Catena 139 (2016) 241–249

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Vegetation influences near-surface hydrological characteristics on a surface coal mine in eastern USA

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ARTICLE INFO

Article history:
Received 15 September 2015
Received in revised form 4 January 2016
Accepted 5 January 2016
Available online 16 January 2016

Keywords:
Reclamation
Surface coal mining
Subsurface flow
Dye tracer
Infiltration

ABSTRACT

Mining processes alter natural landscapes worldwide, and methods for restoration of mined areas are widely studied. Establishment of vegetation is essential to mined land restoration. Prior research has addressed vegetative influence on erosion and runoff, but effects of vegetation type on surface hydrologic processes are less studied. We measured infiltration rates and observed subsurface flow paths in mine soils on a reforested area and a grassed area on a former surface coal mine in the eastern United States. The two areas were constructed and reclaimed fourteen years prior to our study using processes similar in all aspects except vegetation. MiniDisk tension infiltrometers and Brilliant Blue FCF dye staining analyses were utilized to evaluate near-surface flow processes in the vegetated mine soils. Mean infiltration rates were 16.5 ± 10.7 cm h^{-1} and 10.4 ± 7.7 cm h^{-1} for the reforested and grassed areas, respectively. Infiltration rates, hydraulic conductivities, dye coverage, and dye stained areas were significantly higher in the reforested area. The grassed area had constant dye coverage with depth but more flow paths than the reforested area. A transition from vegetation-controlled subsurface flow to abiotic-control at greater depths was evident in the stained soil profiles. Results highlight the heterogeneous nature of mine soils and the influence of vegetation type in development of mine soil hydrologic processes.

1. Introduction

Surface mining for ores and minerals disturbs landscapes and influences water resources in many world regions (Atanackovíc et al., 2013; Younger and Wolkersdorfer, 2004); thus methods for restoring environmental quality on mine sites are widely studied. Vegetation establishment is commonly viewed as essential to restoration of environmental quality on mine sites (Barnhisel et al., 2000; Bradshaw and Chadwick, 1980). Furthermore, the presence of suitable and productive vegetation is often necessary for economic post-mining land use and the development of viable post-mining ecosystems, and is generally required for legal compliance (Cao, 2007; MacDonald et al., 2015; Skousen and Zipper, 2014).

The establishment and development of vegetative cover on mine sites also contribute to restoration of hydrologic processes, including infiltration capacity (Jorgensen and Gardner, 1987; Loch, 2000; Moreno-de las Heras et al., 2009; Parr and Bertrand, 1960) and erosion control (Carroll et al., 2000; Duran-Zuazo and Pleguezuelo, 2008; Moreno-de Las Heras et al., 2009; Ritter and Gardner, 1993). Mechanisms associated with these effects include those which have been observed on natural soils, including soil organic matter accumulation and soil aggregation (Bronick and Lal, 2005), the inhibition of soil crusting (Awadhwal and Thierstein, 1985), and development of subsurface channels in association with plant rooting (Beven and Germann, 1982; Sidle et al., 2001). Despite these well-known beneficial effects of vegetation on surface hydrologic properties, few studies have described how hydrologic influences differ among vegetation types on the highly disturbed landscapes that constitute reclaimed mines.

Coal surface mining typically disturbs large amounts of earth materials. Following coal extraction, the disturbed materials are placed back on the mined surface as “mine spoil”, which is often shaped to a post-mining landform and then vegetated. With plant community development and weathering, the surface-applied spoils develop into mine soils over time (Haering et al., 1993; Roberts et al., 1988; Sencindiver and Ammons, 2000), and associated soil hydrologic properties and processes change over time with mine soil development (Guebert and Gardner, 2001; Jorgensen and Gardner, 1987; Ritter and Gardner, 1993).

Studies on mine soils have shown that soil and hydrologic properties are not static, but develop over time, and in association with the plant community. Plant communities change after initial revegetation of unmanaged mine areas, as unplanted species invade, become established, and grow (Fields-Johnson et al., 2012; Holl, 2002). As mine soils age, plant communities develop and plant rooting extends deeper, influencing mine soil properties (Akala and Lal, 2001; Haering et al., 1993; Roberts et al., 1988; Rodrigue and Burger, 2004). Although typically constructed from raw rock fragments with little to no prior vegetative influence, mine soils develop identifiable horizons and structure within several years after placement (Roberts et al., 1988;

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http://dx.doi.org/10.1016/j.catena.2016.01.004
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Sencindiver and Ammons, 2000), and that development continues as time progresses (Ciolkosz et al., 1985; Thomas et al., 2000).

Soil hydrologic properties can also change in the years following reclamation and hence, in association with the plant community and soil morphology. On surface coal mines in eastern USA, infiltration capacities increased with time in the years following reclamation (Jorgensen and Gardner, 1987; Ritter and Gardner, 1993), while increasing soil porosity and macropore and structural development were also observed to occur (Guebert and Gardner, 2001; Jorgensen and Gardner, 1987). Although reduced infiltration and greater storm runoff commonly occur on mined landscapes relative to natural systems (Biemelt et al., 2005; Moreno-de las Heras et al., 2009; Negley and Eshleman, 2006; Simmons et al., 2008), with time, mined landscapes may evolve to have decreased runoff and higher sustained baseflow, (Griffith et al., 2012; Guebert and Gardner, 2001; Ritter and Gardner, 1993), or have less stream discharge overall due to increased evapotranspiration associated with plant community development (Sena et al., 2014).

Mine soil hydrologic changes include the development of subsurface flow paths over time. In native soils, typical subsurface flow processes include matrix flows and/or preferential flows, which can be observed in soils using dyes and tracers (e.g. Anderson et al., 2009; Weiler and Flühler, 2004). Previous studies have observed that both matrix and preferential flows are also common in mine soils. In 16 year-old forested German lignitic mine soils, iodine staining showed that preferential "finger flow" paths were common in the subsurface within the upper 60 cm of soil (Hangen et al., 2004; Hangen et al., 2005). Dye stainings also showed preferential flow paths common along coarse-fragment surfaces and through macropores in Appalachian mine soils with herbaceous vegetation (Guebert and Gardner, 2001). These prior studies, however, did not determine if or how infiltration and subsurface flow differed or were influenced by vegetation type.

The benefits of mine-site revegetation for purposes of surface stabilization, erosion control, and post-mining land use are well-known. We expect that the plant communities established during and following reclamation influence mine soil hydrologic development as well, but those relationships have not been well-studied. Few studies have documented subsurface flow patterns occurring in mined landscapes and even fewer have documented influences on mine soil hydrologic properties and processes by vegetation type. As mining disturbances expand globally, improved scientific understanding of how surface vegetation influences the hydrology of reclaimed mine landscapes can aid restoration of such areas.

In this study, two areas on a surface mine in Central Appalachia, USA, reclaimed with similar reconstruction techniques but differing vegetation were studied to compare hydrologic properties and processes on reclaimed landscapes. Specifically, mine soil infiltration rates, hydraulic conductivities, and subsurface flow paths in the contrasting vegetated areas were analyzed. Results from this study can inform reclamation scientists about the hydrologic development of reclaimed landscapes and the influence of vegetative cover on these processes over time.

