrain. This water flows through or over the mine spoil (Figure 3) and is routed to controlled discharge points, as required by SMCRA. While the mining operation is active, water at the discharge points moves through sediment-control ponds prior to release into natural streams (Merricks *et al.*, 2007). When mining is completed and the regulatory requirements for revegetation are met, the sediment-control ponds are often removed. While the mine is under regulatory authority (i.e., during mining and for five or more years after reclamation is complete), water discharges are regulated for quality under the U.S. Clean Water Act (1972) and SMCRA.

Surface Processes: Evapotranspiration

Removal of vegetation by mining reduces ET of water to the atmosphere, which likely contributes to increased peakflows and shortened storm response times that often occur in recently mined areas (Griffith *et al.*, 2012). In an observational study of paired West Virginia streams, Messinger and Paybins (2003) found that nonstorm flows (per watershed area) were 2× higher in streams draining a mined watershed, compared to unmined. They attributed these patterns to decreased ET in the mined watershed, but they did not have pre-mine data to show that the flows were similar before mining and, hence, were unable to control for potential differences among the watersheds. Similarly, Dickens *et al.* (1989) reported results of water monitoring from five mined and one unmined first-order watersheds in eastern Tennessee over 14 years. They found greater base-flow durations and annual streamflows in the mined watersheds relative to unmined controls, a result they attributed (in part) to reduced ET caused by vegetation loss in the mined watersheds. In Kentucky, Sena *et al.* (2014) observed that 0.4-ha research plots supporting productive and fast-growing forest vegetation yielded less groundwater during the growing season in their eighth and ninth years compared to corresponding plots of different spoil types with less productive forest vegetation, a result attributed to increased ET. We expect that as mined areas are reclaimed and vegetation returns, ET will increase over time, decreasing initial impact of ET reductions immediately following mining. However, timing and completeness of ET recovery are poorly studied on mine lands.

Surface Processes: Infiltration

Critical to mine site hydrology is the soil surface control point that partitions precipitation between surface and subsurface flows. This control point is governed by the relationship of precipitation and infiltration rates of mine soils and antecedent soil and groundwater conditions. When precipitation rate exceeds infiltration rate of the mine soil, excess precipitation remains aboveground as ponded water or infiltration excess overland flow (Horton, 1933). Factors affecting water infiltration and this partitioning of water flow on natural soils are well known (Parr and Bertrand, 1960). These include surface porosity, which is influenced by soil texture, presence of rock fragments, and soil aggregation or structure. Soil aggregation, in turn, is governed by soil organic matter content and by related factors such as activity by soil biota (Bronick and Lal, 2005). Soils with larger pores, which occur with well-developed soil structure and particle aggregation, generally allow greater infiltration than soils with smaller pores. Macropores or soil pipes typically formed by roots or animals can create preferential flow paths and accordingly increase infiltration rates in soils (Beven and Germann, 1982; Sidle *et al.*, 2001). Factors influencing movement of water over the soil surface, such as slope, vegetation, and surface roughness also influence water infiltration (Parr and Bertrand, 1960). Rain falling at high rates can also affect infiltration by disaggregating surface soil particles potentially resulting in a thin compacted surface layer, especially if that surface is low in organic matter content and not protected by vegetation (Horton, 1933; Awadhwal and Thierstein, 1985).

Infiltration rates and spoil characteristics that result in infiltration excess overland flow on mined spoil are well documented. The surface flow-path control point that we present in this review is based on this extensive literature that demonstrates surface infiltration is a critical factor that defines the fraction of precipitation exiting the mined landscape as overland flow. On recently established sites with fresh mine soils constructed from rock spoils, researchers have observed a process of "surface crusting" that occurs prior to development of an organic matter influenced surface horizon, with finely textured spoil materials being most susceptible to crust formation (Daniels and Amos, 1985; Burger and Evans, 2010). Soil crusting also occurs on natural soils resulting from rainfall effects that cause soil dispersion and surface-segregation of silts and clays (Awadhwal and Thierstein, 1985). Crusting is inhibited by development of vegetation (Daniels and Amos, 1985) and incorporation of organic matter into surface soils. Fields-Johnson *et al.* (2012) observed that presence of herbaceous vegetation on young mine soils increased infiltration rates and attributed these effects to interception by vegetation and effects by stems and roots of living plants that provide channels into the subsurface. Studies in other mining regions have also observed crusting of young, unvegetated mine soils, and infiltration increases with increased vegetative cover (Loch, 2000; Nicolau, 2002; Moreno-de las Heras *et al.*, 2009).

