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Characterizing runoff responses in a mountaintop mine impacted and forested catchment in the coalfields of West Virginia

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Abstract

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Mountaintop mining (MTM) represents the largest land cover/landuse change in the Central Appalachian region. By 2012, the U.S. EPA estimates that MTR will have impacted approximately 6.8% of the predominately forested Appalachian Coalfield region of West Virginia (WV), Kentucky, Tennessee, and Virginia with nearly 4,000 miles of headwater streams buried under valley fills (VF). In spite of the scale and extent of MTM, its hydrologic impacts are poorly understood. Several devastating floods in the region have been attributed to MTM, but there is little evidence to either confirm or refute this belief. Existing research on the hydrologic impacts of MTM has documented a range of potential impacts to the storm hydrograph and seasonal flow regimes but has also revealed considerable variability in hydrologic responses to differing storm events, extents of disturbance, and stage of reclamation. Additional uncertainty stems from our poor understanding runoff processes of forested catchments in the southern coalfields of West Virginia. This study begins to address this knowledge gap by exploring rainfall-runoff relationships in two headwater catchments in southern West Virginia: a predominantly forested catchment with no active surface mining and another undergoing active MTM and VF that disturbs 20% of its catchment area. Streamflow (Q) and precipitation (P) were measured in each catchment from 01 September 2011 to 30 September 2012 and 23 discrete storm events were selected for analysis. Both catchments responded rapidly to precipitation inputs but the MTM-impacted catchment experienced significantly greater total runoff (3x), higher peak runoff (2x), greater runoff ratios (Q/P) (2x), greater baseflows, and shorter time lags from peak precipitation to peak runoff (2x). Hydraulic response time, a fundamental hydraulic parameter that controls the conversion of rainfall to runoff, was modeled with a transfer function rainfall-runoff model and found to be more rapid in the MTM-impacted catchment. The source of these differences is likely attributable to some combination of three factors: surface disturbance of MTM/VF operations, the smaller drainage area of the MTM-impacted catchment and additional water inputs from legacy underground mining in the MTM-impacted catchment. Results from this study reflect the hydrologic complexity of runoff generation the southern coalfields of West Virginia. Future research efforts should quantify the physical processes that control hydrologic response in these heavily disturbed landscapes.

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Chapter 3

1. Introduction

Mountaintop mining (MTM) is massive in its magnitude of disturbance at both local and regional scales. In order to access coal seems from the surface, heavy machinery and explosives are used to remove as much as 300 m of rock, soil, and vegetation from mountain ridges [*Peng*, 2000]. Material that cannot be replaced on the mine surface is dumped in to adjacent headwater streams in valley fills (VF), completely burying the springs, ephemeral channels, and perennial streams that comprise the incipient drainage network [*Griffith et al.*, 2012; *USEPA*, 2011]. A common result of reclamation of the mine surface is a flat or rolling landscape with compacted soils [*Chong and Cowsert*, 1997; *Ritter and Gardner*, 1993] and vegetation dominated by exotic grasses and legumes with little to no tree succession [*Graves et al.*, 2000]. At the regional scale, MTM has been the dominant driver of landcover change in the Appalachian Region [*Sayler*, 2008]. The U.S. Environmental Protection Agency (EPA) estimates that, by 2012, MTM will have impacted 6.8% of the predominantly forested 4.86 million hectare Central Appalachian coalfields region within West Virginia, Kentucky, Virginia, and Tennessee and approximately 4000 km of headwater streams will be buried under VF [*USEPA*, 2011]. *Hooke* [1999] documented nationwide rates of geomorphic activity and found that surface coal mining in the Central Appalachian coalfields resulted in more earth movement per year than both urbanization and fluvial systems in the western United States.

Such a dramatic change to landscapes at local and regional scales warrants rigorous scientific investigation to understand the impacts on social, economic and environmental systems. Regarding natural systems, most research efforts have focused on chemical and biological impacts to downstream aquatic ecosystems. Great strides have been made by researchers in understanding MTM's downstream impacts on water chemistry [e.g., *Lindberg et* *al.*, 2011], biology [e.g., *Pond et al.*, 2008], and geomorphology [*Fox*, 2009]. Yet surprisingly little is known about MTM's impact on the processes the control how water is collected, stored, and released in these headwater catchments. Existing research on the hydrologic impacts of MTM has documented a range of potential impacts to the storm hydrograph and seasonal flow regimes but has also revealed great variability in hydrologic responses to differing storm events, extents of disturbance, and stage of reclamation [*Messinger*, 2003; *Messinger and Paybins*, 2003; *Wiley and Brogan*, 2003]. At present, all investigations into the hydrologic impacts of MTM have been quantified by measuring streamflow at the catchment outlet or have utilized hydrologic models in ungaged catchments [e.g., *Phillips*, 2004]. The limitations of conducting controlled scientific investigations in drastically disturbed areas [see *Bonta*, 2005] have made such approaches appropriate and valuable information about the variability associated with MTM has been gleaned from the aforementioned studies. But the inherent limitations of "black box" studies where only catchment inputs (i.e. precipitation) and outputs (i.e. streamflow) are measured limit the process level data that can be used to understand variability and inform models that are necessary to extend research beyond study catchments to the entire region impacted by MTM.

Confounding the task of quantifying the impact of MTM on hydrologic systems in the Central Appalachian coalfields is the paucity of hydrologic data in this region. While the area effected by MTM lies between well studied forested catchment research sites at the Fernow Experimental Forest (Parson, WV) and the Coweeta Hydrologic Laboratory (Otto, NC), the knowledge we can draw from this work is limited by differing climatology, geology, and legacy land disturbances in the Central Appalachian coalfields. A dearth of stream gages at the headwater scale not only inhibits our understanding the function of headwater catchments in the heterogeneous conditions of the Central Appalachian coalfields but also our ability to place limited recent data in the proper context of a history of land disturbance and climate variability. In short, it is difficult to understand the hydrologic *change* attributable to MTM when our understanding of the landscape on which it is occurring is already so limited. Therefore, in order to advance understanding of catchments impacted by MTM, studying catchments unaffected by MTM is imperative in future research.

The broad goals of this study are to expand on a limited number of investigations of headwater catchment responses to MTM and initiate a new direction in hydrologic studies of land disturbance in the Central Appalachian coalfields, one based on process level investigations of the controls of water storage and movement affected by MTM. To accomplish this objective, we will investigate the hydrologic responses of two headwater catchments in the Central Appalachian coalfields: one predominantly forested with no active surface mining and another undergoing active MTM/VF operations. Statistical comparisons of catchment inputs and outputs are used to characterize rainfall-runoff responses in each catchment and rainfall-runoff modeling is used to characterize hydrologic response times. Stable isotopes of water are used for hydrograph separation to gain a preliminary understanding of the temporal sources of runoff of these two catchments.

This thesis is broken into four chapters. Following this introduction (Chapter I) is a brief summary of small catchment hydrology and review of the existing literature related to MTM (Chapter II). In this section, the existing literature on the hydrologic impacts surface mining, MTM, and VF is explored. The section concludes with identification of critical knowledge gaps and recommendations of future priorities related to MTM research. Chapter III documents the methods, results and discussion related to my research characterizing hydrology in a forested and

MTM-impacted headwater catchments using hydrometric data, rainfall runoff modeling and tracer based hydrograph separations of runoff. Chapter IV completes this thesis with a review of the major conclusions from this study and finishes with a discussion of the context of this work and future research that is needed to advance our understanding of the hydrologic change associated with this dramatic landscape disturbance.

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2. Impacts of mountaintop mining on streamflow response: a review

1. Introduction

Mountaintop mining and valley fill (MTM/VF) coal extraction practiced in the Central Appalachian region represents a dramatic change to the landscape. Post mining topography, vegetation, landuse, soils, and runoff pathways can be severely altered during the mining process and subsequent reclamation. Surface mining represents the largest landcover/landuse change in the Central Appalachian region [*Sayler*, 2008] and by 2012, the US EPA estimates that MTM/VF will have impacted approximately 6.8% of the predominately forested Appalachian coalfield region of West Virginia, Kentucky, Tennessee, and Virginia with nearly 4,000 kilometers of headwater streams buried under valley fills [*US EPA*, 2011] (Figure 1). While the U.S. Energy Information Administration projects a reduction in Appalachian coal production through 2035, this decline is relatively minimal (-0.6%) indicating that the low-sulfur Appalachian Coal extracted by cost effective MTM/VF practices will continue to be a significant component to the energy future of the United States[*US EIA*, 2012].

In spite of the magnitude, scale, and potential for continued development of MTM/VF, its effect on catchment hydrology is poorly understood. While MTM/VF has a well-established pattern of downstream chemical and biological water quality degradation [*Lindberg et al.*, 2011; *Merriam et al.*, 2011; *Palmer et al.*, 2010; *Petty et al.*, 2010; *Pond et al.*, 2008], its effect on the quantity and timing of catchment runoff is less clear. Much of the existing literature focuses on surface strip mining and does not consider the role of VFs, which present additional uncertainties. These studies suggest that surface mining generally increases total and peak runoff by decreasing the amount of water lost to evapotranspiration [*Dickens et al.*, 1989; *Messinger*, 2003] and reducing the infiltration rate of the soil [*Ferrari et al.*, 2009; *Guebert and Gardner*, 2001; *Negley and Eshleman*, 2006; *Ritter and Gardner*, 1993].

VFs present additional complexities to catchment hydrology that are not yet fully understood. The mine spoil that forms VFs has been described as acting as unconsolidated headwater aquifers [*Dickens et al.*, 1989], but others have shown that mine spoil develops preferential flow paths [*Caruccio and Geidel*, 1995] and is capable of both storage and rapid routing of water [*Wunsch et al.*, 1999]. Investigations into contemporary MTM/VF operations have involved hydrologic modeling or measurement of catchment outlet streamflow responses to precipitation inputs. These studies have observed an increase in baseflow in MTM/VF impacted catchments [*Green et al.*, 2000; *Messinger and Paybins*, 2003; *Wiley et al.*, 2001] and generally showed increases in discharge for larger storm events [*Messinger*, 2003; *Phillips*, 2004; *Wiley and Brogan*, 2003]. However, these studies reveal variability in the runoff responses of catchments impacted by MTM/VF due to climate characteristics and stage of mining operations and stress the need for more research to understand this inconsistent response.

The studies to date have been successful in documenting changes in runoff characteristics in response to MTM/VF. However, these studies cannot be expected to address the full range of hydrologic responses to variable precipitation inputs, excavation and reclamation practices utilized, extents of disturbance, interactions with other land disturbances, temporal and spatial scales, and diverse catchment characteristics needed to develop a complete understanding MTM/VF impacts. Exacerbating this knowledge deficit is the need for thorough scientific investigations to inform public debate, and legal and policy decisions. MTM/VF has become an increasingly polarizing issue in the communities in which it is practiced, as well as nationally. Local citizens, environmental advocacy groups, and regulators have expressed concerns over

MTM/VF's long term impacts on downstream water quality, public health, and safety. After a series of severe floods in southern West Virginia during the summer of 2001, public concerns were raised about the potential of surface mine operations to exacerbate flooding in coal region communities, which typically abut streams and rivers in narrow valleys due to the region's steep topography. Industry has countered these concerns by emphasizing the economic benefits of the coal industry [*Higginbotham et al.*, 2008] and, more effectively, citing the absence of conclusive scientific evidence to support the MTM/VF operations' culpability in the alteration of downstream hydrology.

In short, there is a lack of data to inform our understanding of how hydrologic systems are responding to this drastic alteration to the landscape. This review paper seeks to aggregate the existing knowledge base on hydrologic impacts of MTM/VF and identify areas where further scientific investigation is critically needed. The specific objectives of this paper are to: (1) explore the relevant catchment hydrology concepts and processes critical to understanding MTM/VF's potential to alter catchment hydrology, (2) review existing literature on hydrologic impacts of surface coal mining and MTM, and (3) identify critical knowledge gaps in our understanding of these altered systems, and recommend directions for future research.

2. Catchment hydrology concepts

Small catchments (<1 km^2 to 100 km^2) have been the primary experimental unit for many hydrologic studies because inputs and outputs of the system are relatively easy to measure. How catchments collect, store, and release water is largely a function of their unique characteristics. Therefore, hydrologic behavior varies between catchments and understanding and quantifying the unique processes that result from varying climates, topographies, geologies, soil types, and land covers are critical in developing conceptual models of how catchments process water. How water is stored and flows through a catchment effects a number of processes including the quantity and timing of runoff, soil erosion and sediment transport, downstream water chemistry and biology, and biogeochemical cycling. Headwater catchments dominate the Central Appalachian coalfield region [*Nadeau and Rains*, 2007] and provide many valuable ecological services to the region that link streams to the people living in these areas [*Meyer and Wallace*, 2001; *US EPA*, 2011].