2. Materials and methods

2.1. Study area

The study area is located in Wise County, in the Appalachian Plateau geologic province of Virginia, USA (Fig. 1). The dominant geology is the Pennsylvanian-age Wise Formation, consisting of horizontally oriented sandstones, siltstones, shales and coal seams (Nolde et al., 1986; Haering et al., 2005) that are typically low in pyritic sulfur (Howard et al., 1988). Two areas of contrasting vegetation were identified on the mine site: a fully grassed hillslope and a reforested hillslope (Fig. 2). Both areas were constructed in 2000 and reclaimed by applying a topsoil substitute of mixed sandstone and shale over a reconstructed slope comprised of undifferentiated ("run of mine") spoil. Grading techniques were applied as advised by university researchers, and consisted of end-dumping spoils into closely-spaced piles, then using a dozer to lightly-grade the material to a thickness of 1.2 to 1.8 m (Sweigard et al., 2007). The experimental areas occur on the same reconstructed landform, have a south-facing aspect, are separated by ~500 m, and were reclaimed contemporaneously. The two areas also have similar ages, climates (mean annual rainfall of 120 mm), spoil types, and aspect; thus the main difference between the two areas is vegetative cover.

The grassed area (Fig. 2) was vegetated using traditional reclamation grasses and legumes in ~2001. The conventional seeding mix used on this mine site includes the following grasses: orchardgrass (*Dactylis glomerata*), perennial ryegrass (*Lolium perenne*), redtop (*Agrostis gigantean*), and weeping lovegrass (*Eragrostis curvula*) and the following legumes: birdsfoot trefoil (*Lotus corniculatus*) and ladino clover (*Trifolium repens*). Because the seeded grasses tend to dominate in the years following reclamation, this site is described as "grassed". However, the slopes are now fully covered with a herbaceous cover that is dominated by sericea lespedeza (*Lespedeza cuneata*). Autumn olive (*Eleagnus umbellata*) and black locust (*Robinia pseudoacacia*), which established as volunteer species, are also present, but sparse, in the grassed area. To limit the influence of trees on results in the grassed area, field experiments were conducted in locations away from the influence of these volunteers. The grassed area had 100% vegetative cover, and the average slope was 45% (Table 1). Soil texture of nine samples was estimated in the field using "texture-by-feel" analyses (Thien, 1979), and consisted of coarse sand to silt loam with most soils consisting of a loamy texture.

The reforested area (Fig. 2) was initially grassed in ~2001 and then planted in early 2002 with a mix of native hardwood trees including the following: tulip poplar (*Liriodendron tulipifera*), white oak (*Quercus alba*), Northern red oak (*Quercus rubra*), chestnut oak (*Quercus prinus*), sugar maple (*Acer saccharum*), and white ash (*Fraxinus Americana*) that have grown well and are creating a woody plant community with a closed canopy in some places. Visible estimations of non-woody vegetative cover in the reforested areas ranged from 40 to 100% cover, with an average slope of 50% (Table 1). Field-estimated soil texture (Thien, 1979) of nine samples ranged from fine sand to silt loam, with most soils having a sandy loam texture.

2.2. Field experiments

2.2.1. Tension infiltration

Each area (~100 m × 100 m) was measured and divided into thirds vertically and across the slope to establish a grid for sampling transects. Cross-slope transects were established near the center of each area's upslope, midslope, and downslope segments, and vertical-slope transects were established on the right, middle, and left side of each area. Nine sampling locations were established for each slope position, three on each transect. Individual sampling locations will henceforth be referred to by transect and location (i.e. Reforested Upslope-Left, Grassed Midslope-Right, etc).

To control for antecedent moisture conditions, the infiltration tests took place over a two day rainless period (7/16/2014–7/17/2014), two days after a 10 mm rain event. Before conducting the infiltration tests, herbaceous vegetation was cut to the top of the organic soil horizon (O horizon) carefully as not to disturb soil structure. Soil O horizons were thicker in the reforested (3–7 cm) than in the grassed areas (0–5 cm) on average, but were removed from all sampling areas prior to the infiltration tests because they did not provide solid contact layers. Mini Disk tension infiltrometers (Decagon Devices, Inc.) with 4.5 cm disc diameters were used for the infiltration tests. A total of 54 infiltration tests were completed on the two areas (27 individual tests per vegetation type). A suction of −2 cm was consistently used for all infiltration tests and the drop in water level in the water chamber was manually recorded every 30 s until steady-state conditions were achieved. The tension infiltration test was repeated three times at

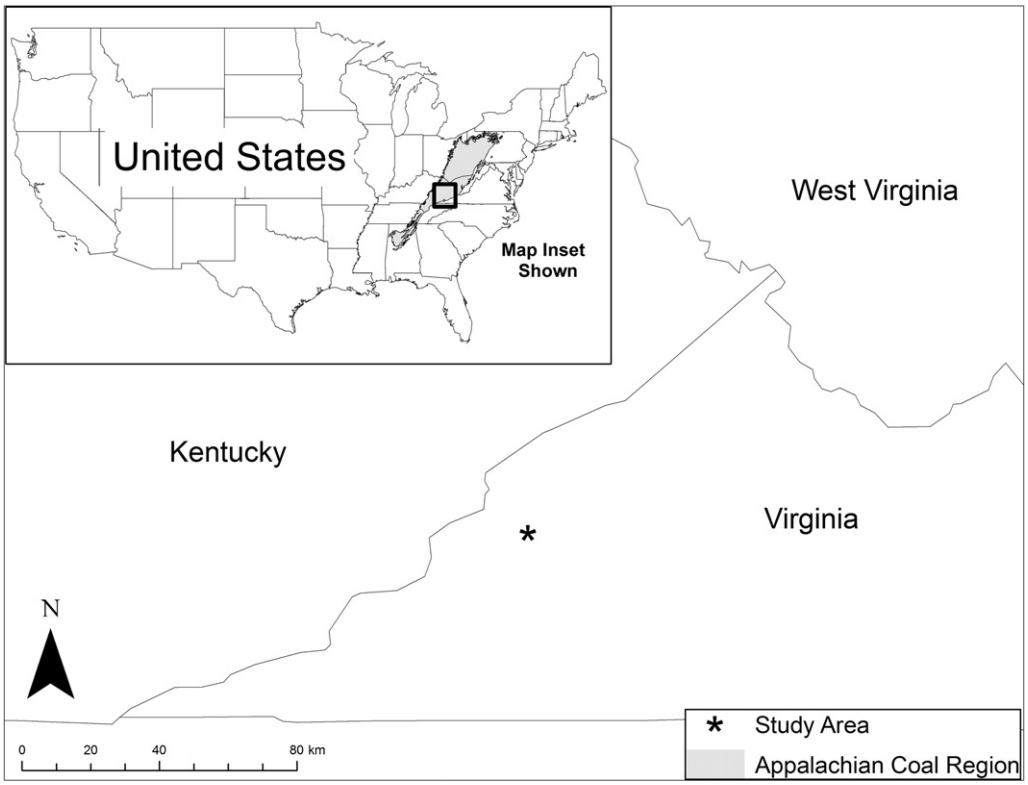

Fig. 1. Location of the study area in southwestern Virginia, USA. The Appalachian coalfields of the United States are shown in gray.

each sampling point by moving the infiltrometer approximately 50 cm laterally along the slope. Cumulative infiltration (I) was calculated using the method of Zhang (1997) and Eq. (1):

$$I = C_1 t + C_2 \sqrt{t} \tag{1}$$

where I is cumulative infiltration, C_1 (m s^{-1}) is a parameter related to hydraulic conductivity (k), C_2 (m s^{-1}) is a parameter related to soil sorptivity, and t is the time interval. The parameter C_1 was then used to calculated k in the following equation:

$$k = \frac{C_1}{A} \tag{2}$$

where C_1 is the slope of the curve of I vs $\sqrt{t}$. The parameter A is a value related to the suction rate and infiltrometer disk radius corresponding to van Genuchten parameters for a soil type and was calculated using the equations detailed in Zhang (1997) and Decagon Devices (2014).