Researchers have found that Appalachian mine soil infiltration is influenced by factors similar to those influencing infiltration on native soils such as presence of high soil densities constraining infiltration capacity. Working in an Ohio watershed that was mined and reclaimed using native soil cover and soil compaction, Weiss and Razem (1984) found increased rainfall runoff and slower groundwater recharge despite an increase in subsurface hydraulic conductivity shortly after mining and reclamation, a result they attributed to surface soil compaction.

In an early controlled experiment using mine soils from one to four years of age and 0.4 m^2 infiltration boxes, Jorgensen and Gardner (1987) found that infiltration capacities on fresh mine soils, constructed as controlled mixtures of rock spoils and salvaged soil, in the Alleghany Plateau of central Pennsylvania were influenced by slope, bulk density, vegetation, and soil texture. Spoil lithography was also found to be influential, with mine soils developed from more acidic and fine-textured geologic materials exhibiting lower infiltration capacities than mine soils developed from other materials with more durable rock fragments. Initially, infiltration capacities on mine soils were an order of magnitude lower than those in the adjacent forest soils (Table 1). However, infiltration capacities approached those of native forest soils by year 4, a change that occurred in association with development of plant cover and consequent organic matter accumulation. Mine soils without plant cover,

TABLE 1. Infiltration Rates Recorded on Appalachian Mine Soils, and Infiltration Rates Recorded Using Similar Methods on Forest Reference Sites.

Rate (cm/h)	Type of Site	Age (years)	Location	Method
Rogowski and Pionke (1984)				
5.3 & 45	Natural soil reference	N/A	Pennsylvania	0.2 m^2 infiltrometer (average over measurement period)
1.1 & 2.8	“Topsoiled material” on mine site	Unknown	Pennsylvania	0.2 m^2 infiltrometer (average over measurement period)
0.3-1.7	Mine spoil	Unknown	Pennsylvania	0.2 m^2 infiltrometer (average over measurement period)
Jorgensen and Gardner (1987)				
0.73 (0.47-1.40 range)	Mix soil/spoil surface	1	Pennsylvania	Simulated rainfall, 0.4 m^2, 30 min
1.83 (0.85-2.92)	Mix soil/spoil surface	4	Pennsylvania	Simulated rainfall, 0.4 m^2, 30 min
0.73 (0.12-1.86)	Mix soil/spoil surface	1	Pennsylvania	Simulated rainfall, 0.4 m^2, steady state
3.04 (0.78-5.82)	Mix soil/spoil surface	4	Pennsylvania	Simulated rainfall, 0.4 m^2, steady state
8	Forested reference (cited from prior study)	N/A	Pennsylvania	Simulated rainfall, 0.4 m^2, steady state
Guebert and Gardner (2001)				
2.4 (average)	Mix soil/spoil surface	2	Pennsylvania	Simulated rainfall, 0.4 m^2, steady state (data summarized from prior studies, n = 174 total)
3.9 (average)	Mix soil/spoil surface	3	Pennsylvania	Simulated rainfall, 0.4 m^2, steady state (data summarized from prior studies, n = 174 total)
4.9 (average)	Mix soil/spoil surface	4	Pennsylvania	Simulated rainfall, 0.4 m^2, steady state (data summarized from prior studies, n = 174 total)
Shukla et al. (2004)				
9.4	Topsoil, pasture/hay, not fertilized	~26	Ohio	Double-ring infiltrometer, 15/27 cm, 2.5 h
7.9	Topsoil, pasture/hay, fertilized annually for 16 years	~26	Ohio	Double-ring infiltrometer, 15/27 cm, 2.5 h
13.5	As above, with higher fertilization rates	~26	Ohio	Double-ring infiltrometer, 15/27 cm, 2.5 h
5.2	Unmined reference (average)	N/A	Ohio	Double-ring infiltrometer, 15/27 cm, 2.5 h
Simmons et al. (2008)				
0.3	Mine spoil, compacted	15	Maryland	Small plot rainfall runoff
>30	Forested reference	N/A	Maryland	Small plot rainfall runoff

and with surface crusts, were found to be highly erosive.

Also working at Pennsylvania mine sites, Ritter and Gardner (1993) measured infiltration, runoff, and drainage channel morphology and found that mine surface hydrology is not in equilibrium on recently established mine sites. Initial infiltration rates were low, with rainfall commonly producing infiltration excess overland flow as evidenced by high peakflow rates and rapid formation of skeletal surface-stream networks. Over 12 years, they observed increasing infiltration capacities on most of the study sites. Where infiltration capacities recovered to at least 3 cm/h, they observed changes to surface-drainage channel morphology and runoff responses to rainfall and interpreted those changes as indicating saturation excess overland flow had become a dominant runoff generation mechanism.