In the most basic conceptualization, catchment hydrology can be viewed as a budget where inputs equal outputs through time where change in storage is negligible. The primary input is precipitation in the form of rain or snow and outputs are evaporation (from foliage, soils, and surface water stores) and plant transpiration (collectively evapotranspiration, *ET*) and stream and groundwater discharge. *ET* in the Central Appalachian coalfields is a major component in the water budget. The percent of annual precipitation lost to *ET* for a 25 year period in the Fernow Experimental Forest ranged from 35 – 72% with a mean of 47% [*Adams et al.*, 1994]. Canopy interception of rainfall in Eastern deciduous forest accounts for approximately 10% - 20% of precipitation [*Carlyle-Moses and Price*, 1999; *Helvey and Patric*, 1965]. Additional water losses can occur on the leaf litter layer on the forest floor and can account for 1-5% of precipitation with greater losses occurring after leaf fall [*Helvey and Patric*, 1965]. Transpiration is generally the largest component of *ET* in deciduous forest and can account for over 50% of total *ET* in Central Appalachian forests [*Wilson et al.*, 2001]. Evaporation from the soil profile is generally reduced in forested catchments due to diminished net radiation on the forest floor compared to the canopy [*Wilson et al.*, 2000] but is still a significant component of total *ET* [*Wilson et al.*, 2001].

Water that eventually becomes streamflow may take a variety surface and subsurface flowpaths from hillslope to the stream channel which will control the timing and magnitude of runoff. Additionally, the chemical and biological composition of water discharged to the stream channel is a function of how long rainfall and snowmelt remains in the catchment; longer residence time implies greater contact time for biogeochemical transformation [*Burns et al.*, 2001; *Hornberger et al.*, 2001]. Therefore, runoff flowpaths exert important controls downstream aquatic ecosystems that extend beyond physical hydrology. The following section will review the potential flow paths that runoff in forested catchments and are conceptualized in Figure 2.

A small fraction of rainfall falls directly in to the stream channel as direct channel precipitation. This source generally represents a small fraction (1.1 – 6.4 %) of streamflow though it can be more significant during dry antecedent moisture conditions [*Crayosky et al.*, 1999]. Water not lost to canopy interception will fall to the forest floor as throughfall or stemflow. The fate of water reaching the forest floor will be dictated by the rate at which it is falling and the infiltration capacity of the soil. Where the rate of precipitation exceeds the soil's infiltration rate, water becomes infiltration excess overland flow and continues rapidly downslope to the stream channel. Forest soils generally have high hydrologic conductivity [*Moore et al.*, 1985; *Price et al.*, 2010] due to high soil porosities and macropores, therefore infiltration excess overland flow is not considered to be a major source of runoff in forested catchments [*Bonell*, 1993]. Precipitation may also become saturation excess overland flow if it falls on already saturated soils. This generally occurs on the lower hillslopes adjacent to stream channels where subsurface water flows to the surface as return flow. These saturated areas can rapidly expand during storm events and can become a major source of runoff in forested catchments [*Dunne and Black*, 1970].

Water that infiltrates the soil surface will become part of a complex network of flow paths that will result in it being lost to the atmosphere through *ET*, percolated through the soil profile to deeper groundwater reservoirs, or routed to the stream channel through near surface and deeper pathways. Hydraulic conductivity generally diminishes with depth [*Van Den Berg*, 1989]; water moves more slowly through limited flow paths causing groundwater discharges to lag behind storm events by days, weeks, or even years [*Plummer et al.*, 2001]. Therefore, baseflow is sustained by groundwater, though contributions from unsaturated soils can also be significant [*Hewlett and Hibbert*, 1963]. Water movement in the vadose zone (i.e. the unsaturated zone between the water table and soil surface) can be both slow and rapid. Similar to groundwater movement, water can take tortuous flow paths through the shallow soil profile. However, soil water (and groundwater) can be rapidly displaced into the stream at the onset of precipitation due to a change in pressure gradients [*Hewlett and Hibbert*, 1967; *Horton and Hawkins*, 1965; *Zimmermann et al.*, 1966]. Macropores from animal burrows, decaying tree roots, and soil cracks and larger soil pipes [*Jones*, 1971] can also provide preferential flow paths for soil water movement to the stream channel [*Beven and Germann*, 1982; *McDonnell*, 1990]. These macropore networks are particularly important in streamflow generation in forested catchments [*Mosley*, 1979], particularly during large events [*Uchida et al.*, 2002].

The processes described above have been aggregated into conceptual models to explain the dominant runoff processes in headwater catchments and provide a framework for hydrologic model development. *Horton's* [1933] model of infiltration excess overland land driven systems represents the first widely adopted theory of runoff generation [*Beven*, 2004b], though it ultimately was insufficient forested catchments, including his own research site [*Beven*, 2004a]. The Variable Source Area (VSA) theory by *Hewlett and Hibbert* [1967], explains storm runoff as a function of the growth of near-stream saturated areas thereby making saturation excess overland flow the dominant runoff process, proved more applicable but ultimately didn't consider the role of stored hillslope water in the rapid response of forested catchments to storm events. The importance of pre-event water (i.e. water stored in the soils and geology of a catchment prior to the onset of rain) in the storm hydrograph was confirmed using geochemical [*Pinder and Jones*, 1969] and isotopic [*Buttle*, 1994; *Sklash and Farvolden*, 1979] tracers. Condensing the contributions in hydrologic research of the past 40 years into a single model is difficult, in part because that work has revealed the complex, site-specific processes that make formulating such a broad theory limited in its application [*McDonnell*, 2003]. In short, our current understanding of streamflow generation in forested headwater catchments is embodied by a "double paradox" [*Kirchner*, 2003] where old water is stored in catchments for long time periods then is promptly released during storm events, the mechanics of which are not fully understood.

The study of landcover disturbance and its consequences has garnered much attention in multiple scientific fields in the past decade [*Eshleman*, 2004]. Within hydrology, disturbance in forested catchments has been extensively studied in the context of timber harvesting [e.g., *Hornbeck et al.*, 1970; *Jones and Grant*, 1996; *Thomas and Megahan*, 1998], agriculture [e.g., *Potter*, 1991], and urbanization [e.g., *Gremillion et al.*, 2000; *O'Driscoll et al.*, 2010; *Rose and Peters*, 2001]. Landcover disturbance in forested catchments has the potential to alter hydrology by a number of mechanisms. Most importantly, intensive vegetation removal reduces interception and transpiration [e.g., *Jones and Grant*, 1996]. Changes to the soil surface either through compaction or impervious surface can alter how water is stored and transported within the catchment [e.g., *Gremillion et al.*, 2000; *Jones et al.*, 2000; *Ritter and Gardner,* 1993]. Changes in runoff flowpaths in response to urbanization have been explored using geochemical and isotopic tracers [*Gremillion et al.*, 2000; *Meriano et al.*, 2011], but have yet to be explored in the context of MTM/VF operations.

3. Review of pertinent MTM-VF literature

3.1. MTM-VF operations

MTM is a special form of surface mining adapted to mountainous terrain in which the forest, topsoil, and overlying bedrock is removed using explosives and heavy machinery to gain direct access to deeper coal seams. While MTM/VF can be broadly categorized as surface mining synonymous with surface "strip" mining and contour mining, its scale is drastically different; as much as 300 m of overburden is removed from ridge tops to access underlying coal seams [*Peng*, 2000]. Because the expanded volume of displaced overburden often precludes replacing it on the ridge tops, much of this excess material is placed in adjacent headwater stream valleys to create VFs, which bury headwater streams and springs. VF construction techniques vary; the sorting and placement of spoil material, management of water fluxes through or on top of VFs, and soil conditions of the VF face are often site-specific and can vary considerably across the MTM region.

This type of mining is permitted under the Surface Mining Control and Reclamation Act (SMCRA) of 1997 [*US Congress*, 1977]. Under this act, mining operators are required to restore the topography to approximate original contour (AOC) which states "…*backfilling and grading of the mined area so that the reclaimed area, including any terracing or access roads, closely* *resembles the general surface configuration of the land prior to mining and blends into and complements the drainage pattern of the surrounding terrain…",* though interpretation and enforcement of this language is left to regulators at the state level [*US Congress*, 1977]. Additionally, variances to the AOC requirement are granted if mine operators propose a post mining land use that would constitute an "improvement" over pre-mining conditions (i.e. industrial, commercial, residential, agriculture, and public land uses). In such cases, mine operators are under no requirement to recreate pre-mining topography, the result of which is flattened ridge-top topography and large VF structures.

The primary objective of reclamation since the passage of SMCRA has been on slope and soil stability to prevent soil erosion from the mine surface [*Angel et al.*, 2006]. To achieve this objective, mine soils are heavily compacted using heavy machinery and aggressive, fast growing herbaceous cover is seeded to quickly establish a vegetative surface. A consequence of the emphasis on slope stability has been the loss of natural tree succession on mine surfaces [*Graves et al.*, 2000]. The Forestry Reclamation Approach (FRA) advocated by the Appalachian Region Reforestation Initiative (ARRI) has shown loose dumped spoil to be an effective growing medium for Appalachian hardwood tree species [*Zipper et al.*, 2011]; while this method of surface mine reclamation has become more commonplace, it does not represent the predominant reclamation practice on surface mines in the Central Appalachian coalfields.

Thus, MTM/VF operations create two distinct disturbed landforms, each with unique physical and hydrologic impacts: 1) the reclaimed mine surface on the former ridgeline 2) the VFs constructed in headwater valleys adjacent to the mine surface. The following sections will investigate our knowledge of each these components in the MTM/VF system individually, followed by an examination of studies of MTM/VF hydrology at the catchment scale.

3.2 The surface mine

Surface mining for coal in the Appalachians began in the mid-20th century and has continues today. Much of the mining in the early part of this period constituted small contour and strip mining operations that only disturbed areas less than 400 hectares. MTM in the coalfields of southern WV, southwestern VA, and eastern KY and TN in the 1980s disturbed areas on the scale of thousands of hectares [*Phillips*, 2004]. Prior to the passage of SMCRA in 1977, the methods and diligence of surface mine reclamation varied greatly. While some operations loosely regraded disturbed areas and planted hardwood trees that ultimately developed into healthy forests [*Rodrigue and Burger*, 2000], many areas were left untouched after extraction causing prolific water chemistry and erosion and sedimentation problems downstream. It was this disparate state of reclamation that prompted the passage of SMCRA, a key objective of which was creating stable landforms to prevent erosion and stream sedimentation [*Angel et al.*, 2006]. To achieve this goal, regulators emphasized heavily grading mine spoils to achieve AOC and the use of quick growing herbaceous grasses and legumes to prevent soil erosion. This methodology resulted in heavily compacted soils and competitive groundcovers that prevented natural succession, growth, and survival of native trees species [*Bussler et al.*, 1984; *Graves et al.*, 2000]. Some natural succession of tree species from adjacent forest land occurred, but the overall basal area and species diversity lagged behind unmined forests, even after decades [*Holl*, 2002]. Thus, the predominant state of reclaimed surface mines across Appalachia are grasslands with heavily compacted soils with diminished to no tree growth [*Conrad et al.*, 2002; *Graves et al.*, 2000]. More recent research has recognized the utility of loose dumped mine spoil as a growing medium for hardwood tree species in surface mine reclamation [e.g., *Angel et al.*, 2006;

Burger et al., 2005; *Groninger et al.*, 2007; *Zipper et al.*, 2011]. While this method, termed the Forestry Reclamation Approach (FRA), has shown very promising results in re-establishing hardwood forests on surface mined lands, it does not represent the condition of the majority of reclaimed surface mines across Appalachia or the predominant reclamation practice currently employed.

The post SMCRA reclaimed surface mine is characterized by herbaceous grasses and groundcovers growing on heavily compacted mines soils [*Holl*, 2002]. Common grasses seeded for revegetation include fescues (*Festuca spp* L.), redtop (*Agrostis alba* L.), and perennial rye grass (*Lolium perenne* L.). Crownvetch (*Coronilla varia* L.) and Chinese bushclover (*Lespedeza cuneata*), both legumes, are also commonly used in mine reclamation due to their nitrogen fixing potential [*Barnhisel and Hower,* 1997; *Bradshaw*, 1990]. While these species have been successful in quickly establishing vegetative cover on disturbed soils, they lack the structural complexity of a mature deciduous tree canopy. Consequently, rainfall interception storage capacities in grasslands are less than forested canopies, though the rates of evaporation from each are quite similar [*Kelliher et al.*, 1993]. Losses to evapotranspiration will also be reduced compared to forest as grasslands use less water than forested ecosystems [*Webb et al.*, 1978]. Therefore, surface mining results in more precipitation being converted to runoff [*Dickens et al.*, 1989; *Ritter and Gardner*, 1993].

During the mining process, soils are removed, stockpiled, and then replaced during reclamation [*Bell et al.*, 1994]. The reconstructed post-mining soil structure is drastically altered from pre-mining condition [*Bell et al.*, 1994; *Indorante et al.*, 1981]. “Minesoils” (as termed by *Ciolkosz et al.* [1985]) are heavily compacted with increased bulk density [*Bussler et al.*, 1984; *Chong and Cowsert*, 1997] and reduced porosity near soil surface [*Bussler et al.*, 1984; *Silburn* *and Crow*, 1984], though porosity may increase with depth [*Ciolkosz et al.*, 1985; *Potter et al.*, 1988] due to the introduction of large, non-soil rock fragments [*Power et al.*, 1978]. Excessive surface compaction limits downward root penetration in mine soils [*Bell et al.*, 1994; *McSweeney and Jansen*, 1984] and lowers the available water holding capacity [*Pedersen et al.*, 1980; *Silburn and Crow*, 1984]. While the conditions described above are nearly ubiquitous for reclaimed surface mines in Appalachia, variation in soil structure and properties have been observed depending on the machinery and techniques utilized in reclamation [*Indorante et al.*, 1981; *McSweeney and Jansen*, 1984] and the lithology of pre-mining overburden [*Indorante et al.*, 1981; *Jorgensen and Gardner*, 1987].