2.2.2. Dye staining experiment

Three dye staining experiments were conducted on each vegetated area: one each at the upslope, midslope, and downslope positions. Brilliant Blue FCF (BB) dye was chosen for this study due to its good visibility in soils, low toxicity, low sorption, and transport properties similar to water (Flury and Flühler, 1995). An apparatus was used to apply a dye solution to the reclaimed soil surface (Fig. 2). The apparatus is a wooden structure ~1 m long by ~0.5 m wide that has extendable/retractable legs on one end. The top of the apparatus is placed on the ground and the bottom of the apparatus with the extendable legs is placed downslope, then the legs are adjusted to level the dye application vessel, and clamped. A 62.5 L plastic bin (500 by 350 cm, in the horizontal

Fig. 2. The left photo is of the reforested area and the right photo is of the grassed area. Both photos show the dye staining apparatus in place during a dye staining experiment.

Table 1
Descriptions of site conditions.

Vegetation type	% cover[a] range	% cover mean	Slope (%) range	Slope (%) mean	Soil and surface description
Reforested	40–100	75	40–65	50	Silt loam to fine sand, thick leaf litter, coarse fragments
Grassed	100	100	30–50	45	Silt loam to coarse sand, very rocky, no leaf litter

[a] Herbaceous cover.

dimension) with 2 mm diameter holes drilled into the flat bottom in an equidistant grid was placed atop the apparatus and leveled to ensure even dye distribution on the surface. For each application, a total of 32 L of dye solution at a concentration of 4 g L^{-1} was poured into the plastic bin. The dye solution emerged from the drilled holes, falling directly onto the soil surface over a period of 10–15 min, and was allowed to infiltrate for 1 h.

The application site surface was then excavated, beginning 2 m downslope from the lower edge of the application area and gradually moving upslope until the BB dye was found. Once BB dye was found, a soil profile was excavated. After completing the first soil profile, the application area was excavated upslope in equal distances in order to create four soil profiles total. For example, if dye was found 100 cm downslope of the application area, soil profiles were produced at 25, 50, 75, and 100 cm downslope from the dye application area. To prepare a profile, the subsurface was carefully excavated by hand to prevent the disturbance of soil structure, then a flat tool was used to carefully scrape away excess material that may have filled in voids or macropores during excavation. The soil profile was extended laterally and vertically until a 30 × 30 cm wooden frame with an internal grid could be placed flat against the profile with the top of the frame aligned with the soil surface. An opaque plastic sheet was placed above the application area to reduce the interference of sunlight and associated shading with the profile. The profile was then photographed from a distance of 1 m using a Nikon Coolpix digital camera. Extensive field notes and observations were taken to ensure accurate and precise digitization of the dye movement. If dye was found deeper than the 30 cm frame, the site was excavated deeper, if possible using hand tools with moderate effort, and a second profile was prepared beneath the top profile.

2.3. Data analysis

The digital images were uploaded and cropped to the edge of the wooden frame, then imported into the photo editing software Image J, a Java-based open-source image processing program (Abràmoff et al., 2004). First, the number of pixels within the frame was determined and used to set the scale (i.e. n pixels = 30 cm) for converting the photo to field-scale measurements. The color threshold of the image was adjusted to exclude all non-blue colors, then double-checked with the detailed field notes to ensure consistency. The image was then converted to an 8-bit color palette, changing all colors except blue into grayscale. The area of dye was measured using the "Measure Particles" tool, producing an output of dye coverage area in the profile recorded in x–y coordinates. The x–y output data was then broken into four equal-depth bins of 75 mm (depth quartiles), as per the wooden frame's internal grid. The area of dye within each depth quartile was calculated and used to produce profiles of dye coverage with depth. Each distinct dye-stained area was identified by the software; these were tallied by mid-point depth, depth-quartile, and area. If a stained area was bisected by the wooden frame's internal grid, the individual pieces were tallied as separate areas. Each separately dye-stained area was interpreted to represent a flow path. Mean numbers of flow paths per depth quartile were calculated by determining the number of separately stained areas in 5 mm horizontal segments, then averaged over the depth quartiles. Lastly, the stained areas were ordered by size; and those stained areas within the top 5% (95th quantile) by area were analyzed separately to investigate patterns of stained area size with depth.

2.3.1. Statistical analysis

All statistical analyses were completed using the software JMP (v. 11.0, SAS Institute: Cary, N.C.) and R (R Core Team, 2013). For the infiltration tests, outliers were identified using the Generalized Extreme Studentized Deviate (ESD) test for multiple outliers (Rosner, 1983) and those values considered outliers statistically were omitted from further analyses. All identified outliers were high values. A Shapiro–Wilk test was used to confirm non-normal data. Mann Whitney tests were used to test for statistical differences between the reforested and grassed areas for mean infiltration rates, numbers of flow paths, and dye-stained areas. A Steel–Dwass test was also utilized to identify any statistical differences among infiltration rates and dye stainings based on the within-area locations (upslope, midslope, and downslope). Regression analysis was used to test variables such as the numbers of flow paths and mean patch-size areas for significant trends with depth in the dye profiles. All statistical tests were conducted at the $\alpha = .05$ significance level.

3. Results and discussion

3.1. Infiltration rates and hydraulic conductivity

Infiltration rates were highly variable in both the grassed and the reforested areas (Fig. 3), but most infiltration rates were <40 cm h^{-1}. There were no apparent infiltration-rate trends with slope location, but differences among slope locations were found. Of the nine locations tested on each vegetation area (each with three replicate infiltration rates measured and averaged) two major outliers occurred, one in each vegetated area (Fig. 3); all three data points at both outlier locations had infiltrations of >40 cm h^{-1} and were identified as outliers. These six data points skewed the data distribution; mean infiltration rates were 22.2 ± 19.6 and 21.4 ± 31.8 cm h^{-1} for the reforested and grassed areas, respectively. The measured infiltration rates of these outliers are greater than typical infiltration values observed in soils. The heterogeneous nature of mine soil materials with variable in-spoil hydraulic conductivities may have enabled water to be displaced from the infiltrometer quickly and account for outlying infiltration values. A

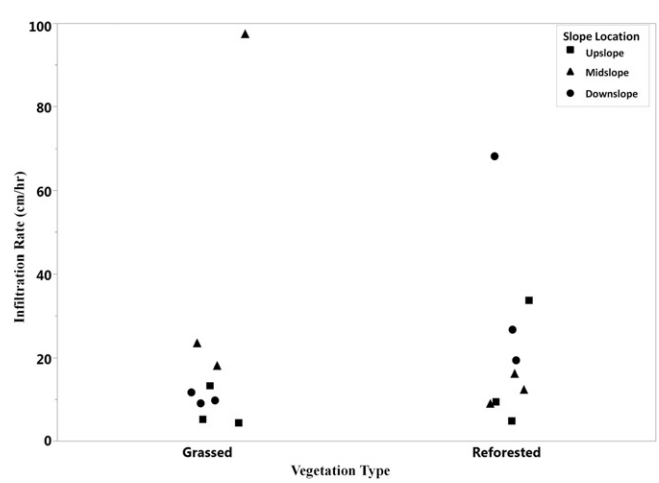

Fig. 3. Comparison of infiltration rates in the reforested and grassed areas. Each symbol is a mean of three infiltration tests.

matrix of large coarse fragments just below the soil surface may also account for the large infiltration values. Greer (2015) conducted a geophysical analysis of our sites and found high rock contents close to the surface in some areas, a finding that is consistent with our results. Wells et al. (1983) and Taylor et al. (2009) found that runoff from loosely placed Appalachian mine soils could not be produced by rainfall-runoff experiments due to high infiltration rates enabled by high rock contents of the materials.