Guebert and Gardner (2001) conducted detailed studies of hydrologic processes on one of the mine sites studied by Ritter and Gardner (1993). The mine site had been reclaimed using a mixture of salvaged topsoil with mine overburden to construct a thin (up to 30 cm) mine soil over a mine overburden backfill. Using simulated rainfall, Guebert and Gardner (2001) found consistently low infiltration capacities on young mine spoils compared to native soils. However, after two years, they observed macropore development, mostly within the upper 12 cm, that appeared to influence hydrologic flow paths. They also measured relatively fast time lags (<72 h) for water moving to lower areas of the research site indicating that infiltration and matrix flow could not account for the water movement. They suggested that macropores around large rocks, cavities, and roots shift the dominant flow path from runoff to shallow subsurface storm flow through the upper 10-12 cm of mine soil. This shallow flow was found to rejoin the surface water as seeps or saturation overland flow at lower locations. Guebert and Gardner (2001) interpreted these runoff patterns as resulting from low porosities of mine spoil at depth, as the deeper mine spoils (>10-12 cm) transmitted water more slowly than the overlying soil (salvaged and revegetated native soil) and did not demonstrate the macropore development that they observed in the reconstructed soils closer to the surface.

Collectively, the central Pennsylvania studies (Jorgensen and Gardner, 1987; Ritter and Gardner, 1993; Guebert and Gardner, 2001) demonstrate relatively rapid hydrologic development on recently established mine sites. However, generalization of these findings to the larger population of Appalachian mine sites is limited because the studies were conducted using mine soil construction methods that differ from those commonly employed elsewhere in Appalachia. The Pennsylvania sites used salvaged soils for mine soil construction, but rock spoils are commonly used for that purpose on many Appalachian mine sites. Shukla *et al.* (2004) conducted infiltration studies on 26-year-old mine soils constructed from salvaged soils in Ohio that had been managed for pasture and hay. They found that infiltration capacities of these older mine soils exceeded those of natural soils in similar terrains and management, supporting the research reported in Pennsylvania. However, working in a small Maryland catchment Simmons *et al.* (2008) found very low infiltration rates (<3 mm/h) on 15-year-old compacted mine soils, relative to an adjacent natural forest (300 mm/h), demonstrating that temporal effects on infiltration may not be consistent across all sites.

The observation that mine spoil compaction inhibits rainfall infiltration is consistent with soil science principles (Parr and Bertrand, 1960) and with studies conducted in other mining regions (Ward *et al.*, 1983; Chong and Cowsert, 1997; Haigh and Sansom, 1999). A more recent study by Taylor *et al.* (2009) studied rainfall runoff from recently established uncompacted loose-dumped mine spoils constructed from sandstones and found it to be similar to runoff from forested watersheds, suggesting higher infiltration capacities in the sandstone mine spoils. Similarly, Hoomehr *et al.* (2013) studied rainfall runoff characteristics of young Tennessee mine soils that had been reclaimed using grading techniques intended to minimize soil compaction as a means of preparing the mine site for reforestation. They found less runoff than predicted by models developed from conventional mine reclamation with smooth grading and compacted soils despite the low levels of vegetative cover on these young mine soils.

Subsurface Hydrologic Flow Paths

After water infiltrates into the surface mine soil it reaches a subsurface flow-path control point that partitions water between subsurface storm flow and flow into the deeper bulk-fill (Figure 3). Hydrologic studies to date have not been designed to determine how this controlling feature influences hydrologic flow paths on Appalachian mine sites. However, several studies have documented subsurface features and mechanisms that are consistent with the control-point concept.

Existence of subsurface flows (including storm flows) on mine sites was documented by the Pennsylvania researchers (Ritter and Gardner, 1993; Guebert and Gardner, 2001). On those mine sites, the partitioning of subsurface water was largely controlled by hydraulic conductivity of the surface material/bulk-fill interface. If a layer of uncompacted soil or spoil is placed or develops on top of the highly compacted bulk-fill layer, subsurface storm flow can occur directly above that interface (Guebert and Gardner, 2001). At this interface, water can flow parallel to the surface as subsurface storm flow and exit the shallow mine soil as seeps or springs (Ritter and Gardner, 1993). Hence, the subsurface control point determines the fraction of infiltrated water that is routed to deeper or longer flow paths through the bulk-fill.

Although conditions documented by Guebert and Gardner (2001) are not always observed on Appalachian mines, it is logical to expect that features separating subsurface storm flows from water flowing deeper into bulk-fill may develop on other mine sites as well. Soil compaction is common on Appalachian mines; both on the surface and in subsurface materials (Thurman and Sencindiver, 1986; Haering *et al.*, 2004; Acton *et al.*, 2011) and such compaction can restrict water movement (Jorgensen and Gardner, 1987; Skousen *et al.*, 1998). Also, it has been documented that mine soil surfaces develop soil-like properties with time (Ciolkosz *et al.*, 1985; Roberts *et al.*, 1988a; Sencindiver and Ammons, 2000; Haering *et al.*, 2004). Hence, it is logical to expect that (1) zones of enhanced water flow will develop near and within mine soil surfaces; (2) these zones will enable subsurface storm flow; and (3) hydraulic conductivities of spoil materials below the zone of enhanced subsurface flow will govern water movement into the deeper fill. However, the prevalence of subsurface storm flow on region wide mine lands has not been documented.