Infiltration rates can be an order of magnitude lower than undisturbed soils [*Jorgensen and Gardner*, 1987; *Negley and Eshleman*, 2006; *Ritter and Gardner*, 1993] due to the reduction in porosity, increase in bulk density, and reduction of macropore volume at the soil surface [*Dunker et al.*, 1995; *Potter et al.*, 1988]. This reduction in infiltration rate causes the initiation of infiltration excess overland flow which dominates storm runoff in mined areas [*Jorgensen and Gardner*, 1987; *Ritter and Gardner*, 1993]. The dominance of surface pathways in runoff generation in mined catchments is further evidenced by the increase in total suspended solids downstream of mining activities [*Bonta*, 2000] originates from the mine surface during the period immediately after reclamation [*Fox*, 2009]. However, *Ritter and Gardner* [1993] observed variability in the infiltration rate of mine soils through time; some mine soils maintain low infiltration rates with only minor recovery, while other mine soils return to near pre-mining rates in as little as four years. *Jorgensen and Gardner* [1987] attribute this variability to overburden lithology which ultimately controls the mineralogy and grain size during the redistribution of soils onto the mine surface and initial weathering. Surprisingly, there is little observed change in the bulk density of the shallow minesoils [*Jorgensen and Gardner*, 1987; *Lemieux*, 1987; *Ritter*, 1990]. This dissonance is explained by *Guebert and Gardner* [2001], who show the increase in infiltration rate is due to the development of an extensive macropore structure. As this macropore structure develops, subsurface flow paths will become more significant which causes a reduction in the peak discharge during storm events.

The impact of surface mining and reclamation on catchment outlet responses has been explored for nearly as long as the practice of surface mining in Appalachia, though studies are relatively few in number. Early investigations on the impact of surface mining used a paired catchment approach [e.g., *Collier et al.*, 1970] where change through time was observed in a treatment catchment and a separate control catchment. *Collier et al.* [1970] investigated changes in the Beaver Creek Basin of Kentucky from 1955-66 and found that a surfaced mined catchment had dampened peak stormflow and greater baseflow compared to the undisturbed control catchment. They were unable to link the modulated runoff response to surface mining due to an inadequate the lack of a calibration period in the mined catchment, but other early studies observe similar effects in mined catchments [*Agnew*, 1966; *Grubb and Ryder*, 1972; *Traux*, 1965]. *Curtis* [1972] observed a marked increase in the peak flow volume in surface mined catchments, but later noted that such an increase only occurred during active mining and may be ameliorated by reclamation [*Curtis*, 1979], particularly sediment retention ponds [*Curtis*, 1977]. *Bryan and Hewlett* [1981] also observed increases (36%) of peak flow in surface mined catchments but this effect was limited to the summer season; peak discharge in winter and spring months were unchanged and possibly reduced. Citing the difference in magnitude between winter in summer peak flows, *Bryan and Hewlett* [1981] concluded that the increases in summer peak flows from surface mining does not represent a serious flood risk.

In a study of the impact of surface mining on headwaters of the New River in TN from 1972 – 1985, *Dickens et al.* [1989] elaborated on the mechanisms that control the runoff modulation observed in prior studies. Radically increased baseflows (10x) in mined catchments was a result of infiltration, storage, and slow release of water stored in mine spoil. Utilizing monitoring wells, total spoil storage was estimated to be 4,949,000 m^3 (44% of annual catchment yield) in Indian Branch, a catchment mined in the 1950s-60s. However, the authors observe differences in water storage in spoil banks due to mining and reclamation practices. Mine spoil in Bill's Branch, reclaimed under Tennessee's partial backfill reclamation standards [*Tennessee Legislature*, 1972], stored just 193,000 m^3 (11% of annual catchment yield) of water. Contrary to earlier studies, *Dickens et al.* [1989] observed a increases in the total catchment water output which was attributed to reduction in evapotranspiration from deforestation and water storage in mine spoil.

More recent studies of surface mining after the implementation of SMCRA observed different results than the aforementioned studies. In a study of three headwater catchment undergoing surface mining in Ohio, *Bonta et al.* [1997] observed increases in peak stormflow from undisturbed to reclaimed conditions with no consistent pattern in baseflow response to mining. In western MD, *Negley and Eshleman* [2006] observed significantly different runoff responses between a forested and mined headwater catchment at the storm event scale. The mined catchment exhibited higher storm runoff coefficients (2.5x), greater total storm runoff (3x), and higher peak hourly runoff rates (2x). In spite of the large storm response, total annual runoff did not significantly differ between the two catchments. The authors attribute this to the heavily compacted soils in the mined catchment; infiltration rates on the reclaimed mine surface were two orders of magnitude lower than those in the forested catchment. This led to a greater magnitude, infiltration excess overland flow driven storm response in the mined catchment, but poorly sustained baseflows during the winter and spring due to insufficient subsurface flow contributions. *Negley and Eshleman* [2006] also analyzed storm responses using unit hydrograph theory [*Sherman*, 1932], where the unit hydrograph is the time distribution of surface runoff plus interflow (or quickflow) that occurs at the basin outlet for a unit depth of rainfall excess during a time period, *t* [*Negley and Eshleman*, 2006]. Surprisingly, the unit hydrographs for the mined and forested catchments were remarkably similar. The authors attributed this similarity to differences in catchment sizes and slopes (the mined catchment was an order of magnitude larger and significantly flatter) that offset the differences in runoff processes caused by landuse change. The authors stress the importance of selecting catchments with similar size, shape, and physical characteristics because these confounding variables may mask or augment the observed effects of landuse change.

Few studies attempt to assess the impacts of surface mining at the river basin scale. *McCormick et al.* [2009] explored runoff responses from the mined George's Creek basin (187.5 km^2) and unmined Savage River basin (127.2 km^2). Results showed that George's Creek had higher peak runoff and shorter lag times (precipitation centroid to runoff centroid) that were attributed to landuse. However, George's Creek only produced two thirds of the total stormflow volume of Savage River which the authors attribute to infiltration of subsurface flow into abandoned underground mines and a large, subsurface inter-basin diversion that draws water from George's Creek. Thus, assessing surface impacts may be complicated by legacy subsurface mining. *Ferrari et al.* [2009] modeled runoff responses in the George's Creek basin under increasing mining scenarios. Results showed that runoff magnitude increased linearly with increased mining disturbance, a trend that more closely resembled urbanization than deforestation from forest harvesting. The authors call into question the efficacy of modern reclamation practices in returning mined areas to the hydrologic regime that existed prior to mining.

3.3 The valley fill

Few studies have explored the nature of water storage and release of VFs in contemporary MTM operations. Much of our understanding of contemporary VF behavior comes from studies of unconsolidated spoil piles associated with pre-SMCRA surface mining operations. While some inferences about VF hydrology can be made from these studies, the scale and construction methods of contemporary VFs drastically differ from spoil piles from early surface mining operations. The size of modern VFs varies, but the largest have volumes of over 150 million m^3 and lengths over 3 km [*US EPA*, 2003]. In a period from 1985 – 2001 the *US EPA* [2003] found that average VF area was increasing through time in the southern coalfields of West Virginia.

There are multiple methods for constructing VFs but the predominant technique utilized in rugged topography of Appalachia is the durable rock fill technique where spoil is end-dumped from the mine surface in "lifts" (Figure 4). VFs are required to be composed of at least 80% "durable rock" (rock that will not slake in water or degrade to soil material) so that fine material that could prevent water movement in the underdrain is minimized. Other VF construction techniques require that an underdrain be built before the placement of fill material but this regulation is waived for durable rock fill methodology because it is assumed that spoil will naturally segregate during dumping so that fine spoil material stays at higher elevations on the VF and large rock and boulders fall to the valley floor. In a study by the Office of Surface

Mining (OSMRE) and the Kentucky Division of Mine Reclamation and Enforcement (KYDMRE) over half of 44 VFs studies were constructed with less than 80% durable material and that gravity formed underdrains are often poorly formed or even nonexistent [*Michael and Superfesky*, 2007].

The storage and slow release of water from surface mine spoil described by *Dickens et al.* [1989] has been shown to apply to VFs as multiple studies have observed longer flow durations and augmented baseflow downstream of VFs [*Messinger and Paybins*, 2003; *Wiley et al.*, 2001]. However, this conceptualization of mine spoil as a storage reservoir may not capture the complexity of water movement in VFs. *Caruccio and Geidel* [1995] observed perched aquifers and highly developed preferential flow paths in the base of a large spoil bank and describe the hydrologic environment as pseudokarst. The most complete picture of VF hydrology comes from a series of investigations of water movement and storage in a large mine spoil area at the Star Fire Mine in eastern Kentucky [*Wunsch et al.*, 1992; *Wunsch et al.*, 1999; *Wunsch et al.*, 1996]. Utilizing groundwater monitoring wells, dye tracers, measured discharge from VF outflows, and structural and topography maps, the authors present a conceptual model of mine spoil hydrology with distinct but interconnected saturated zones. Water stored on the former mining bench is slow moving but eventually drains towards two surrounding VFs where water movement is rapid [*Wunsch et al.*, 1999]. Recharge to the VFs occur from streams, adjacent bedrock and coal aquifers, and surface water that infiltrates into the mine spoil from the bedrock-spoil interface [*Wunsch et al.*, 1999]. The hydraulic conductivity (*K*) values within the mine spoil varied, but there was no discernible difference between *K* values in the spoil interior and the VFs. Therefore, the discrepancy between water movement in the spoil interior and valley fills was a function of topographic gradients and continued recharge to the VFs and not differences in the spoil material itself. The authors conclude that movement of water within the spoil body is mostly a function of gradients created from recharge and discharge interactions and the subsurface topography created by the impermeable pavement below the lowest mined coal and drainage patterns in the valleys prior to the onset of mining.

3.4 Mountaintop mining and valley fill

Assessing the hydrologic impacts of MTM is difficult because it is a two part system, each with potentially contradictory effects on the storage and movement of water. While post-SMCRA reclaimed surface mines generally produce rapid, higher magnitude runoff response to storm events, VFs appear to act as storage reservoirs that dampen storm responses and sustain baseflow. The physical processes that control runoff generation in these disturbed landscapes remain unclear, as investigations into the impacts of MTM have measured catchment outlet responses or utilized hydrologic models in ungaged catchments.

The U.S. Geological Survey's (USGS) study of extensively mined (0.5 km^2; 44% VF), partially mined (5. 7 km^2; 40% MTM), and forested (1.4 km^2; no MTM) subcatchments of Ballard Fork in southern West Virginia offers the most complete picture of hydrologic impacts of MTM. *Messinger and Paybins* [2003] investigated relations between precipitation and daily and monthly mean flow in the three watersheds from 1999 – 2001. Total unit flow in the extensively mined catchment was nearly twice that of the partially mined and forested catchments. The greatest difference in flow between the catchments occurred during low flow (80% duration) where the forested catchment went dry during the fall of 2000 but the extensively mined catchment sustained flow year round. This corroborates the findings of *Wiley et al.* [2001], where 90% flow duration was 6–7x greater downstream of VFs. High flows (20% duration) were similar between the extensively mined and forested catchments. *Messinger and Paybins* [2003] attribute the increased runoff responses to a reduction in evapotranspiration in UNT due to the removal of soil and vegetation from mining operations.

Messinger [2003] examined storm responses in the same catchments during the same study period and found a variable outlet response to different storm intensities. Peak unit runoff for storms where rainfall exceeded 25 mm hr^{-1} was greater in the extensively mined catchment than the forested and partially mined catchments. This relationship was reversed during smaller storms; the extensively mined catchment showed a smaller peak compared to the other two study catchments. For storm events with sufficient intensity (greater than 6 mm hr^{-1}), hydrographs from the extensively mined catchment showed a distinct double peak, where infiltration excess overland flow likely contributed to the first peak and delayed discharges from VFs constituted the second peak (Figure 5), though hydrograph separations were not conducted in this study. Total unit flows in the extensively mined catchment were generally twice that of the forested catchment where the greatest differences in flow among the three catchments occurred during the receding limb of the storm hydrograph (Figure 5). *Messinger* [2003] notes that that the largest storm event during the study period only produced a return interval of 1.1 years in the forested catchment and that rainfall runoff relations might be different during extreme events.

Wiley and Brogan [2003] examined peak discharges in six small catchments in the headwaters of the Clear Fork River in West Virginia for a single, large storm event on July 6-7, 2001. Peak discharge was indirectly calculated for the six catchments using the slope-area method [*Benson and Dalrymple,* 1967]. Three of these catchments were undisturbed and the other three had varying degrees of MTM and VF development. Flood recurrence intervals were calculated for the storm event for each catchment. The three undisturbed catchments had recurrence intervals of 10, 10, and 25 years. The disturbed catchments showed greater variability with return intervals ranging from less than 2 years to over 100 years. Variability was likely a due to differing extents of VF development within each watershed; the lowest return interval occurred in a watershed with one large, reclaimed VF while the largest occurred in a catchment with active MTM and an unreclaimed VF.