High outliers were excluded from statistical comparisons as the likely cause for the outlying values is not influenced by vegetation. Excluding outliers, the reforested infiltration rates ranged from 1.4 to 38.2 cm h^{-1} and the grassed area infiltration rates ranged from 2.5 to 28.1 cm h^{-1} (Table 2). Mean infiltration rates were 16.5 ± 10.7 cm h^{-1} and 10.4 ± 7.7 cm h^{-1} for the reforested and grassed areas, respectively. Mean infiltration was more rapid on the reforested areas than on the grassed areas ($p < 0.05$), implying that vegetation influences infiltration rates on these loosely-graded mine soils.

Mean infiltration rates in both the reforested and grassed areas were greater than measured rates at other mine sites. Prior studies have shown infiltration rates ranging from 0.3 cm h^{-1} to 13.5 cm h^{-1} on Appalachian surface-mined sites, whereas forested references had measured infiltration rates ranging from 5.3 to 45 cm h^{-1} (Guebert and Gardner, 2001; Jorgensen and Gardner, 1987; Shukla et al., 2004; Simmons et al., 2008). In prior studies, the lowest infiltration rates occurred on the youngest mine soils (1–4 yr. old) comprised of a mix of soil and spoils that may have been compacted by mining equipment (Jorgensen and Gardner, 1987), and the highest infiltration rates occurred on the oldest mine soils (>25 yr) that had a topsoil amendment added to the mine soil surface and was reclaimed to hayland/pasture land use (Shukla et al., 2004). Reynolds and Reddy (2012) measured infiltration rates on different aged arid and semi-arid mine sites in Wyoming, USA and found that 5–15 year old plots had the smallest infiltration rates, whereas 20–25 year old plots had comparable infiltration rates to reference plots. The mine soils in our study were 14 years old and covered with a topsoil substitute that was loosely-graded for the purpose of avoiding soil compaction, promoting infiltration of water into mine spoils, and providing a suitable medium for vegetation re-establishment (Sweigard et al., 2002). Therefore, the difference in infiltration rates between this study area and other mine sites is likely a function of mine soil construction technique and time; however, it is also important to note that the difference in infiltration rates could be due to measurement technique, as studies have shown infiltration rates and hydraulic conductivity values are influenced by and are dependent on the methods used to measure infiltration (e.g. Mohanty et al., 1994; Reynolds et al., 2000).

Calculated hydraulic conductivities (k) ranged from 3.1×10^{-3} to 3.0×10^{-4} cm s^{-1}. Reforested area k-values ranged from 3.1×10^{-3} to 5.0×10^{-4} cm s^{-1} (mean = 1.47×10^{-3} cm s^{-1}) and are greater, on average, than those of the grassed area (range: 1.2×10^{-3} to 3.0×10^{-4} cm s^{-1}, mean = 5.70×10^{-4} cm s^{-1}). Hawkins (2004) measured saturated hydraulic conductivities of Appalachian mine spoils at depths below the influence of vegetation using monitoring wells, piezometers, and slug tests. Resulting values ranged from 4.45×10^{-9} to 7.58×10^{-3} cm s^{-1}. Our measured values are within that range, and our overall mean (1.47×10^{-3} cm s^{-1}) is similar to the mean values found by Hawkins (2004) (1.93×10^{-3} cm s^{-1}), and greater than the Hawkins (2004) minimum values. Higher k-values suggest that in-spoil water movement is in response to larger substrates, whereas a smaller k suggests flow through finer material and/or compacted zones with little void space due to spoil settling or in-filling of voids with smaller particles. Therefore, based on the limited range in magnitude and larger k-values measured in our study, it appears that a majority of near-surface flows in these mine soils are controlled by soil matrices with large particle sizes capable of transporting soil water through the mine soil rapidly.

K-values and infiltration rates in the two areas were highly variable, implying abiotic factors such as spoil type, degree of weathering and surface microtopographies are likely influential factors in the transport of rainwater into and through the subsurface. The variability of the results also highlights the highly disturbed and heterogeneous composition of mine soils at the hillslope scale, but also at the microscale. It is understood that the soil infiltration and hydraulic conductivity measurements in this study were measured at a microscale and covered a very small area on two reclaimed hillslopes, but similar observations within and between the vegetated areas indicate similar conditions throughout the reclaimed hillslopes. Both vegetative covers had mean infiltration rates greater than other mine sites, and no gullying or erosional areas were visible on either hillslope, indicating that the loose-grading technique was adequate for limiting runoff and erosion, and promoting rainwater infiltration into the mine soil on this mine site. Since the two vegetated areas were similarly reclaimed and controlled for abiotic factors such as age, reclamation technique and aspect, results indicate that the influence of growing trees significantly increases rainwater infiltration and transport of rainwater through the shallow subsurface relative to herbaceous vegetation effects.

Table 2
Infiltration rates and hydraulic conductivities in the reforested and grassed areas.

Test area	Infiltration rate (cm h^{-1})			Hydraulic conductivity (cm s^{-1})
	Range	*Median*	*Mean*[†]	*Mean*[†]
FOR-UP	1.4–38.2	9.0	16.0 ± 14.5[a]	0.00129
FOR-MID	5.7–22.7	12.6	12.6 ± 4.7[a]	0.00115
FOR-DOWN	10.8–32.8	23.7	23.0 ± 8.7[b]	0.00222
Reforested (all)			16.5 ± 10.7[*]	0.00147[*]
GR-UP	3.6–24.4	4.7	7.6 ± 6.8[a]	0.00055
GR-MID	8.6–28.1	14.4	16.0 ± 7.6[b]	0.00079
GR-DOWN	2.5–27.4	9.0	10.2 ± 7.7[a]	0.00045
Grassed (all)			10.4 ± 7.7	0.00057

[†] Test area mean values for each vegetated area followed by the same letter are not significantly different from one another.
[*] Designates experimental area means that are significantly greater than the other vegetated cover ($p < 0.05$).

3.2. Dye staining

Six dye stainings were applied at an upslope, midslope, and downslope location on each of the two vegetated areas. Four soil profiles were prepared for each of the six stainings, but only two profiles were able to be excavated below 300 mm. All other profiles were too compacted, too rocky, or both to be excavated below the 300 mm depth with moderate physical effort using hand-operated shovels and picks. In the data analysis that follows, only the ≤300 mm depth data are considered.

Both visual interpretations (Fig. 4) and data analyses reveal that most staining occurred within the profiles as distinct and separate areas, and those areas occurred in a wide range of sizes. Each stained area is interpreted as a cross-section of a separate flow path, but with no assumption of flow path orientation relative to the profile plane. The large contiguous areas were interpreted as matrix flows, and smaller stained areas with no contact by other dye stainings or those with a clear direction of travel were interpreted as macropore or preferential flows. Dye was present in a wide range of patch sizes, suggesting a gradient of flow mechanisms, and both matrix and preferential flows. Dye movement appeared to be controlled by factors such as heterogeneity of substrate materials and densities, voids, presence of variably-sized rocks (with preferential flows along their outer surfaces), and plant roots. Large stained areas suggestive of matrix flows occurred close to the soil surfaces in the profiles, with lower boundaries that appeared to be controlled by "contact zones" of dissimilar material, likely the bulk spoil that was used to construct the landform prior to application of the topsoil substitute.