Although some hillslope-scale studies indicated development of subsurface storm flow once infiltration rates had increased at their study sites (Ritter and Gardner, 1993; Guebert and Gardner, 2001), other landscape-scale studies have observed flow patterns that are indicative of deeper flow pathways and greater residence times in the bulk-fill spoils. In an early work addressing hydrologic impacts of pre-SMCRA coal mining at the landscape scale, Larson and Powell (1986) studied long-term flow recession curves for the Russell Fork River in southwestern Virginia. They found that this large mined watershed was associated with increased base flow when compared to an unmined watershed. Hydrograph recession curves for a mined watershed showed a flattening over time compared to a continued drop in the unmined watershed hydrograph, which they suggest is caused by increases in storage (i.e., deeper flow paths) in the extensive mine spoils in the mined watershed. In an earlier review, Miller and Zegre (2014) suggested that the VF portion of the newly constructed watersheds plays an important role in storage of subsurface water and subsequent maintenance of base flow.

One of the most complete experimental studies of subsurface hydrology in mined sites in the Appalachian region took place on three small watersheds with gently rolling relief in eastern Ohio that were intensively monitored before, during, and after surface mining and reclamation (Bonta *et al.*, 1992). They found hydraulic conductivities of spoil after mining varied over the reclaimed areas, and ranged from an order of magnitude lower to four orders of magnitude greater than pre-mining conditions. They identified significant structural changes to the background hydrologic framework, such as changes in the probable watershed size (15-16% increase), relief, and aspect, and noted shifts of surface hydrology from the native branching stream patterns to post-mining diversion ditches or single channel systems. Their primary hydrologic findings showed that new subsurface flow paths formed during the mining and reclamation process, and groundwater-level recovery at these sites was slow and erratic after mining and reclamation had stopped.

Hawkins and Aljoe (1992) conducted slug tests using groundwater wells drilled into a West Virginia surface mine. These studies yielded results that caused them to describe the mine spoil fill as "pseudokarst" terrain, adopting a term from Caruccio *et al.* (1984), as two distinct patterns of groundwater movement were noted. Water drainage from certain wells occurred rapidly, a phenomenon that the authors interpreted to indicate the existence of macropores transmitting large volumes of water within the mine spoil. Other areas of the mine spoil fill demonstrated hydrologic patterns consistent with spoil matrix storage and release. Tracer tests led the researchers to conclude that macropores were relatively isolated and poorly interconnected.

Based on subsurface investigations using 120 wells drilled into 18 reclaimed mines in four states, Hawkins (2004) found that the conditions documented by Hawkins and Aljoe (1992) occurred more generally. The author described deep bulk-fill materials functioning in a manner similar to unconfined aquifers in karst geology, with large void volumes and large capacities to store and transport water because of high physical heterogeneity of the spoil materials. Groundwater recharge rates were found to be related to spoil type with higher rates in sandstone dominated spoils, compared to shale dominated spoils with rocks that generally break down more quickly and form geologic matrices with finer textures, lower porosities, and fewer macropores. The saturated thickness of the post-mining spoil fills was also found to be related to total fill thickness, indicating that deeper spoil fills have higher potential aquifer volumes and greater potentials for storage.

Diodato and Parizek (1994) studied subsurface water storage and movement in a Pennsylvania surface mine. They found that subsurface spoils had reduced densities relative to unmined terrain, which they interpreted as an indicator of increased porosity because of fragmentation, but those subsurface material densities were highly variable. Zones with higher density maintained relatively high moisture contents, demonstrating water storage. Using tracers, they found that subsurface water flows demonstrated a dual-permeability mechanism: a rapid and transient response to rain events, which they interpreted as occurring as a result of water flowing through larger voids; and a more sustained response over multiple-day periods, which they interpreted as water moving through relatively smaller pores within a fine-grained spoil matrix created by subsurface spoil materials. Other authors have reported observational stream data that support the hypothesis that there are longer flow paths or greater storage in the bulk-fill materials in mining operations compared to native geologic conditions (Dickens *et al.*, 1989; Messinger and Paybins, 2003; Wiley and Brogan, 2003).

Streamwater Discharge

A number of studies have contrasted streamwater discharge and base-flow characteristics from Appalachian watersheds containing mine sites to either pre-mining conditions or to discharge from nearby watersheds lacking mining disturbance. In a multiyear study of three mined watersheds in Ohio, Bonta *et al.* (1997) found higher daily runoff volumes and peakflow responses to rainfall after mining compared to pre-mining conditions, but did not find consistent changes in base flow (Bonta *et al.*, 1997).