Due to the dearth of gaged headwater catchments in the MTM region, several studies have utilized hydrologic models to explore the impacts of MTM. In response to extreme flooding events in May and July of 2001, the Governor of West Virginia created the Flood Advisory Technical Taskforce (FATT) to investigate the possible impacts from logging and surface mining operations. Using a hydrologic model based on NRCS curve numbers, *FATT* [2002] found that surface mining (including MTM) and timbering increased peak flows between 3 and 21% but the significance of this additional input was lessened in the furthest downstream reaches in the modeled catchments. *McCormick and Eshleman* [2011] calculated curve numbers for surface mined and reclaimed catchments using rainfall runoff data and found that they were generally higher than curve numbers estimated from prevailing engineering methods. Therefore, modeled runoff in surface mined catchments (including *FATT* [2002]) likely underestimate the magnitude of discharge in model simulations. *Phillips* [2004] examined runoff production and surface and subsurface flow detention utilizing hydrological models that considered differences in runoff producing conditions in mine and unmined catchments in eastern Kentucky. Results from this study showed that runoff production was likely to increase in MTM- impacted catchments compared to unmined catchments but there was large variability in catchment response due to the local geologic, topographic and pedologic conditions as well as differences in the stage and method of valley fill construction and mine reclamation. *Zégre et al.* [2013b] modeled hydrologic response time, defined as the time it takes a catchment to discharge a volume of water equal to an input of effective precipitation (i.e., rainfall that produces runoff) [*Nippgen et al.*, 2011], using a transfer function rainfall-runoff model. The authors observed steep response curves (the fraction of the effective precipitation input discharged from the catchment outlet through the storm event) that indicated the rapid translation of rainfall to runoff and little variability between four storm events, but the absence of a control (i.e. unmined) catchment makes it difficult to place these results in the context of change from a forested system.

Few studies have addressed the hydrologic impact of MTM at larger spatial scales. Long term studies of the Tug Fork basin in West Virginia and Kentucky from 1947-78 [*Hirsh et al.*, 1982] and the Russell Fork basin in Virginia from 1927-1980 [*Larson and Powell*, 1986] show some general trends of increased flood magnitudes [*Hirsh et al.*, 1982] and increased baseflows [*Larson and Powell*, 1986] but the extent of MTM in those basins during the respective study periods is unclear and likely limited. *Zégre et al.* [2013b] explore changes in runoff of the Big Coal River basin in southern West Virginia from 1973 – 2010 in the context of increased land disturbance from MTM during this time period. While season and inter-annual climatic variability makes detecting trends difficult [*Zégre et al.*, 2013a], statistically significant decreasing trends were observed for maximum discharge and interquartile range normalized by median discharge (a measure of variability). Additionally, using the hydrograph separation model PART [*Rutledge*, 1998], a statistically significant increasing trend in the composition of total runoff attributable to baseflow was detected. However, the authors note that "*the lack of significant trends in the other hydrologic metrics do not necessarily confirm the absence of hydrologic change, rather reflect our ability to detect change based on appropriate hydrologic metrics, timescales, and change detection methods*" [*Zégre et al.*, 2013b].

4. Knowledge gaps and future directions

Existing research on the hydrologic impacts of MTM has documented a range of potential impacts to the storm hydrograph and seasonal flow regimes but has also revealed considerable variability in hydrologic responses to storm events, extents of disturbance, and stage and method of reclamation. Currently, we lack the data to understand the cause of this variability. What are the dominant runoff generation processes in MTM catchments? How do these processes change with increasing disturbance from MTM? How do these processes change with differing reclamation techniques? How do contemporary VFs store and release water? What variability exists within forested catchments in the Central Appalachian coalfields? These critical questions remain unanswered and little progress can be made in understanding and quantifying the hydrologic impacts of MTM until the volume and type of data necessary to understand the variability observed in the existing literature is collected. The following section identifies the key knowledge gaps in our understanding of the hydrologic change from MTM operations and the research directions necessary to answer those questions.

Dominant streamflow generation processes in MTM

At present, all investigations into the hydrologic impacts of MTM have been measured at the catchment outlet or have utilized hydrologic models in ungaged catchments. The limitations of conducting controlled scientific investigations in drastically disturbed areas [see *Bonta*, 2005] have made such approaches appropriate and valuable information about the variability associated with MTM has been gleaned from the this work. But the inherent limitations of "black box" studies limit the process level data required to understand variability and inform models that are necessary to extend research beyond study catchments to the entire region impacted by MTM.

The differing runoff responses in pre-SMCRA unconsolidated spoil banks and the post-SMCRA heavily compacted surface mine is well documented in existing literature. However, the dominant streamflow generation processes in MTM catchments where both compacted surface mines and large spoil piles are present are yet to be explored.

In order to understand the hydrologic implications of this practice, future research needs to focus on catchment processes that control the storage, transport, and flowpaths of water. Geochemical and isotopic approaches should be incorporated into hydrometric studies to discern geographic sources of runoff in addition to its magnitude and duration. How these processes change in response to differing climatic inputs, extents of disturbance, and reclamation techniques will provide insight into the variability observed in the hydrologic studies to date. Isotopic and geochemical tracers have been applied in catchments disturbed by urbanization [*Gremillion et al.*, 2000; *Meriano et al.*, 2011], but have yet to be utilized in catchments impacted by surface mining. This will ultimately require cooperation between landowners (i.e. industry) and scientists as quantifying catchment wide streamflow generation processes will require access to all reaches of the catchment, not just the outlet. This schism has been an obstacle to past research in these systems [*Zégre et al.*, 2013b] and must be bridged in order to understand and ameliorate the environmental problems associated with this mining practice.

Hydrology of non-MTM catchments in the Central Appalachian coalfields

As *Wiley and Brogan* [2003] demonstrate, adjacent, similarly sized catchments show different storm responses, irrespective of landcover. What is the source of this variability? Is it solely attributable to patchy climatic inputs or is the complex and heavily fractured topography of the Central Appalachian coalfields a major source of this variability? How does this heterogeneous landscape affect hydrologic response to MTM; is variability normalized by the landscape scale disturbance of MTM or does the displacement of mountain ridges augment preexisting hydrologic differences caused by topography, geology, and legacy land disturbance?

Surprisingly little is known about the hydrologic processes responsible for movement and storage of water in the context of multiple episodes of land disturbance. While the MTM region lies between forested catchment research sites at the Fernow Experimental Forest (Parson, WV) and the Coweeta Hydrologic Laboratory (Otto, NC), the knowledge we can draw from this work is limited due to differing climatology, geology and landuse in the Central Appalachian coalfields. Work in adjacent areas has shown that stormflow is dominated by subsurface flow [*DeWalle et al.*, 1988]. In the Central Appalachian coalfields, groundwater movement is predominantly controlled by a complex network of stress relief fractures in hillslopes and valley bottoms [*Kipp and Dinger*, 1987; *Wyrick and Borchers*, 1981]. However, a long history of underground coal mining throughout much of this region has drastically altered the structure of the subsurface system [*Puente and Atkins*, 1989]. Subsidence associated with abandoned underground mines creates additional fractures which can increase the hydrologic connectivity between the surface and subsurface as well as between water-bearing subsurface geologic units [*Hawkins and Dunn*, 2007; *Hobba*, 1981]. Consequently, underground mines and associated subsidence fractures can become major conduits for subsurface water movement. Headwater drainage networks downdip and stratigraphically below the mined coal beds can receive significant amounts of water while streams underlain by underground mines lose water, especially during baseflow conditions [*Puente and Atkins*, 1989]. At the headwater scale, substantial volumes of water can be transferred between basins, increasing the complexity of assessing hydrologic change related to surface and subsurface mining [*Borchers et al.*, 1991]. While *Borchers et al.* [1991] examine the combined effects of deep mining and surface strip mining, no study has examined the interactions between contemporary MTM and VF operations and legacy deep mining. A thorough examination of the spatial and temporal variability of individual catchments due to heterogeneity in catchment characteristics and legacy disturbances is necessary to understand the impacts of this practice across the landscape. A robust hydrologic monitoring network comprised of numerous MTM-impacted *and* unmined catchments will be necessary to address this variability.

Valley fill hydrology

How do VFs store and release water? *Wunsch et al.* [1999] began to address this question in their study of a large spoil pile from a MTM operation in eastern Kentucky. Their research provides valuable insight into the complexity of VF hydrology but uncertainty remains regarding the processes involved in the movement and storage of water in VFs. Little is known about the geographic sources of water that supply VFs, the spatial distribution and residence time of water within VFs, or how water is released during periods of drought and storm events. Heterogeneity in the surrounding geology coupled with legacy land disturbance (i.e. underground mining) and the multitude of different VF construction techniques creates additional complexity. Insights into these uncertainties extend beyond physical hydrology as VFs are particularly important in terms of downstream water chemistry; overburden placed in drainage pathways forces contact time between runoff and unweathered rock. Numerous studies document increased concentrations of dissolved solutes that degrade downstream aquatic ecosystems [e.g., *Lindberg et al.*, 2011; *Merriam et al.*, 2011; *Palmer et al.*, 2010]. While the work of *Wunsch et al.* [1999] is a starting point for understanding, research should address different size, construction and reclamation techniques, and geologic and topographic settings to represent the range of conditions present across the region. Isotopic and geochemical tracers should also be utilized to discern the origin and flowpaths of water in VFs.

MTM and VF reclamation techniques

The Forestry Reclamation Approach (FRA) advocated by the Appalachian Region Reforestation Initiative (ARRI) has gained traction as a viable reclamation technique amongst industry and regulators [*Zipper et al.*, 2011]. In the FRA, mine spoil is dumped and loosely graded to create a minimally compacted growing medium for high value native hardwood tree seedlings [*Burger et al.*, 2005]. This technique has shown to be an effective method for establishing forests in on mine lands [*Angel et al.*, 2006], but its effect on catchment hydrology is still not known. *Taylor et al.* [2009] describe runoff responses of plots of loose dumped soil to have low discharge volumes (as % of rainfall), small peak discharges, and long flow durations. Due to the high infiltration capacities of loose dumped mine spoil [*Rogowski and Jacoby*, 1979], the broad application of the FRA to large surface mines would likely result in the restoration of subsurface flowpaths in reclaimed mined areas. However, given the reduced slopes on reclaimed MTM surfaces, residence time of water stored in the loose dumped spoil profile may be longer than in central Appalachian forested hillslopes that are generally thought to have thin soils with little storage capacity [*Ehlke et al.*, 1982]. Therefore, storm hydrographs from FRA-reclaimed hillslopes might produce more damped hydrographs than pre-mining forests. Hillslope and catchment scale studies of bare and vegetated loose dumped mine reclamation operations are needed to understand the effects of this mining practice.

Thresholds in MTM systems

Thresholds in disturbance area to detect measurable changes in streamflow have not been established for MTM or traditional surface mining. *Bosch and Hewlett* [1982] and *Caissie et al.* [2002] observed a threshold of 20% catchment disturbance from forest harvesting operations to detect change in catchment runoff responses. Similarly, *Bernhardt et al.* [2012] established thresholds of disturbance and water chemistry to biologic integrity of aquatic ecosystems downstream of MTM /VF operations. The question how much mining does it take to alter hydrology remains unanswered. *Messinger* [2003] observed drastically different runoff responses in a heavily MTM-impacted catchment (49.2 ha; 44% MTM/VF) and moderately MTM-impacted catchment (567.2 ha; 12% MTM/VF) across multiple storm events indicating that the extent of mining and catchment size are likely factors influencing outlet responses.

Climatic thresholds such as depth and rate of precipitation and antecedent moisture conditions should be explored in future research. *Messinger* [2003] observed a threshold of 25mm hr^{-1} in precipitation intensity that dictated whether peak unit flow was greater in a MTM-impacted catchment (> 25 mm hr^{-1}) or a forested catchment (< 25 mm hr^{-1}). Establishing thresholds in this light is particularly relevant for engineers, land managers, and regulators tasked with managing the environmental impacts of the post mined landscape.

5. Concluding remarks

MTM represents a dramatic disturbance to the landscape with local and regional impacts. In spite of MTM's scale of disturbance and potential for future growth, key knowledge deficits regarding its hydrologic consequences exist. Water storage and movement in these disturbed landscapes has critical implications for the well documented downstream water quality issues associated with this mining practice. The culpability of surface mining operations in extreme flooding events in the Appalachian coalfields is still being debated amongst citizens, industry, and regulators. Thus, hydrologic studies of the impacts of MTM play a critical role in elucidating the consequences of this mining practice.