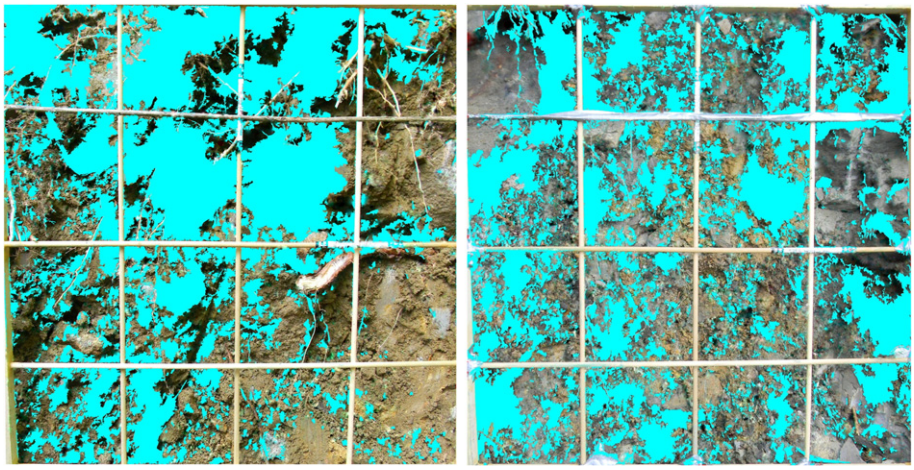

Fig. 4. Dye profile examples for the reforested (left) and grassed (right) areas.

Visible differences between the soil profiles influenced by the two vegetation types included the stained area distributions and the numbers of individual stains (Fig. 4). The reforested profiles typically had greater matrix staining near the top of the profile (Figs. 5 and 6) that transitioned to a preferential pattern with depth along coarse root channels and around obstructions (large rocks and voids) in the material. Evident in many of the grassed profiles were staining patterns consisting of small patches of dye that were randomly dispersed throughout the profile. In this type of dye movement, it appears the dye preferentially traveled through tiny cracks and pores in the spoil material with little interaction or exchange with the soil matrix. The dye-staining patterns appear to reflect the predominant rooting patterns of the two vegetation types. The grassed mine soils had a dense matrix of fine roots that appeared evenly distributed throughout the upper portions of the soil profile (top 5–10 cm on average, maximum 20 cm), whereas the reforested mine soils had fewer fine roots near the surface and had larger roots at depth in the subsurface.

The reforested dye staining profiles had <45–50% of soil stained at all depths, excluding one profile (Reforested-Midslope 2). The greatest dye coverage was in the upper 150 mm and generally decreased in coverage with depth. No reforested profiles had >30% of the soil stained below the 250 mm depth. Furthermore, a majority of the reforested profiles (8 of 12) exhibited declining dye coverage with depth ($p < 0.05$) (Fig. 5).

Like the reforested profiles, the grassed profiles had <50% stained area for all profiles. However, a majority of the profiles (10 out of 12) had no significant trend in coverage with depth, and only two profiles had a significant increase or decrease in stained area with depth ($p < 0.05$) (Fig. 5). Stained area coverage within the grassed profiles was variable with depth, and dye coverage changed by no more than 20% with depth in all the grassed profiles.

3.2.1. Flow path distributions with depth

There were significantly more flow paths in the grassed area than in the reforested area ($p < 0.001$) (Fig. 6), and the average numbers of flow paths in the reforested and grassed dye profiles, averaged over all depth quartiles (i.e. mean number of flow paths per soil profile), were 7.2 ± 4.8 and 12.7 ± 7.8, respectively (Table 3). In the grassed area, the average number of flow paths increased based on slope location; the

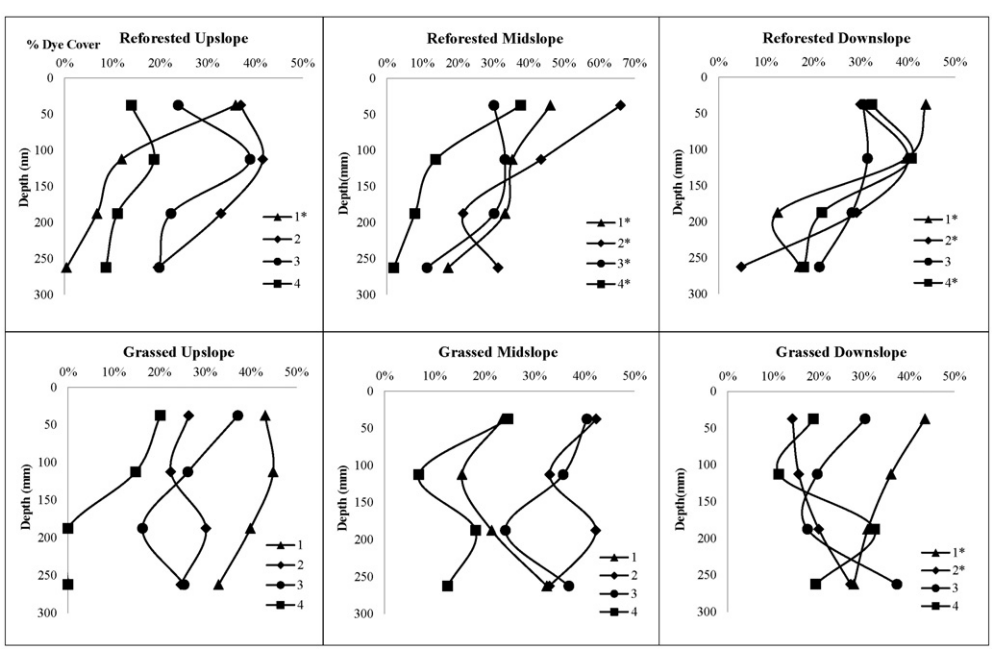

Fig. 5. Profiles of % dye cover with depth for the reforested and grassed areas. The legend represents the four soil profiles created at each staining from the most upslope (1) to the furthest downslope (4). Labels denoted with * in the legend indicate a significant trend in dye coverage with depth ($p < 0.05$).