A series of studies in western Maryland, which compared mined watersheds to nearby unmined areas, reached similar findings. Negley and Eshleman (2006) studied streamwater discharge from a 27-ha watershed containing less than 20-year-old surface mines (~46% of land area), including the compacted mine site studied by Simmons *et al.* (2008). McCormick *et al.* (2009) studied streamwater discharge-rainfall relationships from the same area, but at a larger scale: a 187-km^2 watershed that contained 17% mined area. McCormick and Eshleman (2011) also studied rainfall and streamwater discharge from three small mined and partially mined watersheds (including the 27-ha watershed studied by Negley and Eshleman, 2006), but using a curve number approach. All studies reached similar findings: the mined and partially mined watersheds exhibited increased storm event runoff and higher storm peakflows, when normalized to an area basis, but little difference in base flows compared to the unmined and forested controls. They attributed those effects to lower infiltration capacities of surface spoils, likely caused by surface compaction, and consequent infiltration excess overland flows. Ferrari *et al.* (2009) used a modeling approach to test the association between watershed mining disturbance within a larger (187 km^2) watershed area, and found that modeled storm-driven flood magnitudes increased linearly with increased mined areas. The authors suggest that mined areas exhibited hydrologic functions similar to urban landscapes with low infiltration capacities and high runoff potentials.

Working in West Virginia, Messinger (2003) found that per-unit-area peakflows from a mined watershed exceeded those from an adjacent unmined watershed for storms with rainfall rates >2.5 cm/h, but peakflows from the unmined watershed were greater for storms of lesser intensity. Data from the same study sites led Messinger and Paybins (2003) to conclude that nonstorm flows were approximately two times greater in the unmined watershed.

Wiley *et al.* (2001) surveyed 54 streams in southern West Virginia, measuring instantaneous streamwater discharge, delineating watershed areas, and quantifying VFs as fractions of watershed area. Several of the streams were also gauged for continuous streamflow measurement. Using models, they estimated 90% flow durations for ungauged streams and interpreted these results as indicators of base flows. In general they found 90% flow durations from streams draining watersheds with VFs to be greater than those of unmined watersheds. However, 90% durations from some VF streams did not differ from those of unmined watersheds. Working with three streams in the same area, Messinger and Paybins (2003) also found nonstorm flows to be greater in the two streams draining watersheds with mining, compared to the stream unaffected by mining.

Summary of Hydrologic Alterations

Conceptually, we can hypothesize a hydrologic system that can explain both increased peakflows (Bonta *et al.*, 1997; Messinger, 2003; Negley and Eshleman, 2006; McCormick *et al.*, 2009; McCormick and Eshleman, 2011) and higher base flows (Larson and Powell, 1986; Dickens *et al.*, 1989; Wiley *et al.*, 2001; Messinger and Paybins, 2003) that have been identified on surface mine lands in this region. Prior studies suggest that a range of factors interact to define the flow paths, processes, and response to a storm event of a particular site (Figure 4). These include the time since reclamation, soil construction methods, vegetation and soil development, subsurface flow path development, land surface form and slope, and rainfall intensity. During mining and just after reclamation using rock spoils for soil construction with smooth grading and compaction, infiltration excess overland flow may dominate and route much of a storm event flow off steep mined sites into lower streams (surface control point, Figure 3). This is most likely for high-intensity storms or very young mine spoils (Phillips, 2004) with little vegetation or subsurface flow-path development. However, older reclaimed mine sites with more advanced vegetation and soil development, and flatter reclaimed areas with surface ponding and potential for deeper, slower flow paths may route water deeper into the bulk-fill of the mining operation and may partially explain the observed higher base flows (subsurface control point, Figure 3). Reduced ET on reclaimed mine sites, relative to mature Appalachian forests that dominate

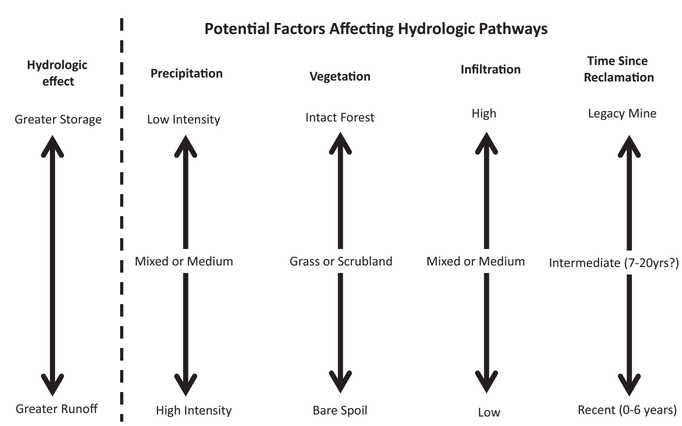

FIGURE 4. Conceptual Model Demonstrating the Potential Range of Hydrologic Effects of Surface Mining Based on Example Site Conditions.

the region's nonmined landforms, may also contribute to the higher base flows.