Most investigations into the hydrologic impacts of surface mining involve tradition contour and strip techniques with occur at different scales and do not consider the role of VFs which present additional uncertainties. These studies demonstrate that since the enactment of SMCRA, heavily compacted mine surfaces have decreased infiltration capacity [e.g., *Jorgensen and Gardner*, 1987] and woody vegetation [e.g., *Conrad et al.*, 2002] and consequently produce flashier, higher magnitude runoff responses to storm events [e.g., *Negley and Eshleman*, 2006]. Few studies have explored the nature of water storage and release of VFs in contemporary MTM operations; *Wunsch et al.* [1999] describe water movement in a large spoil pile from MTM operations as simultaneously slow in the spoil in the spoil interior and rapid in the buried stream valleys. Previous studies of the hydrologic impacts MTM operations have been successful in establishing a range of possible hydrologic responses to MTM, but these authors stress that heterogeneity in catchment characteristics and responses limits our understanding of the downstream consequences and warrants further investigation [*Messinger*, 2003; *Phillips*, 2004; *Wiley and Brogan*, 2003].

MTM's expected proliferation in the coming decades [*Townsend et al.*, 2009] coupled with the adjacency of communities to streams and rivers in the Central Appalachian coalfields makes understanding the hydrologic consequences of this practice necessary. Such progress will ultimately depend on expanding the number of hydrology studies in the Central Appalachian coalfields and concentrating research efforts to the physical processes that control hydrologic response in these disturbed systems.

6. References

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7. Figures

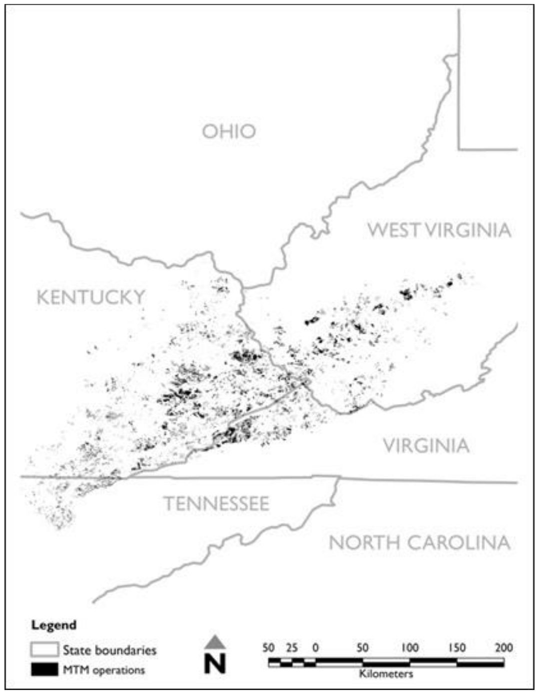

Figure 1. MTM operations of the Central Appalachian coalfields. The *US EPA* [2011]estimates that 6.7% of this predominantly forested region has been impacted by MTM and approximately 4000 km of headwater streams have been buried under VF. MTM boundaries remote sensed from aerial photography by SkyTruth (methodology described here: https://dl.dropboxusercontent.com/u/17278551/SkyTruth-MTR-methodology.pdf)

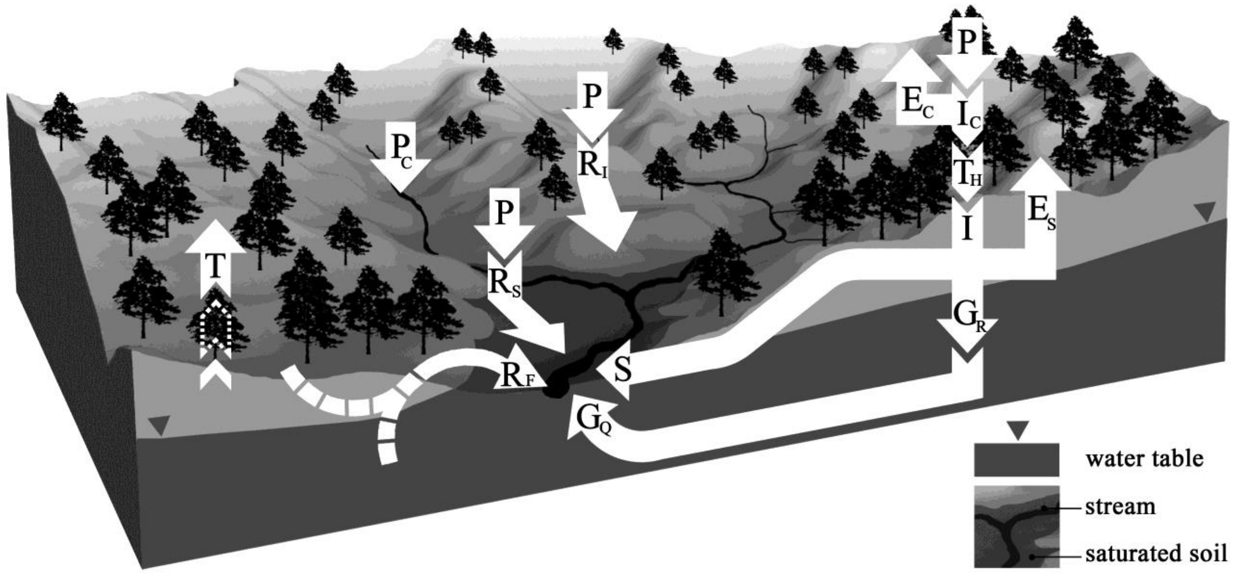

Figure 2. Conceptualization of the headwater catchment hydrologic processes. Water is added to the catchment as precipitation (**P**), some of which falls directly into the stream channel ($\mathbf{P_C}$). Precipitation falling on forested hillslopes is intercepted by the tree canopy ($\mathbf{I_C}$) and is either lost to evaporation ($\mathbf{E_C}$) or falls to the forest floor as throughfall ($\mathbf{T_H}$). On the forest floor, water is infiltrated (**I**) into the soil and is either lost to evaporation ($\mathbf{E_S}$) and plant transpiration (**T**) or percolates to the water table and becomes groundwater recharge ($\mathbf{G_R}$) which will be stored then discharged to the stream channel ($\mathbf{G_Q}$) or to the adjacent riparian area as return flow ($\mathbf{R_F}$). Infiltrated water may also take shallow subsurface flow paths as matrix flow or through macropores and soil pipes (**S**). Water not infiltrated into the soil will either be lost to evaporation or runoff to the stream channel as infiltration excess overland flow ($\mathbf{R_I}$). Precipitation falling on saturated soil becomes saturation excess overland flow ($\mathbf{R_S}$).

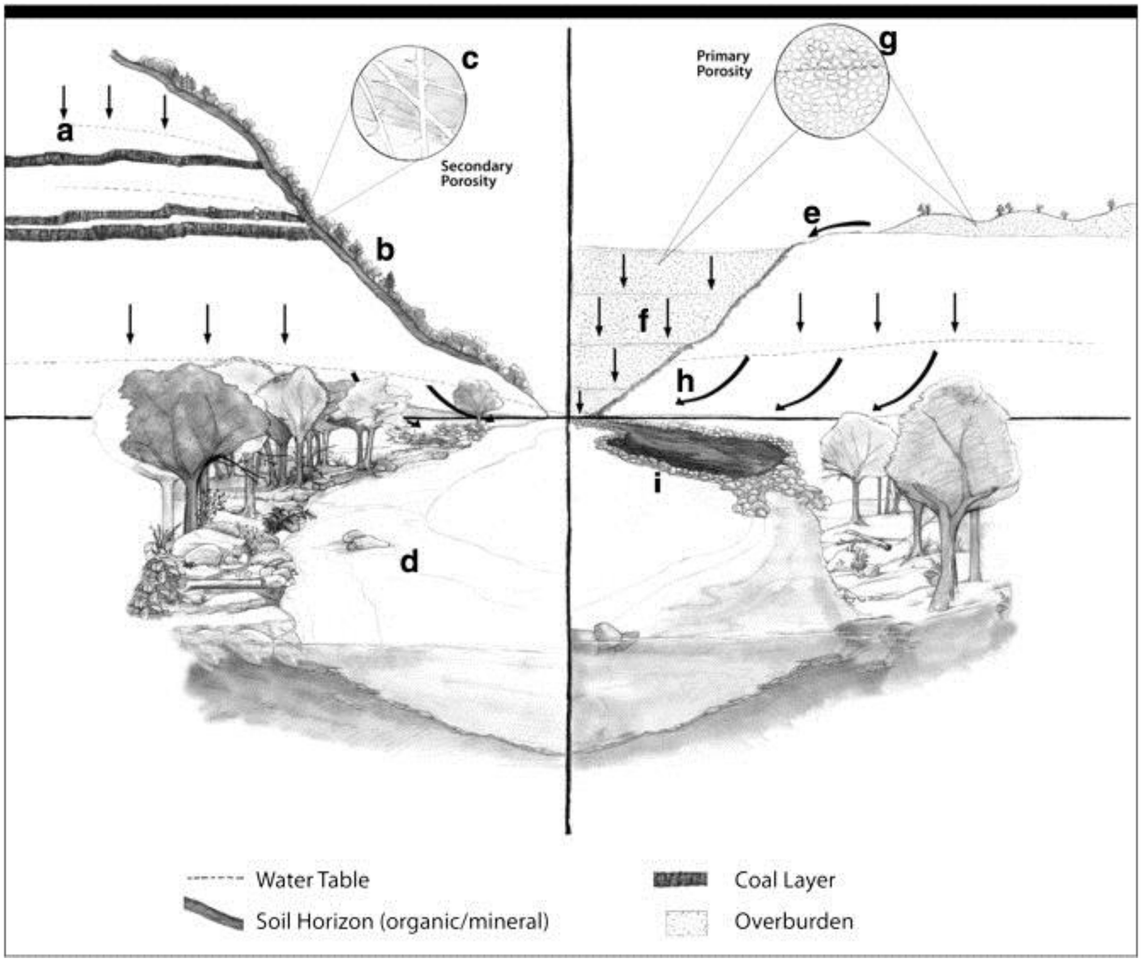

Figure 3. A conceptual model of the hillslope (upper) and stream channel (lower) are shown for pre-mining (left) and post-mining (right) conditions. The natural topography, drainage features, and geologic strata are shown for a headwater catchment in the Central Appalachian coalfields. Valleys contain naturally formed stream channels which drain hillslopes primarily through a subsurface system of local aquifers (a), soil layer interflows (b), and minute stress fractures in the geologic strata of the parent mountain (c). During mining, vegetation, soil, and overburden are removed, crushed, and then replaced in the stream valley and mine surface. Infiltration on minesoils is diminished due to the increased bulk density and decreased porosity of the soil surface (g). Therefore surface runoff into constructed drainage channels (e) and valley fills (f) is increased (height of valley fill is approximate). Water movement through the valley fill is not adequately understood but is generally considered to be slow, thereby increasing the contact with unweathered rock and increases baseflow. Groundwater flow in adjacent intact geologic strata (h) may become obstructed by the valley fill and delay its flow path to the stream, further augmenting baseflow. Water is generally routed through a sedimentation pond (i) before entering the stream. Original figure from *US EPA* [2011]; modified by *Griffith et al.* [2012].

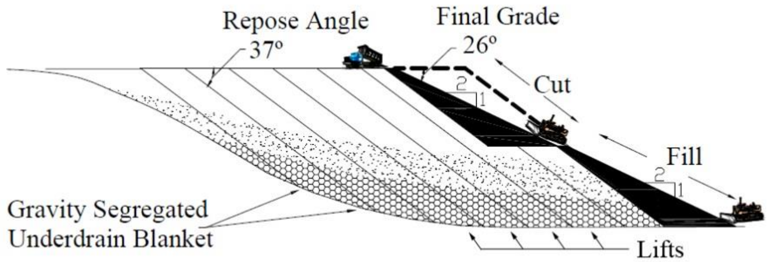

Figure 4. A diagram of durable rock fill VF construction process. Durable spoil is end-dumped in lifts and the VF face is graded into less steep terraces. An underdrain is formed by gravity segregation of the spoil material. Figure modified from *Michael and Superfesky* [2007].

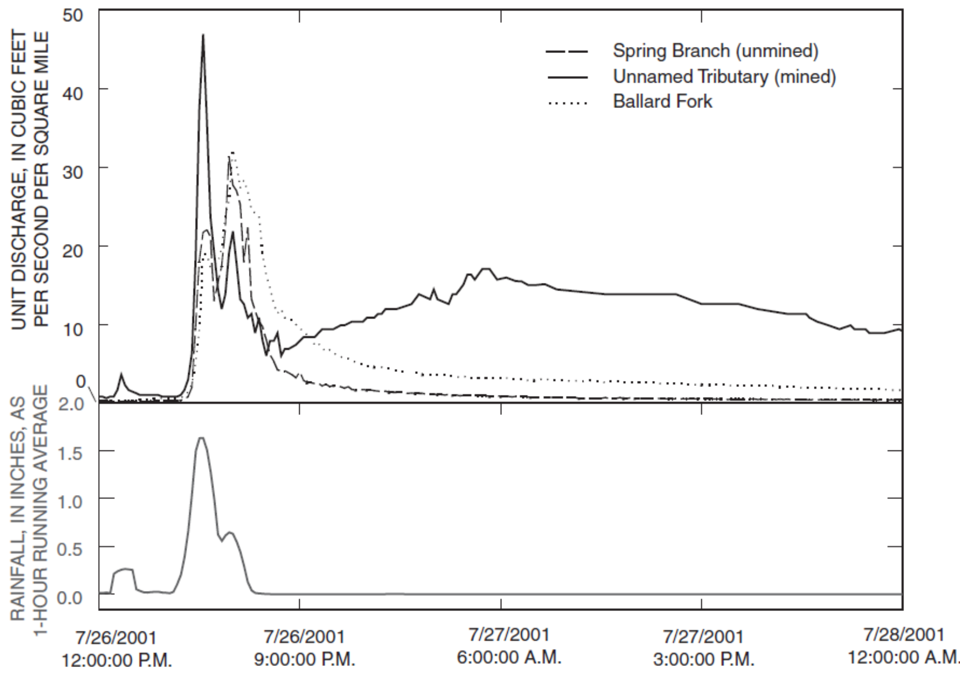

Figure 5. Storm hydrograph for July 26–28, 2001, for SB, UNT, and BF. UNT has a distinct double peaked hydrograph which the authors attribute to rapid surface runoff from the mine surface and a delayed peak caused by slow discharge from the VF. From *Messinger* [2003].