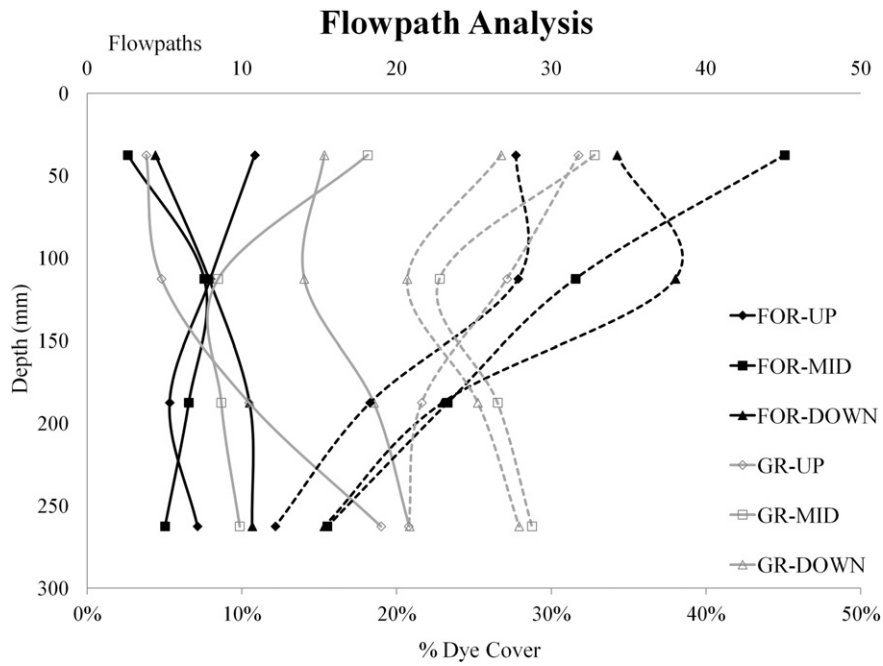

Fig. 6. Profiles of the number of flowpaths (solid lines) per depth quartile and % dye cover (dashed lines) for the reforested and grassed areas with depth.

upslope location had an average of nine flow paths, the midslope staining averaged 11 flow paths, and the downslope location averaged 17 flow paths overall. Similar trends were not present in the reforested area.

In the reforested stainings, dye coverage generally decreases with depth (Fig. 5), whereas the number of flow paths remains constant (Fig. 6). This pattern suggests that as dye moves deeper into the subsurface of the reforested area, flow paths narrow and become increasingly preferential with depth. The dye coverage and flow path patterns in the grassed stainings are variable with depth (Fig. 6), though regression analysis did not indicate a significant difference in the number of flow paths with depth. There were, however, significantly more flow paths overall in the grassed area in the 225–300 mm depth quartile (Fig. 6) than the reforested area ($p < 0.05$). Greater stained areas and more flow paths at depth in the grassed profiles suggest a different flow mechanism. In the reforested area, it is possible that coarse roots are extending deeper into the reforested mine soil and creating conduits for dye movement through the subsurface, enabling the dye to move preferentially through flow paths along the root system. In contrast, the lack of a dense root system at depth in the grassed area may lead to the dye spreading out into many flow paths through tiny voids and macropores in the subsurface, hence more flow paths occur overall in the grassed soil.

Table 3
Results of the dye staining analyses for the reforested and grassed areas.

Test area	Stained area range (% of profile area)	Stained area mean (% of profile area)†	Mean visible flow paths†	Individual stained areas†	
				Mean (mm^2)	*95th quantile* (mm^2)
FOR-UP	0.1–50.3	21.5[a]	7.8[a]	57.0[a]	859.0[a]
FOR-MID	1.9–74.9	28.9[a]	5.5[a]	60.6[a]	858.8[a]
FOR-DOWN	3.7–48.9	27.6[a]	8.4[a]	51.3[a]	802.8[a]
Reforested (all)		26.0	7.2	55.9***	837.6*
GR-UP	5.4–53.4	28.9[a]	9.5[a]	50.3[bc]	1100.7[c]
GR-MID	6.1–48.7	27.7[a]	11.3[ab]	34.0[ab]	702.2[ab]
GR-DOWN	8.3–50.9	25.2[a]	17.2[b]	22.8[a]	419.4[a]
Grassed (all)		27.3	12.7*	33.0	680.4

† Test area mean values for each vegetated area followed by the same letter are not significantly different from one another.
* Designates experimental area means that are significantly greater than the other vegetated cover ($p < 0.05$).
*** Designates experimental area means that are significantly greater than the other vegetated cover ($p < 0.001$).

3.2.2. Stained-area size distributions

A total of 14,670 unique stained areas were identified in the 24 soil profiles: ~5800 and 8800 individual stained areas for the reforested and grassed areas, respectively. The average sizes of the individual stained areas were greater in the reforested (55.8 ± 374.5 mm^2) than in the grassed (32.9 ± 248.9 mm^2) profiles (Table 3). Most of the individual stained areas were <25mm^2 for both the reforested (88%) and the grassed (90%) staining; the <25 mm^2 stainings occur at all depths in the profiles. In contrast, 338 of the total reforested and 336 of the total grassed stainings were ≥75 mm^2, representing the 95th quantile or largest 5% of total stained areas in the profiles.

We interpreted the largest individual stained areas as indicators of dye transfer through zones of matrix flow (if no apparent direction of movement was apparent), thus the distribution of the largest stained areas (95th quantile) was analyzed separately to evaluate the likelihood of large stained areas occurring at depth in the subsurface. The largest individual stain detected by our technique was 8953mm^2 in the reforested area and 9847 mm^2 in the grassed area. Larger stained areas may have occurred; but if so, their measurements were limited by the frame. Large stained areas occurred at all depths of the profiles in both vegetated areas; however, the largest stained areas occurred predominantly in the top quartile (0–75 mm). Regression analysis indicated a significant decrease in stained area with depth in the profiles ($p < 0.001$) of both the reforested and grassed profiles. The average stained-area patch size was significantly larger in the reforested profiles than in the grassed profiles ($p < 0.05$) (Table 3).

3.3. Summary

Both the infiltration and dye-staining analyses indicate clear differences between the grassed and reforested areas. In the grassed area, dense rooting systems in the top ~10 cm of soil correspond with apparent matrix flows, as revealed by the dye staining in the near-surface soil. Below the root-influenced soil in the grassed area, subsurface flow

patterns transition to apparent control by abiotic factors. The transition to abiotic-influenced transport of dye through the subsurface combined with the increased number of flow paths relative to the near-surface soil indicates that flow through the grassed mine soil becomes increasingly random through visibly disconnected flow paths with depth.

Dye staining patterns in the reforested areas differed from those in grassed areas, which we interpret as evidence for differing flow patterns. The presence of larger stained areas in the reforested mine soils indicates a prevalence of matrix flow; however, increasingly-preferential flow at depth indicates flow-path connectivity in the subsurface, likely in response to root penetration. Dye staining results are complemented by the reforested area's larger infiltration rates and hydraulic conductivity values, which imply that the reforested area is effective at promoting rainwater infiltration into and through the soil matrix.

The dye staining analyses highlighted the disturbed nature of mine soils, as flow was concentrated around voids and large rock fragments in the subsurface, and dye penetration below 30 cm was rare. Prior studies on mine soils have found differing subsurface flow patterns and shallower depths of dye penetration relative to native soils (Cey and Rudolph, 2009; Wang and Zhang, 2011). Hangen et al. (2004, 2005) reached similar conclusions in their study of German lignitic mine soils which found that subsurface flow paths are heterogeneous, both spatially and temporally, and are influenced by factors atypical of native soils (e.g. large coarse fragment content, high bulk density, compaction, soil repellency). Dye staining of eastern United States mine soils also found shallow dye penetration and subsurface flow predominantly along coarse-fragment surfaces and through macropores (Guebert and Gardner, 2001). Although differing morphologically from native soils, it is evident that the mine soils in this study enable hydrologic functions such as rainwater infiltration and associated reduction of overland flow, and downward water movement along developed pathways in the subsurface. Furthermore, these developed flow pathways likely evolved over time in response to vegetation establishment and growth. Hence, it appears that near-surface hydrological processes in these mine soils have been influenced increasingly by biotic factors with time and plant community development.