It is possible that a mined site could also exhibit both increased peakflows and increased base flows compared to native conditions, depending on precipitation intensity (Figure 4). Murphy *et al.* (2014) demonstrate this possibility. Working in eastern Tennessee, they found mined water quality-streamwater discharge hysteresis response varied with storm intensity. They interpreted this finding to indicate differences among flow paths activated by storms of differing intensities.

The interaction of land use types and spoil conditions is poorly understood, particularly at larger scales (Zegre *et al.*, 2013), but assessing these interactions is an important step in understanding the impacts of surface mining and reclamation methods on surface hydrology and water quality in higher order streams and rivers, which is often a great concern to the public. The reviewed studies suggest that watersheds with greater areas of young, steep, mine lands with little vegetation and compacted mine soils exhibit greater storm responses and higher peakflows compared to unmined watersheds. Watersheds with older mine areas, less compacted soils, and with better infiltration may actually have increased hydrologic storage in their headwater areas compared to watersheds with native geology, resulting in less potential for increased storm flows and greater potential for higher base flows.

RESEARCH NEEDS

Soil Development and Effects on Hydrologic Flow Paths

Most of the reviewed studies found that surface mining for coal in the Appalachian region has the potential to increase stream peakflows and reduce storm response lag times. However, these studies have been conducted at only a few locations, and reclamation practices at those locations may not be representative of predominant practices throughout the wider region. More research is needed to determine if these effects are consistent across the region and how they might vary with reclamation practices.

Mine spoil selection for soil construction is one reclamation step that may affect the hydrology of a mined landscape and the conceptual control points that we have proposed. Guebert and Gardner (2001) and Ritter and Gardner (1993) demonstrated that infiltration capacities comparable to unmined landscapes developed on mine soils within four years of mine soil establishment. However, these studies were conducted on mine soils constructed using salvaged soil and forest floor organic material. Mine soils constructed from compacted rock spoils may have lower infiltration capacities over extended periods (Simmons *et al.*, 2008). Taylor *et al.* (2009) demonstrated that fresh loosely graded mine spoils have infiltration capacities that are adequate to absorb most precipitation events. These materials, however, were coarsely textured (predominantly sandstones) with coarse fragment contents >70% upon initial placement (Angel, 2008). Several other studies have observed increased hydraulic conductivities in mine spoils relative to native geology caused by presence of rocks and associated macropores and voids (Rogowski and Weinrich, 1981; Ward *et al.*, 1983; Guebert and Gardner, 2001).

Compounding this uncertainty, it is clear that physical properties of mine soils can change over time. Rock materials used to construct Appalachian mine soils weather with time (Ciolkosz *et al.*, 1985). In soils constructed using both sandstones and siltstones, increased fractions of <2 mm fines were observed over three years and attributed to continuing physical breakdown of rock materials (Roberts *et al.*, 1988b). Fine particles have been observed to redistribute (Rogowski and Jacoby, 1979) and fill voids (Roberts *et al.*, 1988a) in young, uncompacted mine soils. Mine soils constructed from rock spoils, when loosely placed, undergo physical settling and consolidation (Rogowski and Jacoby, 1979; Roberts *et al.*, 1988a; Miller *et al.*, 2012), as commonly occurs in disturbed soils more generally (Toy *et al.*, 1999). The physical consolidation that follows spoil placement on mine sites (Wunsch *et al.*, 1996) is consistent with well-known geotechnical processes governing behavior of disturbed geologic materials (Wickland and Wilson, 2005) and is consistent with processes that have been documented to occur in certain natural soils on nonmine landscapes (Bryant, 1989; Assallay *et al.*, 1998). Working in Britain, Haigh (1992) and Haigh and Sansom (1999) found that the physical disintegration of spoil materials combined with physical settling and consolidation, a process they termed as autocompaction, increased soil density, and influenced hydrologic properties. To our knowledge, effects of uncompacted mine spoil particle redistribution and physical consolidation on hydrologic properties of mine soils have not been studied in Appalachia.