3. Characterizing runoff responses in a mountaintop mine impacted and forested catchment in the coalfields of West Virginia

1. Introduction

Mountaintop mining (MTM) and valley fill (VF) coal extraction practiced in the Central Appalachian region represents a dramatic change to the landscape. Post mining topography, vegetation, landuse, soils, and runoff pathways are severely altered during the mining process and subsequent reclamation. Surface mining represents the largest landcover/landuse change in the Central Appalachian region [*Sayler*, 2008] and by 2012, the U.S. EPA estimates that MTM/VF will have impacted approximately 6.8% of the predominately forested Appalachian Coalfield region of West Virginia, Kentucky, Tennessee, and Virginia with nearly 4,000 kilometers of headwater streams buried under valley fills [*USEPA*, 2011]. While the U.S. Energy Information Administration (US EIA) projects a reduction in Appalachian coal production through 2035, this decline is relatively minimal (-0.6%) indicating that the low-sulfur Appalachian Coal extracted by cost effective MTM/VF practices will continue to be a significant component to the United States' energy future [*US EIA*, 2012].

In spite of the magnitude, scale, and continued development of MTM/VF, its effect on catchment hydrology is poorly understood. While MTM/VF has a well-established pattern of downstream chemical and biological water quality degradation [*Lindberg et al.*, 2011; *Merriam et al.*, 2011; *Palmer et al.*, 2010; *Petty et al.*, 2010; *Pond et al.*, 2008], its effect on the quantity and timing of catchment runoff is less clear. Much of our understanding of impacts of MTM/VF is based on earlier studies of surface contour and strip mining which often occur at different scales and in different topography. Additionally, VFs present complexities to catchment hydrology that have not been fully explored. There have been few headwater catchment scale studies that assess the hydrologic impacts of MTM/VF and no studies of streamflow generation processes in this region. The limited existing literature on MTM/VF indicates that there is considerable variability in responses to disturbance across different catchments [*Wiley and Brogan*, 2003; *Wiley et al.*, 2001], climate events [*Messinger*, 2003], and scales [*Zégre et al.*, 2013].

Exacerbating these knowledge gaps is a general lack of understanding of non-MTM catchments in the Central Appalachian coalfields. While extensive research on Appalachian hydrology has been conducted at the Coweeta Hydrologic Laboratory to the south and the Fernow Experimental Forest to the north, the knowledge we can draw from these longterm catchment studies is limited because of differences in climate, geology and the legacy of land disturbances in the Central Appalachian coalfields. Thus there is a need not just to understand the hydrologic impacts of MTM/VF, but also to frame this impact as a change in an already disturbed landscape.

The objectives of this study are to 1) characterize rainfall-runoff responses in a forested and MTM headwater catchment using rainfall-runoff data 2) use a transfer function rainfall-runoff model to quantify response times for storm events and 3) use the stable isotopes of water for hydrograph separation to gain a preliminary understanding of headwater catchment processes.

2. Background

2.1 Landcover disturbance

The study of landcover disturbance and its consequences has garnered much attention in multiple scientific fields in the past decade [*Eshleman*, 2004]. Within hydrology, disturbance in forested catchments has been extensively studied in the context of timber harvesting [e.g., *Hornbeck et al.*, 1970; *Jones and Grant*, 1996; *Thomas and Megahan*, 1998], agriculture [e.g., *Potter*, 1991], and urbanization [e.g., *Gremillion et al.*, 2000; *O'Driscoll et al.*, 2010; *Rose and Peters*, 2001]. Landcover disturbance in forested catchments has the potential to alter hydrology by a number of mechanisms. Most importantly, intensive vegetation removal reduces interception and transpiration [e.g., *Jones and Grant*, 1996]. Changes to the soil surface either through compaction or impervious surface can alter how water is stored and transported within the catchment [e.g., *Gremillion et al.*, 2000; *Jones et al.*, 2000; *Ritter and Gardner*, 1993]. MTM/VF represents both of these impacts as well as significantly altering the topographic organization of headwater catchments.

The Central Appalachian coalfield region has undergone a series of dramatic catchment disturbances in the past 150 years. Clear-cut timbering of old growth deciduous forest in the late 19th and early 20th century was the first major alteration to the landscape. Extensive underground mining of bituminous coal started in the early 20th century and continues today. Due to the region's steep topography, much of the human infrastructure such dwellings, small agriculture plots, transportation networks (roadways and rail lines), and utility lines are located in the narrow but flat floodplains areas along streams and rivers. This proximal impact not only has the potential to alter coalfield hydrology, but it also makes the social and economic consequences of hydrologic change much more severe. Yet little is known about Central Appalachian catchment hydrology, particularly in the context of this legacy of disturbance.

2.2 Surface coal mining

Surface coal mining is a dominant form of disturbance in the Central Appalachian coalfields. MTM/VF is a special form of surface mining adapted to mountainous terrain in which the forest, topsoil, and overlying bedrock (as much as 300 vertical m [*Peng*, 2000]) is removed using explosives and heavy machinery to gain direct access to deeper coal seams [*USEPA*, 2011]. Because the expanded volume of displaced overburden often precludes reforming the ridge tops, much of this excess material is placed in adjacent headwater stream valleys to create VFs, which bury headwater streams and springs. Mined areas are reclaimed to "approximate original contour" (AOC) predicated by the Surface Mining Control and Reclamation Act (SMCRA) [*US Congress*, 1977], though the interpretation and enforcement of AOC is deferred to state regulatory agencies and variances to AOC are often granted with approved post mining land use plans.

The primary objective of reclamation since the passage of SMCRA has been on slope and soil stability to prevent soil erosion from the mine surface [*Angel et al.*, 2006]. As a result, mine soils are heavily compacted [*Bussler et al.*, 1984; *Chong and Cowsert*, 1997] using heavy machinery and fast growing, non-native herbaceous cover is seeded to quickly establish a vegetative surface [*Holl*, 2002]. Consequently, reclaimed mine soils generally have reduced infiltration capacity [*Guebert and Gardner*, 2001; *Negley and Eshleman*, 2006; *Ritter and Gardner*, 1993] and infiltration excess overland flow becomes the primary drainage mechanism on mined surfaces [*Guebert and Gardner*, 2001; *Ritter and Gardner*, 1993]. As a result, several studies have found increases in peak discharge and total runoff and flashier runoff responses at the headwater [*Bonta et al.*, 1997; *Bryan and Hewlett*, 1981; *Negley and Eshleman*, 2006] and river basin scale [*Ferrari et al.*, 2009; *McCormick et al.*, 2009].

VFs present additional complexities in quantifying the impact of MTM/VF. Much of our knowledge of VF hydrology is limited to studies on mine spoil redistributed on the mine surface and not contemporary VF associated with MTM operations. Mine spoil has been shown to act as a storage reservoir within the catchment [*Dickens et al.*, 1989]. Others have described mine spoil as "pseudo-karst" where highly permeable channels within the backfill form an interconnected drainage network [*Caruccio and Geidel*, 1995]. This dichotomy is further explored by *Wunsch et al.* [1999] in a comprehensive study of groundwater storage and movement in large mine spoil areas in eastern Kentucky that are more representative of the scale of contemporary MTM/VF operations. Results showed that the spoil interior placed on the low gradient mine surface maintained a saturated zone that slowly discharged to lower areas while fill placed in stream valleys were fed by adjacent bedrock aquifers and surface-water infiltration at the bedrock-spoil interface and rapidly transported groundwater [*Wunsch et al.*, 1999].

The existing literature on the hydrologic impacts on MTM/VF is limited. While a consistent trend of hydrologic alteration has been observed, the exact nature of this change is highly variable. One consistent observation is the dramatic increase in baseflow in MTM/VF impacted catchments due to the storage and slow release of water from VFs [*Messinger*, 2003; *Messinger and Paybins*, 2003; *Wiley et al.*, 2001]. *Wiley et al.* [2001] observed a 6-7 times increase in the 90 percent flow durations at MTM/VF sites. Total unit runoff of in MTM/VF catchments is generally greater at both the storm [*Messinger*, 2003] and annual [*Messinger and Paybins*, 2003] time scales. More intense storm events (precipitation greater than 25 mm hr^{-1}) produced larger peak unit discharge at MTM/VF sites than forested catchments though the reverse was true for low intensity storms [*Messinger*, 2003]. *Wiley and Brogan* [2003] observed considerable variability in recurrence intervals for an intense storm event in July, 2001;

recurrence intervals varied from 2-100 years in MTM/VF catchments compared to 10-25 years in forested catchments. *Phillips* [2004] found similar variability in modeling subsurface and surface detention times of runoff in MTM/VF catchments in eastern Kentucky. Hydrologic change in MTM/VF catchments were attributed to compaction and subsequent infiltration rate reduction on mine soils [*Messinger*, 2003], reduction in *ET* due to forest clearing [*Messinger*, 2003], and water storage in constructed VF [*Messinger and Paybins*, 2003; *Wiley et al.*, 2001], but are quick to note that significant heterogeneity exists due to unique catchment topography, geology, extent of disturbance, reclamation stage and methodology, and climactic events [*Messinger*, 2003; *Messinger and Paybins*, 2003; *Phillips*, 2004; *Wiley and Brogan*, 2003; *Wiley et al.*, 2001]. Thus, there is a need for investigations into differences in catchment processes to understand this variable response to disturbance.

2.3 Stable isotope hydrology

The stable isotopes of water are a useful tool for tracing the source, movement, and age of water reservoirs. Oxygen and hydrogen isotopes are ideal tracers because they are constituents of the water molecule itself and are relatively conservative in their interactions with plant, soil, and bedrock material [*Kendall and Doctor*, 2003]. Reservoirs of water will develop different isotopic concentrations through fractionation processes (i.e. evaporation and condensation) as the difference in mass between heavy and light isotopes will cause different rates of state change [*Craig*, 1961]. Deviation in isotopic ratios from fractionation and mixing is generally linear and can be predicted and modeled [*Kendall and Doctor*, 2003]. Oxygen and hydrogen isotopes have multiple hydrologic applications, but have been particularly useful as a more objective method of storm hydrograph separation into event (i.e. precipitation) and pre-event (i.e. water stored in catchment soil and geology prior to the onset of rain) water sources [e.g., *Buttle*, 1994; *Sklash and Farvolden*, 1979]. Tracer based hydrograph separations that partition storm response into temporal and geographic sources of runoff provide insight into the mechanisms of streamflow generation. In light of the variability of runoff responses observed in catchments impacted by MTM/VF, isotopic and geochemical studies need to be coupled with hydrometric data to elucidate the processes that control runoff in these variable systems.

3. Methodology

3.1 Site description

This study took place in the headwaters of the Clear Fork of the Coal River in the southern coalfields of West Virginia (Figure 1). A forested and MTM-impacted catchment were selected to characterize two of the dominant headwater drainage systems in the region. The Clear Fork is located in the Appalachian Plateau and is characterized by rugged, deeply incised terrain. Ridges are narrow and winding with a dendritic drainage network dominated by ephemeral to perennial first order streams draining convergent hillslopes. Low slope areas are limited to ridge tops and valley bottoms and hillslopes are steep. The Clear Fork is underlain by sedimentary rocks of the Pennsylvanian Age, specifically the Kanawha Formation of the Pottsville Group [*Cardwell et al.*, 1968]. The Kanawha formation consists of massive beds of sandstone separated by thinner beds of shale, siltstone, and coal [*Ehlke et al.*, 1982]. Soils in the area are associated with the Clymer, Dekalb, and Jefferson (listed in order of prominence) soil series [*Ehlke et al.*, 1982]. Soil drainage is generally poor due to the thin soil mantels of the Clymer and Dekalb series. Groundwater movement occurs primarily in horizontal and vertical stress relief fractures and respond quickly to surface conditions [*Kipp and Dinger*, 1987; *Wyrick and Borchers*, 1981].

Consequently, water storage is limited which leads to rapid hydrograph response to precipitation and drought, even in forested catchments [*Adams et al.*, 2012]. Using a three-component mixing model for isotopic tracer-based hydrograph separation, *DeWalle et al.* [1988] report rapid storm responses dominated by soil and groundwater sources in a headwater catchment in central Pennsylvania, though the soil profile described in that study is thicker and more well-drained than those of the Central Appalachian coalfields.