Hydrologic processes have evolved over time in both the reforested and grassed areas, as seen in the infiltration rates and subsurface flow patterns reported in this study. However, observed hydrologic differences between the two vegetation types indicate that vegetating mined land with trees may promote greater rainwater infiltration, enable faster soil matrix transport, and enhance subsurface transport via preferential flow paths, though these observed patterns may differ depending on factors such as rainfall intensity and duration, scale of measurement, and experimental methodologies. The findings of this study are consistent with well-known and documented influences by forest vegetation on natural landscapes (e.g. Beven and Germann, 1982; Lange et al., 2008; Liang et al., 2011). Trees planted in non-mined environments have been found to aid the development of soil structure and to enable increased infiltration and more effective transport of water vertically downward relative to herbaceous plants (Alaoui et al., 2011; Dexter, 1991; Oades, 1993); our study reveals that emerging forest vegetation has similar influences in a mined-land environment.

4. Conclusions

Infiltration capacities and subsurface flow patterns varied by vegetation type on an eastern United States mine site. Fourteen years after vegetation establishment on loosely-graded mine soils, infiltration rates and hydraulic conductivities were greater on areas revegetated with forest trees than on areas revegetated with grasses but now dominated by herbaceous vegetation. Flow path types and patterns also differed visually and quantitatively between vegetation types, indicating a likelihood that the mine soils developed differing hydrologic properties and patterns of subsurface flow in response to post-mining vegetation type. Future research should determine if the apparent vegetation-type influences on mine soil hydrologic properties observed here occur more widely, apply other soil imaging techniques and/or tracers to further describe and understand hydrologic influence differences among vegetation types, and determine if hydrologic properties and processes of mine soils that have been reforested successfully become similar to those of unmined forest soils with continued forest ecosystem development over time. Such research would assist in understanding deeper subsurface flow mechanisms beyond the scope of this study, as well as the influence of other vegetative covers on soil hydrologic processes, and thus improve the understanding of surface mine hydrology on a larger scale.

Acknowledgements

The authors would like to thank Dr. Robert Krenz for his gracious assistance with the infiltration and dye staining analyses, Kevin McGuire for providing infiltrometers, and Red River Coal Co. and Powell River Project for coordination and site access. The authors would also like to thank the three anonymous reviewers who assisted in manuscript improvement. This research was sponsored in part by the Appalachian Research Initiative for Environmental Science (ARIES) and the Virginia Tech Institute for Critical Technology and Applied Sciences (ICTAS). The views, opinions, and recommendations expressed herein are solely those of the authors and do not imply any endorsement by ARIES employees, other ARIES-affiliated researchers or industrial members. Funding for Carl Zipper's participation was provided in part, by the Virginia Agricultural Experiment Station and the Hatch Program of the National Institute of Food and Agriculture, U.S. Department of Agriculture.

References

Abràmoff, M.D., Magalhães, P.J., Ram, S.J., 2004. Image processing with ImageJ. Biophoton. Int. 11, 36–42.
Akala, V.A., Lal, R., 2001. Soil organic carbon pools and sequestration rates in reclaimed mine soils in Ohio. J. Environ. Qual. 30, 2098–2104.
Alaoui, A., Caduff, U., Gerke, H.H., Weingartner, R., 2011. Preferential flow effects on infiltration and runoff in grassland and forest soils. Vadose Zone J. 10, 367–377.
Anderson, A.E., Weiler, M., Alila, Y., Hudson, R.D., 2009. Dye staining and excavation of a lateral preferential flow network. Hydrol. Earth Syst. Sci. 13, 935–944.
Atanackovíc, N., Dragišić, V., Stojković, J., Papić, P., Zivanović, V., 2013. Hydrochemical characteristics of mine waters from abandoned mining sites in Serbia and their impact on surface water quality. Environ. Sci. Pollut. Res. Int. 20, 7615–7626.
Awadhwal, N.K., Thierstein, G.E., 1985. Soil crust and its impact on crop establishment: a review. Soil Tillage Res. 5, 289–302.
Barnhisel, R.I., Darmody, R.G., Daniels, W.L., 2000. Reclamation of Drastically Disturbed Lands (Agronomy No. 41). American Society of Agronomy, Madison, WI.
Beven, K., Germann, P., 1982. Macropores and water-flow in soils. Water Resour. Res. 18, 1311–1325.
Biemelt, D., Schapp, A., Kleeberg, A., Grünewald, U., 2005. Overland flow, erosion, and related phosphorus and iron fluxes at plot scale: a case study from a non-vegetated lignite mining dump in Lusatia. Geoderma 129, 4–18.
Bradshaw, A.D., Chadwick, M.J., 1980. The Restoration of Land: The Ecology and Reclamation of Derelict and Degraded Land. Univ of California Press.
Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22.
Cao, X., 2007. Regulating mine land reclamation in developing countries: the case of China. Land Use Policy 24, 472–483.
Carroll, C., Merton, L., Burger, P., 2000. Impact of vegetative cover and slope on runoff, erosion, and water quality for field plots on a range of soil and spoil materials on central Queensland coal mines. Aust. J. Soil Res. 38, 313–328.
Cey, E.E., Rudolph, D.L., 2009. Field study of macropore flow processes using tension infiltration of a dye tracer in partially saturated soils. Hydrol. Process. 23, 1768–1779.
Ciolkosz, E.J., Cronce, R.C., Cunningham, R.L., Peterson, G.W., 1985. Characteristics, genesis, and classification of Pennsylvania minesoils. Soil Sci. 139, 232–238.
Decagon Devices, Inc., 2014. Mini Disk Infiltrometer User's Manual Version 10. Decagon Devices, Inc., Pullman, WA (Undated).
Dexter, A.R., 1991. Amelioration of soil by natural processes. Soil Tillage Res. 20, 87–100.
Duran-Zuazo, V.H., Pleguezuelo, C.R.R., 2008. Soil-erosion and runoff prevention by plant covers. A review. Agron. Sustain. Dev. 28, 65–86.
Fields-Johnson, C.W., Zipper, C.E., Burger, J.A., Evans, D.M., 2012. Forest restoration on steep slopes after coal surface mining in Appalachian USA: Soil grading and seeding effects. Forest Ecol. Manag. 270, 126–134.
Flury, M., Flühler, H., 1995. Tracer characteristics of brilliant blue FCF. Soil Sci. Soc. Am. J. 59, 22–27.