Though one study noted potential development of subsurface storm flow (Guebert and Gardner, 2001), there has been little research addressing if, when, or how this flow path develops in mine soils. Such development would require that the near-surface zone would have greater hydraulic conductivity than materials immediately below, such that near-surface spoil would become the preferential flow path for infiltrating waters relative to the bulk-fill. It is possible that these conditions could develop through time in an uncompacted mine soil as a result of (1) organic matter accumulation and soil structure formation within the near-surface zone, (2) plant rooting, (3) downward movement of soil fines to restrict permeability, and (4) physical settling and consolidation of mine spoil materials beneath the near-surface hydrologic zone. However, neither the occurrence of such processes nor the time required for such processes to occur (if they occur) has been documented. Similar processes have been found to occur in certain natural soils over long time periods (Bryant, 1989). It is also not known if these mechanisms will lead to development of a near-surface hydrologic zone with adequate porosity and depth to mitigate the elevated stream peakflows and reduced lag times in storm flow that can occur in headwater streams draining Appalachian mine sites.

Terrestrial Ecosystem Reestablishment

After passage of SMCRA, many mining operations inadvertently shifted toward heavily compacting reclaimed lands, which had unintended consequences for hydrology and plant growth potentials. Spoil compaction has been common on Appalachian surface mines in the past (Angel *et al.*, 2005; Simmons *et al.*, 2008) and it is a potential mechanism for shifting hydrologic flow paths to surface flow caused by precipitation exceeding infiltration capacity. We did not locate an inferential study on mine lands that confirms this hypothesis, but it is consistent with known scientific principles. Several studies have shown that mine soil placement practices that avoid or minimize compaction can enhance mine soil infiltration capacities (Taylor *et al.*, 2009b) and reduce runoff (Hoomehr *et al.*, 2013).

Recently, in the Appalachian mining region, there has been a shift toward reclamation practices intended to establish native forests on reclaimed mine lands. In particular, a set of reclamation methods collectively termed the Forestry Reclamation Approach (Burger *et al.*, 2005), that prescribe ≥1.2 m of noncompacted weathered spoil or topsoil on top of the bulk-fill, are being adopted by some mining firms (Zipper *et al.*, 2011b). Although this reclamation method has been implemented primarily to improve survival and growth of planted trees and volunteering vegetation (Burger *et al.*, 2005), it may also promote infiltration into surface spoils (Taylor *et al.*, 2009). Researchers expect that salvaging native soils, including soil organic matter, roots, and woody debris, along with underlying subsoil and weathered rock, and spreading those materials during reclamation for use as mine soils, will improve both forest reestablishment and mitigation of hydrologic impacts on mine sites (Skousen *et al.*, 2011; Zipper *et al.*, 2013). However, effectiveness of these techniques for mitigation of hydrologic effects has not been documented.

Hydrology and Water Quality Interactions

Impacts to hydrologic flow paths and processes in mined watersheds may have interactions with water quality parameters such as total dissolved solids (TDS). For example, deeper flow paths that penetrate into the bulk-fill of a mined area have potential to allow longer contact time with TDS-generating spoil, which may produce discharge with elevated TDS levels (Murphy *et al.*, 2014). Recently, there has been a focus on understanding and managing TDS draining from mines in the Appalachian region (Daniels *et al.*, 2013; Evans *et al.*, 2014), but there has been little research addressing the inherent interaction of hydrology and TDS production and delivery to streams draining mined watersheds.

Mine reclamation methods intended to mitigate changes to hydrologic flow paths and regimes of watersheds may also help to mitigate water quality impacts. Use of native soils and weathered spoils to produce a surface medium, and spoil placement methods to restrict water movement from the surface materials into the bulk-fill, can be expected to contribute to this outcome. The weathered spoils that are favorable for reforestation (Zipper *et al.*, 2013) also tend to be low in TDS-generation potentials relative to unweathered spoils (Orndorff *et al.*, 2010; Daniels *et al.*, 2013), as are native soil materials. Establishment of productive tree cover on mine spoil fills can be expected to increase ET, removing waters from the near-surface hydrologic zone and thus reducing flow into the bulk-fill where exposure of unweathered spoil materials would generate elevated TDS through interaction with water (Sena *et al.*, 2014). Because of public and regulatory concerns with water quality impacts to streams below mining operations (Copeland, 2013; USEPA, 2013), there is a need to develop mine reclamation practices that will enable reduced TDS in mine water discharges. Improved scientific understanding of mined-land hydrologic processes will be integral to such efforts.

Landscape Structure

Mine spoil fills can be constructed using loose-dump methods with spoil dumped from above or by placing material in layers (1-20 m) that are compacted by mining equipment operations as a means of maximizing stability of constructed landforms. Research has demonstrated that groundwater flows within mine spoil fills are commonly influenced by existence of cavities formed by large rock fragments that can act as conduits for water flow (Hawkins and Aljoe, 1992; Hawkins, 2004). VFs are commonly constructed from durable rock materials using loose-dumped methods that are intended to produce such cavities near the fill base as a means of accelerating movement of groundwater out of the fills (Miller and Zegre, 2014). The extent to which the existence of such cavities within loose-dumped durable-rock fills leads to shorter flow paths and quicker stormwater discharge has not been studied, nor has the potential for layered fill construction to mitigate such accelerated flows if they are occurring.