This region experiences a humid continental climate with warm summers and cold winters. Average temperature during the warmest month (July) is 24 °C and average temperature during the coldest month (January) is 0.5 °C. Average annual precipitation from 1973-2010 measured nearby at Madison, WV is 1224 mm [*Zégre et al.*, in review]. The distribution of precipitation is influenced by prevailing wind direction and surface topography and is generally derived from frontal or tropical storm systems. Intense rainfalls frequently exceed 100 mm in a 24 h period [*Ehlke et al.*, 1982]. Catastrophic flooding in small catchments (<1000 km^2) in this region are dominated by orographic and convectivevthunderstorms [*Smith et al.*, 2011].

Sycamore Creek (SYC, 37°56.47' N, 81°26.01' W) is a 25.5 km^2 drainage that flows from south to north until it discharges into the Clear Fork of the Coal River at the town of Colcord, WV (Figure 1). The predominant landcover in the catchment is 2nd growth and 3rd growth deciduous forest (Table 1). No surface mining occurred during this study, though contour mining on the southwestern ridge of the catchment occurred during the late 1970s but has since been reclaimed to forest. Analysis of aerial photography shows the tree canopy in this area is closed, with the un-reclaimed highwall the only visible remnants of mining operations.

SYC has a number of legacy disturbances that are common throughout the central Appalachian coalfields. Substantial underground mining of coal has occurred in the eastern, southern and western hillslopes of SYC. The West Virginia Geologic and Economic Survey (WVGES) has extensively mapped the coal geology and mining activity in this region. WVGES data indicates that the six coal seams of the Kanawha Formation have been mined below the surface in the catchment area. Several small natural gas wells have been drilled in the central valley of SYC. The well pads are small, but require a gravel road that parallels Sycamore Creek through the length of the central valley. Two deforested right of ways cross SYC: a 50m – wide natural gas pipeline in the southern half of the catchment and a 30m – wide electric transmission line that runs north-south, paralleling Sycamore Creek for much of its length. SYC has been timbered throughout its history though no active forest harvesting operations occurred during the time period of this study. Light residential development is located in the broad floodplain near the catchment outlet, but is downstream from the stream gaging station.

White Oak Creek (WOC, 37°56.47’ N, 81°19.93’ W) drains primarily east to west until it discharges into the Clear Fork of the Coal River at the town of Artie, WV (Figure 1). The stream gage is located approximately 3.4 km upstream of the catchment outlet, draining a 6.5 km^2 area. Approximately 70% of the catchment area of WOC is 2nd and 3rd growth deciduous forest (Table 1). Non-forested landcover is primarily MTM/VF operations on the southern and eastern ridges of WOC. Approximately 1.12 km^2 (17.3%) of the catchment area is impacted by MTM with another 0.11 km^2 (1.6%) under a large, partially reclaimed VF. The MTM area can be classified into three distinct stages: in preparation (3.9%), active mining (10.3%), and reclaimed (3.1%). Areas in preparation are characterized by the excavation of terraces around the section of mountain to be excavated, initial removal of vegetation and development of temporary road networks. Actively mined areas are completely devegetated and are undergoing active excavation. Reclaimed areas have been regraded and revegetated with herbaceous grasses and minimal woody vegetation.

Surface contour mining occurred on the mid-hillslopes of WOC during the mid-1990s. As part of this mining operation, seven small valley fills were created on the incipient drainage network of WOC, though these structures are significantly smaller than contemporary VFs associated with MTM. The total disturbed area from contour mining in WOC is approximately 0.75 km^2 (11.6%) all of which has been revegetated and reclaimed to the standards set by SMCRA. Typical of surface mining operations, two retention ponds (both approximately 0.25 ha) were constructed on White Oak Creek to control the amount of fine sediment transported downstream.

Extensive underground coal mining has occurred in WOC and adjacent catchments. WVGES data shows that seven seems of coal have been mined in the northern, eastern, and southern ridges that form the WOC catchment. Much like SYC, forested areas in WOC have been regularly timbered. Outside of MTM areas, no timber extraction occurred in WOC during the study period. Residential development is limited in the valley floor adjacent to White Oak Creek immediately upstream of the stream gage (0.07 km^2; 1.01% of WOC). Residential lawns are the dominant landcover type and impervious surface from roofs and paved areas is minor.

3.2 Hydrometeorological Measurements

Few headwater catchments have been gaged in the Central Appalachian coalfields [*Zégre et al.*, 2013]. Therefore, an objective of this study was to instrument two headwater catchments representing two common types of headwater catchment in this region: forested and MTM. Stream and precipitation gaging stations were installed in SYC and WOC (Figure 1).

Precipitation and discharge were measured for 13 month period from 01 September 2011 to 30 September 2012. Campbell Scientific (Logan, UT, USA) CR800 data loggers were used to record stream stage measured with a CS450 pressure transducer placed in the stream channel; electric conductivity and stream temperature were measured with the CS547A-L conductivity probe in 10-minute intervals in each catchment. Campbell Scientific TE525-L tipping bucket rain gages were used to measure the volume and temporal distribution of precipitation in each catchment and were also recorded using a CS800 data logger. Air temperature and relative humidity were measured in SYC whereas only precipitation was measured in WOC.

Streamflow was measured using both salt tracer dilution methodology described by *Hudson and Fraser* [2005] and velocity area methodology [*Turnipseed and Sauer*, 2010] using a SonTek Handheld Acoustic Doppler Velocimeter to develop stage/discharge relationships. The stage/discharge relationship was used to estimate streamflow from continuous stage measurements in each catchment. The stage-discharge rating curve in SYC included 10 observations of discharge ranging from 1.00×10^{-3} – 0.84 mm hr^{-1} ($r^2 = 0.99$); the rating curve in WOC included 8 observations of discharge ranging from 0.02 – 1.21 mm hr^{-1} ($r^2 = 0.99$). Only discharge measurements from the velocity area method were used in the development of stage/discharge rating curves; salt tracer discharge measurements were only used to verify velocity area derived discharge measurements. Seven months into the study period, the stream gaging station at SYC was moved approximately 5 meters downstream to a bedrock controlled pool to minimize measurement error associated with channel sedimentation and instability. The original pressure transducer elevation was surveyed and marked using a 1 m rebar pin to develop a correction factor between stage measured at both locations.

Twenty-three rainfall events with complete hydrologic records were selected for analysis during a 13 month period from 01 September 2011 to 30 September 2012 (Figure 2). Storm events during winter months (December – February) were not included in this analysis because rainfall-runoff relationships may be altered by below freezing temperatures. The start of a storm event period was defined as one hour prior to the onset of rain and the end of a storm event was delimited by a return to the stream level prior to precipitation (i.e. baseflow) or when stream recession was interrupted by a 2nd storm event. Storms were analyzed for rainfall duration, total precipitation, storm intensity, maximum precipitation intensity, total unit discharge, unit discharge to precipitation ratio, peak unit discharge, time to peak discharge from the onset of rain, and time lag from peak precipitation intensity to peak discharge. Storm event hydrograph separation into quick flow and baseflow was performed for each of the 23 storm events using the method by *Hewlett and Hibbert* [1967] with a slope constant of 0.002 mm hr^{-1}. Separation of the average daily flow hydrograph for the duration of the study period was performed using PART developed by *Rutledge* [1998].

3.3 Rainfall-runoff modeling

Rainfall-runoff models have been frequently used to discern catchment-level changes in hydrology resulting from forest harvesting [e.g., *Seibert and McDonnell*, *2010; Zégre et al.*, 2010], forest fire [e.g., *Seibert et al.*, 2010], agriculture, [e.g., *Schreider et al.*, 2002], surface mining [e.g., *Ferrari et al.*, 2009; *Negley and Eshleman*, 2006], and a mosaic of landuse changes [e.g., *Hundecha and Bardossy*, 2004; *Ott and Uhlenbrook*, 2004]. More recently, *Nippgen et al.* [2011] demonstrated the utility of rainfall-runoff models in assessing landscape structure and climate on catchment hydrologic response time, defined as the time it takes a for a catchment to produce a runoff response equal to a given volume of effective precipitation [*Nippgen et al.*, 2011]. Response time is a fundamental hydraulic parameter the controls the conversion of rainfall to runoff [*Weiler et al.*, 2003]. Transfer function models date back to early unit hydrograph analysis [*Dooge*, 1959; *Nash*, 1958] where an amount of excess precipitation is convolved into the unit hydrograph and translated into runoff [*Jakeman and Hornberger*, 1993].

In this study we used transfer function rainfall-runoff developed by *Jakeman and Hornberger* [1993] that is included as a routine in the Transfer Function Hydrograph Separation Model (TRANSEP) [*Weiler et al.*, 2003] to model runoff for the 23 storm events in our study period. This model consists of a non-linear module that converts precipitation into effective precipitation (i.e. rainfall that produces as runoff response) and a linear module that transforms the effective precipitation input into streamflow. The non-linear loss function that calculates effective precipitation from precipitation is defined by:

$$s(t) = b_1 p(t) + (1 - b_2^{-1}) s(t - \Delta(t)), \quad (1)$$

$$s(t = 0) = b_3, \quad (2)$$

$$P_{eff}(t) = p(t)s(t), \quad (3)$$

where $s(t)$ is the antecedent precipitation index; b_1 maintains the water balance so that total effective precipitation equals total runoff; b_2 determines the rate at which the catchment dries out; b_3 sets the initial state of catchment wetness at the beginning of the timeseries; P_{eff} is effective precipitation; and $p(t)$ is the measured precipitation input at time t. The linear module describes the convolution of the effective precipitation and runoff transfer function by

$$Q(t) = \int_0^t g(\tau) P_{eff}(t - \tau) d\tau, \qquad (4)$$

where $Q(t)$ is runoff at time t, and $g(\tau)$ is the runoff transfer or unit hydrograph function, thus the modeled catchment runoff is a product of an effective precipitation input convolved with a transfer function.

Based on the authors' experience, the two parallel linear reservoirs (TPLR) model better portrays runoff dynamics in our headwater catchments and was used in this study to determine $g(\tau)$. A preliminary exploration of other models (gamma, exponential, exponential piston flow, [see *Lyon et al.*, 2008; *Weiler et al.*, 2003] showed inferior performance compared to TPLR but future research should more thoroughly explore alternative model structures. TPLR is defined as:

$$g(\tau) = \frac{\Phi}{T_f} \exp\left(-\frac{\tau}{T_f}\right) \frac{1 - \Phi}{T_s} \exp\left(-\frac{\tau}{T_s}\right) \qquad (5)$$

where T_f and T_s are the average residence times of fast and slow responding reservoirs, and the parameter Φ defines the fraction of runoff response from the fast responding reservoir. Parameters in equations 1, 2, and 5 were calibrated to observed stormflow in 10 minute increments using 100,000 Monte Carlo simulations. Model performance for each simulation was evaluated using the Nash-Sutcliffe efficiency (*NSE*) objective function [*Nash and Sutcliffe*, 1970] where complete agreement between measured and modeled discharge results in a *NSE* = 1. Response time (RT_{med}) of the top 1% best performing models for each storm event in SYC and WOC was calculated from the response time cumulative distribution function and represents the median time for a catchment to discharge an input equal to effective precipitation.

3.4 Isotopic data collection and analysis

While process level studies have been conducted in Appalachia [e.g., *DeWalle et al.*, 1988; *DeWalle et al.*, 1997; *McGuire et al.*, 2002; *O'Driscoll et al.*, 2005], none have been conducted in the Central Appalachian coalfields. Therefore, it was our objective to use the stable isotopes of water for hydrograph separation to gain a preliminary understanding of streamflow generation processes in MTM and forested headwater catchments. Isotope sampling occurred throughout the study period except for a four month period from December 2011 to March 2012. At each station, automated water samplers (model 3700, Teledyne ISCO, Inc., USA) collected water samples from precipitation and streamflow. Automated samplers at each precipitation station were synchronized so that incremental samples were taken every hour (or after a 7.0 mm threshold was exceeded) throughout each storm to capture isotopic variation during precipitation events [*Heathcote and Lloyd*, 1986; *Matsuo and Friedman*, 1967] and allow each part of the storm to be appropriately weighted for mixing models. Similarly, automated samplers at stream gaging stations were integrated with stage recorders so that stream samples were taken daily during baseflow conditions and more frequently (3-6 h increments) during the rising, peak, and falling limb of the event hydrograph. ISCO bottles were lined with 2 oz Nasco sample bags pre-treated with mineral oil to prevent fractionation from evaporation. Stream and precipitation samples were separated from mineral oil by puncturing the bottom of the sample bag and draining into a 25 mL cone capped scintillation vial for storage until processing.