Greer, B.M., 2015. Electrical Resistivity Imaging of Preferential Flow Through Surface Mine Valley Fills with Comparison to Other Land Forms M.S. Thesis Virginia Tech.
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 physiochemical quality of stream ecosystems in the central Appalachians: a review. Sci. Total Environ. 417–418, 1–12.
Guebert, M.D., Gardner, T.W., 2001. Macropore flow on reclaimed surface mines: infiltration and hillslope hydrology. Geomorphology 39, 151–169.
Haering, K.C., Daniels, W.L., Galbraith, J.M., 2005. Mapping and classification of southwest Virginia mine soils. Soil Sci. Soc. Am. J. 69, 463–472.
Haering, K.C., Daniels, W.L., Roberts, J.A., 1993. Changes in mine soil properties resulting from overburden weathering. J. Environ. Qual. 22, 194–200.
Hangen, E., Gerke, H.H., Schaaf, W., Hüttl, R.F., 2004. Flow path visualization in a lignitic mine soil using iodine-starch staining. Geoderma 120, 121–135.
Hangen, E., Gerke, H.H., Schaaf, W., Hüttl, R.F., 2005. Assessment of preferential flow processes in a forest-reclaimed lignitic mine soil by multicell sampling of drainage water and three tracers. J. Hydrol. 303, 16–37.
Hawkins, J.W., 2004. Predictability of surface mine spoil hydryologic properties in the Appalachian plateau. Ground Water 42, 119–125.
Holl, K.D., 2002. The effect of coal surface mine revegetation practices on long-term vegetation recovery. J. Appl. Ecol. 39, 960–970.
Howard, J.L., Amos, D.F., Daniels, W.L., 1988. Phosphorus and potassium relationships in southwestern Virginia coal-mine spoils. J. Environ. Qual. 17, 695–700.
Jorgensen, D.W., Gardner, T.W., 1987. Infiltration capacity of disturbed soils: temporal change and lithologic control. Water Resour. Bull. 23, 1161–1172.
Lange, B., Luescher, P., Germann, P.F., 2008. Significance of tree roots for preferential infiltration in stagnic soils. Hydrol. Earth Syst. Sci. Discuss. 5, 2373–2407.
Liang, W.L., Kosugi, K., Mizuyama, T., 2011. Soil water dynamics around a tree on a hillslope with or without rainwater supplied by stemflow. Water Resour. Res. 47 http://dx.doi.org/10.1029/2010WR009856.
Loch, R.I., 2000. Effects of vegetation cover on runoff and erosion under simulated rain and overland flow on a rehabilitated site on the Meanda Mine, Tarong, Queensland. Aust. J. Soil Res. 38, 299–312.
Macdonald, S.E., Landhäusser, S.M., Skousen, J., Franklin, J., Frouz, J., Hall, S., Jacobs, D.F., Quideau, S., 2015. Forest restoration following surface mining disturbance: challenges and solutions. New For. 1–30.
Mohanty, B.P., Kanwar, R.S., Everts, C.J., 1994. Comparison of saturated hydraulic conductivity measurement methods for a glacial-till soil. Soil Sci. Soc. Am. J. 58, 672–677.
Moreno-de Las Heras, M., Merino-Martín, L., Nicolau, J.M., 2009. Effect of vegetation cover on the hydrology of reclaimed mining soils under Mediterranean-continental climate. Catena 77, 39–47.
Negley, T., Eshleman, K., 2006. Comparison of stormflow responses of surface-mined and forested watersheds in the Appalachian mountains, USA. Hydrol. Process. 20, 3467–3483.
Nolde, J.E., Lovell, J.A., Whitlock, W.W., Miller, R.I., 1986. Geology of the Norton Quadrangle, Virginia. Virginia Div. of Mineral Resources Publ. 65Commonwealth of Virginia. Department of Mines, Minerals, and Energy. Division of Natural Resources, Charlottesville, VA.
Oades, J.M., 1993. The role of biology in the formation, stabilisation and degradation of soil structure. Geoderma 56, 377–400.
Parr, J.F., Bertrand, A.R., 1960. Water infiltration into soils. Adv. Agron. 12, 311–363.
R Core Team, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria (URL http://www.R-project.org/).
Reynolds, B., Reddy, K.J., 2012. Infiltration rates in reclaimed surface coal mines. Water Air Soil Pollut. 223, 5941–5958.
Reynolds, W.D., Bowman, B.T., Brunke, R.R., Drury, C.F., Tan, C.S., 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. Soil Sci. Soc. Am. J. 64, 478–484.
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.
Roberts, J.A., Daniels, W.L., Bell, J.C., Burger, J.A., 1988. Early stages of mine soil genesis in Southwest Virginia spoil lithosequence. Soil Sci. Soc. Am. J. 52, 716–723.
Rodrigue, J.A., Burger, J.A., 2004. Forest soil productivity of mined land in the midwestern and eastern coalfield regions. Soil Sci. Soc. Am. J. 68, 833–844.
Rosner, B., 1983. Percentage points for a generalized ESD many-outlier procedure. Technometrics 25, 165–172.
Sena, K., Barton, C., Angel, P., Agouridis, C., Warner, R., 2014. Influence of spoil type on chemistry and hydrology of interflow on a surface coal mine in the Eastern US coalfield. Water Air Soil Pollut. 225, 2171.
Sencindiver, J.C., Ammons, J.T., 2000. Minesoil genesis and classification (Ch. 23) In: Barnhisel, R.I., Daniels, W.L., Darmody, R.G. (Eds.), Reclamation of Drastically Disturbed LandsAgronomy Series No. 41. American Society of Agronomy, Madison, WI.
Shukla, M.K., Lal, R., Underwood, J., Ebinger, M., 2004. Physical and hydrological characteristics of reclaimed minesoils in southeastern Ohio. Soil Sci. Soc. Am. J. 68, 1352–1359.
Sidle, R.C., Noguchi, S., Tsuboyama, Y., Laursen, K., 2001. A conceptual model of preferential flow systems in forested hillslopes: evidence of self-organization. Hydrol. Process. 15, 1675–1692.
Simmons, J., Currie, W., Eshleman, K., Kuers, K., Monteleone, S., Negley, T., Pohlad, B., Thomas, C., 2008. Forest to reclaimed land use change leads to altered ecosystem structure and function. Ecol. Appl. 18, 104–118.
Skousen, J., Zipper, C.E., 2014. Post-mining policies and practices in the Eastern USA coal region. Int. J. Coal Sci. Technol. 1, 135–151.
Sweigard, R., Burger, J., Zipper, C., Skousen, J., Barton, C., Angel, P., 2002. Low compaction grading to enhance reforestation success on surface coal mines. Forestry Reclamation Advisory no. 3 Available at http://arri.osmre.gov/FRA/Advisories/FRA_No.3.pdf UDSI Office of Surface Mining Reclamation and Enforcement, Washington, D.C.
Sweigard, R., Burger, J.A., Zipper, C.E., Skousen, J.G., Barton, C.D., Angel, P.N., 2007. Low compaction grading to enhance reforestation success on coal surface mines. U.S. Office of Surface Mining Reclamation and Enforcement, Appalachian Regional Reforestation Initiative, Forest Reclamation Advisory No. 3.
Taylor, T.J., Agouridis, C.T., Warner, R.C., Barton, C.D., Angel, P.N., 2009. Hydrologic characteristics of Appalachian loose-dumped spoil in the Cumberland Plateau of eastern Kentucky. Hydrol. Process. 23, 3372–3381.
Thien, S.J., 1979. A flow diagram for teaching texture-by-feel analysis. J. Agron. Educ. 8, 54–55.
Thomas, K.A., Sencindiver, J.C., Skousen, J.G., Gorman, J.M., 2000. Soil horizon development on a mountaintop surface mine in southern West Virginia. Green Lands 30, 41–52.
Wang, K., Zhang, R., 2011. Heterogeneous soil water flow and macropores described with combined tracers of dye and iodine. J. Hydrol. 397, 105–117.
Weiler, M., Flühler, H., 2004. Inferring flow types from dye patterns in macroporous soils. Geoderma 120, 137–153.
Wells, L.G., Ward, A.D., Phillips, R.E., 1983. Predicting Infiltration and Surface Runoff from Reconstructed Spoils and Soils. Water Resources Research Institute, University of Kentucky, Lexington, Kentucky.
Younger, P.L., Wolkersdorfer, C., 2004. Mining impacts on the fresh water environment: technical and managerial guidelines for catchment scale management. Mine Water Environ. 23, 2–80.
Zhang, R., 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Sci. Soc. Am. J. 61, 1024–1030.