An additional but unstudied factor that could lead to increased water storage on mine lands is related to Meerveld and McDonnell's (2006) fill and spill theory. Mine pits that are filled and buried by mine spoils have the potential to store water in their void space. This water would have little potential to leak out of the bottom of the pit floor through the intact bedrock below. Hence, subsurface flows could be stored until the pit filled and began to release this water. However, we could find no research that addressed this potential storage mechanism directly, nor could we find any studies that explain the patterns of discharge that they observed using the fill and spill theory.

Landscape Form

Potentials for restoration of hydrologic processes on mined areas may also be influenced by landscape form. The original contour of the landscape can be considered as an optimal hydrologic form for the unmined geologic structure in highly weathered and stable landscapes such as Appalachia (Toy and Chuse, 2005). Geomorphic reclamation methods seek to produce post-mining landscapes that replicate natural conditions (Toy and Chuse, 2005). Modeling studies suggest that geomorphic reclamation approaches to manage excess spoil disposal may reduce the hydrologic consequences of coal surface mining in Appalachia (Quaranta *et al.*, 2013; Snyder, 2013), but the hydrologic effectiveness of such approaches have not been demonstrated in the field. Additionally, such approaches are challenging in Appalachia because of needs for excess spoil disposal while also reconstructing contours of naturally steep terrain.

Mitigation of Mining Impacts on Hydrology

We found few studies that directly address mine reclamation practices to restore pre-mining hydrologic flow paths or mitigate hydrologic impacts of surface coal mining in the Appalachian region. One can speculate that such practices might include construction of landforms that more closely mimic the general form of the pre-mining terrain, reconstructing a surface medium that allows for infiltration, restricting water movement into the bulk-fill, and re-establishment of native forest plant communities on those mine soils. However, effectiveness of such practices at restoring or simulating native flow paths on unmined landscapes, and thus reducing hydrologic impact on mine lands, has not been assessed.

Effects of time on hydrologic processes of mine lands are also poorly understood. The information reviewed above can be interpreted to suggest that the passage of time will be accompanied by return of some degree of hydrologic function on many mine soils, particularly those where potential for restoration has not been irreparably damaged by excessive soil compaction. For example, several studies have documented soil infiltration capacities that approach natural conditions with increasing time (e.g., Guebert and Gardner, 2001). Also, development of mine soil properties, including organic matter content, that more closely resemble those of natural soils has been thoroughly documented (Haering *et al.*, 1993). Although these findings suggest some level of hydrologic function return with the passage of time on natural landforms with uncompacted mine soils and productive native vegetation, such effects have not been studied directly. Similarly, application of reclamation and mitigation practices for the purpose of accelerating hydrologic restoration has not been studied directly.

SUMMARY AND CONCLUSIONS

Here, we reviewed hydrology studies on surface coal mine lands. In general, the studies indicate that peakflows often increase and storm-flow lag times decrease on freshly reclaimed mine lands, and on older mine lands with compacted soils. Research at the plot scale suggests that surface hydrologic flow paths are not stable for the years directly after mining ceases and reclamation is completed. Rather, there can be an evolution of new and abandoned flow paths that develop and change as the spoil or site characteristics change in response to mining and reclamation, and the hydrologic processes shift toward a new equilibrium. Most reviewed studies found reduced infiltration capacities, elevated peakflows, and/or more rapid runoff from mine sites, relative to unmined forested areas, occur when conventional post-SMCRA reclamation processes are used. Some studies attributed these results to soil compaction caused by mine reclamation practices. Other studies demonstrated development of increased infiltration capacities with time and consequent alteration of hydrologic flows in mine soils constructed using salvaged soil mixed with mine overburden, resulting in decreasing peakflows and increasing lag times. This suggests that surface mining can increase the potential for quicker and greater storm responses in streams below mining operations. However, mined sites with established vegetation, soils that are uncompacted with high soil C and soil structure, and improved infiltration are expected to reduce the level of hydrologic impacts caused by mining, compared to unmined conditions by shifting flows from the surface control point to the subsurface control point. These approaches are compatible with other practices that are intended to improve impact mitigation on coal surface mining such as reestablishment of forest vegetation and improved water quality mitigation. Even within the range of these expected responses, there will be high variability caused by site-specific factors that are poorly understood. Future reclamation practices that minimize short-term hydrologic effects while producing hydrologic flow paths that resemble those of unmined landscapes in the Appalachian Mountains will require improved understanding of the hydrology of mine lands. Research on development and function of hydrologic flow paths on mine lands is critical to developing mitigation strategies for past, current, and future mining operations.

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