To determine the composition of deuterium (δD) and oxygen-18 ($\delta^{18}O$), stream and precipitation samples were analyzed on a laser liquid-water istope spectrometer (DLT-100 Version 2, Los Gator Research, Inc., USA) at the West Virginia University Watershed Hydrology Laboratory in Morgantown, WV. Laboratory standards were developed using

Hawaiian spring water (enriched with heavy isotopes), Colorado spring water (depleted of heavy isotopes), and Morgantown distilled water (approximately between Hawaii and Colorado spring water isotopic compositions). In house standards were calibrated against the Vienna-Standard Mean Ocean Water (VSMOW) issued by the International Atomic Energy Association (IAEA). For a detailed description on the operations of the DLT-100, see *Lyon et al.* [2009]. Isotope values are reported as delta (δ) permil (‰) relative to VSMOW where δ is calculated by:

$$\delta\ (in\ ‰) = (R_{sample}/R_{VSMOW} - 1)\ x\ 1000, \qquad (6)$$

where *R* is the ratio of heavy to light isotopes [*Craig*, 1961].

A two-component mixing model is commonly used for tracer based hydrograph separations [e.g., *Brown et al.*, 1999; *Buttle*, 1994; *Sklash and Farvolden*, 1979] and was applied in this study. The two-component mixing model is defined as:

$$Q_tC_t = Q_{pe}C_{pe} + Q_eC_e, \qquad (7)$$

where Q_t is streamflow, Q_{pe}, and Q_e represent the respective contributions from pre-event and event water, and C_t, C_e, C_{pe} are the associated tracer (e.g. δD and δ^{18}O) concentrations. Because isotopic concentration of precipitation often varies dramatically during storm events [*Heathcote and Lloyd*, 1986; *Matsuo and Friedman*, 1967], isotopic composition of rainfall was weighted incrementally by intensity using the following equation:

$$\delta D = \frac{\sum_{i=1}^{n} Ii\delta i}{\sum_{i=1}^{n} Ii}, \qquad (8)$$

where I_i is the average mm hr^{-1} rainfall intensity during the sampling increment, δ_i is the measured isotopic composition of precipitation during that increment [*McDonnell et al.*, 1990].

TRANSEP, a more complex two-component mixing model, was also utilized for tracer based hydrograph separations to account for the temporal variability of the isotopic composition of rainfall. Only brief description TRANSEP's framework is provided here; for a more thorough description of TRANSEP's model structure see *Weiler et al.* [2003]. TRANSEP integrates the instantaneous unit hydrograph into hydrograph separation through three sequentially optimized modules. First, the runoff module is described in *Section 3.3* calculates effective precipitation and convolutes this input into streamflow using a user-selected transfer function. This effective precipitation input is partitioned into rainfall producing event water and rainfall activating pre-event water using the same non-linear loss module described for the runoff module. The event water module routes the event water fraction of effective precipitation through the catchment using the transfer function described in the runoff model to simulate isotopic concentrations of streamflow during the storm event and is optimized to measured concentrations in the stream. The pre-event module routes the remaining fraction of effective precipitation through the catchment with the transfer function and is optimized to pre-event runoff calculated by subtracting the event water runoff calculated in 2nd module from measured streamflow. The runoff, event, and pre-event modules are optimized using ant colony optimization (ACO) [*Abbaspour et al.*, 2001] where the optimum parameter set is obtained by iteratively optimizing the model to a measured solution and model efficiency is measured by an objective function. It has been shown that ACO is effective in finding the optimum solution [*Weiler et al.*, 2003] but future research should utilize Monte Carlo simulation to assess parameter identifiability in tracer modules.

4. Results

4.1 Hydrometric data

Streamflow and precipitation during the 13 month study period are shown in Figure 2. Precipitation (*P*) totaled 1511 mm in SYC and 1470 mm in WOC during the study period. Based on the US Geological Survey (USGS) water year (01 October 2011 to 30 September 2012), *P* in SYC and WOC averaged 1337 mm. This is slightly greater than the 1231 mm average annual *P* measured at Dry Creek, WV (COOP Station 462462; 9.5 km from SYC and 14.5 km from WOC) from 1969 to 2008. *P* was distributed throughout the study period but was more concentrated in the spring and early summer.

Total discharge (Q_t) for the study period totaled 322 mm (21% of *P*) in SYC and 914 mm in WOC (62% of *P*). 72% and 68% of Q_t in SYC and WOC were recorded during the dormant season from November – April [*Adams et al.*, 2012]. Runoff was dominated by baseflow (Q_b) in both SYC (73% of Q_t) and WOC (91% of Q_t). The fraction of Q_b in Q_t in WOC remained constant (91%) through the dormant and growing season in WOC, but varied from 74% in dormant months to 57% during the growing season in SYC. Unit flow duration in WOC was characterized by substantial differences in streamflow values during rarely exceeded flows (0 – 10%, i.e. flow during storm events) but considerably less variability during moderately and frequently exceeded flows (Figure 3). Unit flow duration in SYC shows a similar pattern as WOC for rarely exceeded flows, but much greater differences in streamflow for moderately and frequently exceeded flows.

Precipitation totals for the 23 storm events ranged from 12.7 mm to 90.9 mm with a median of 32.7 mm and a standard deviation of 20.4 mm. Storm intensity ranged from 0.2 to 14.7 mm hr^{-1} with a median of 0.8 mm hr^{-1} and a standard deviation of 2.7 mm hr^{-1}. Generally speaking, storm events during the dormant season (November – April) were lower intensity, longer duration events with more total precipitation, whereas storms during the growing season (May-October) were shorter duration, higher intensity storms with less total rainfall. While there was some inter-catchment variability between climate characteristics for the same storm event, no statistically significant differences were observed in total precipitation, storm intensity, and maximum instantaneous intensity (mm 10 min^{-1}) using a Wilcoxon signed rank sum test (α = 0.05) (Figure 4).

Runoff responses between the two catchments were highly variable and significantly differed (Figure 5, Table 2). Median total unit discharge (Q) was 5.5 mm (range: 0.6 – 30.4 mm, SD: 7.4 mm) in SYC and 16.4 mm (range: 1.1 – 57.5 mm, SD: 14.2 mm) in WOC. Median ratio of streamflow to precipitation (Q/P) was 0.16 in SYC (range: 0.03 – 0.73, SD: 0.08) and 0.36 in WOC (range: 0.07 – 1.02, SD: 0.10). Median peak discharge was 0.09 mm hr^{-1} (range: 0.01 – 0.58 mm hr^{-1}, SD: 0.14 mm hr^{-1}) in SYC and was 0.19 mm hr^{-1} (range: 0.05 – 1.30 mm hr^{-1}, SD: 0.27 mm hr^{-1}) in WOC. The temporal runoff response to precipitation varied between the two catchments. The median time from onset of precipitation to peak Q was 17.8 hr in SYC (range: 1.2 – 86.5 hr, SD: 23.4 hr) and 19.7 hr in WOC (range: 1.5 – 84.0 hr, SD: 22.8 hr). The time lag from peak precipitation to peak discharge showed similar patterns; median time lag was 11.3 hr in SYC (range: 1.0 – 55.3 hr, SD: 15.1 hr) and 5.0 hr in WOC (range: 0.8 – 65.2 hr, SD: 16.0 hr).

Storm hydrographs were separated into baseflow (Q_b) and quickflow (Q_q) using the method methodology of *Hewlett and Hibbert* [1967]. Surprising, only a small fraction of the total storm response was determined to be Q_q. The average ratio of Q_q to total discharge ($Q_{q:t}$) was 0.17 (range: 0.02 – 0.43; SD: 0.14) in SYC while substantially lower in WOC, 0.05 (range: 0.00 – 0.46, SD: 0.11). $Q_{q:t}$ varied seasonally where $Q_{q:t}$ was greatest during the dormant season and smaller during the growing season. This seasonal variation was most evident in SYC where average $Q_{q:t}$ ranged from 0.15 (growing) – 0.29 (dormant), while WOC showed less variation (growing: 0.08, dormant: 0.13).

4.2 Rainfall-runoff modeling

RT_{med} was calculated from the top 1% best performing models (SYC average NSE = 0.95, WOC average NSE = 0.96) of 100,000 Monte Carlo simulations. The average RT_{med} of the top 1% best performing models were reported for each storm in SYC and WOC in Table 3. RT_{med} in SYC ranged from 9.2 to 68.4 hr with a median of 28.4 hr and a SD of 15.3 hr. RT_{med} in WOC ranged from 5.6 to 76.8 hr with a median of 24.6 hr and SD of 17.1 hr.

Median RT_{med} was greater during the dormant season for both SYC (dormant: 28.4 h, growing: 26.8 h) and especially WOC (dormant: 32.2 h, growing: 20.6 h). Variability in RT_{med} was also greater during the growing season in both catchments (Table 4). During the dormant season, the median of RT_{med} was more rapid in SYC (28.4 hr) than WOC (32.2 hr). This relationship was reversed during the growing season where WOC (20.6 hr) was more rapid than SYC (26.8 hr). Variability was similar in SYC and WOC during the dormant season but WOC experienced more variability than SYC during the growing season (Table 4).

The average parameter values for the top 1% best performing models are reported in Table 3. Parameter sets were remarkably similar in SYC and WOC. The median model parameters for the 23 storm events in SYC and WOC showed almost no difference between SYC

(b_1 = 0.01, b_2 = 4.06, b_3 = 0.40, T_f = 11.47 h, T_s = 112.88 h, and Φ = 0.36) and WOC (b_1 = 0.03, b_2 = 3.99, b_3 = 0.39, T_f = 11.60 h, T_s = 109.86 h, and Φ = 0.37). Inter-catchment trend similarly in parameters was consistent in both growing and dormant seasons. However, inter-seasonal variability was observed across both catchments (Table 4). During the dormant season, nonlinear loss parameters b_1, b_2, and b_3 were all larger than storms during the growing season, indicating that P_{eff} was greater dormant season events. Fast and slow reservoir residence times (T_f and T_s) were similar; however, a larger fraction of water was assigned to the fast reservoir (Φ) during the growing season (growing season median Φ = 0.36, dormant season Φ = 0.25).

4.3 Isotope hydrograph separations

Precipitation and stream samples were collected during storm events for the purpose of partitioning storm hydrographs into temporal sources of runoff. Only storm events where complete hydrologic and isotopic records of precipitation and streamflow in both SYC and WOC were used. Storm events where precipitation fell as snow were also removed from the analysis. Following these criteria, only 9 events (event 2, 5, 13, 14, 15, 17, 20, 21 and 23) were analyzed (Table 5). Storm events were partitioned into pre-event (Q_{pe}) and event water (Q_e) using two approaches (1) a simple, two-component mixing model where temporally variable precipitation samples were weighted by precipitation intensity [*McDonnell et al.*, 1990] and (2) TRANSEP model where the TPLR is utilized as the model transfer function [*Weiler et al.*, 2003]. Two-component separations where an incremental value of Q_{pe} or Q_e was negative were considered unsuccessful. Likewise, TRANSEP separations where the runoff, event tracer, or pre-event tracer modules resulted in *NSE* < 0.50 were deemed ineffective (Table 5).

Hydrograph separation of the temporal sources of runoff using the stable isotopes of water proved to be ineffective for these catchments. Of the 9 events with complete isotopic records, only one (event 20) was successfully separated using the two-component and TRANSEP model. In many events, the signature of event water from the precipitation event was not apparent in the sequential samples of streamflow or this signal was lost to the natural variability of the isotopic composition of stream water in SYC and WOC (Figure 6). Considerable temporal variability was observed in the isotopic composition of precipitation; rainwater earlier in the storm event was significantly more enriched than pre-event stream water but rapidly depleted throughout the storm event. Changes in isotopic composition of precipitation of over 100 ‰ δD and 15 ‰ δ^{18}O were observed for certain events. This often resulted in the event water signal "crossing" the pre-event signal measured at the start of the storm event. While the two-component and TRANSEP models incorporate the temporal variability in the isotopic composition of precipitation, it is not possible to discern water sources with similar isotopic signatures [*Sklash and Farvolden*, 1979]. Therefore, any precipitation with similar isotopic composition to pre-event water will be unaccounted for in both models. The ineffectiveness of stable isotopes as tracers for hydrograph separation will be discussed further in the next section.

Event 20 was successfully partitioned into temporal sources of runoff using both the two-component (Figure 7) and TRANSEP (Figure 8) models. Runoff response in SYC and WOC was predominantly pre-event water (Table 6), a common observation in forested catchments [*Bonell*, 1993]. Little difference was observed between SYC and WOC in the total fraction of runoff attributable to event water (Q_e:Q_t); total Q_e:Q_t ranged from 0.22 – 0.24 in SYC and 0.21 – 0.28 in WOC through the different separation techniques and tracers (δD and δ^{18}O). Differences in

Q_e:Q_t at peak flow were observed between SYC and WOC. Peak Q_e:Q_t ranged from 0.35 – 0.43 in SYC but was significantly less in WOC, ranging from 0.17 – 0.26. Results of the other events (events 2, 21, and 23) mostly agree with a higher fraction of pre-event water in WOC compared to SYC (Table 5), but given the overall poor model performance, it is difficult, if not impossible, to draw conclusions about the temporal sources of runoff in these systems.

5. Discussion

5.1 Hydrometric data

Despite the similar amounts of total precipitation between SYC and WOC, runoff in WOC was nearly 3x that of SYC during the 13 month study period. Approximately 62% of precipitation in WOC becomes runoff while only 21% of precipitation in SYC leaves the catchment as streamflow. Daily baseflow determined by PART was substantially greater in WOC (91% of total Q) than SYC (73% of total Q), particularly during the growing season. Storm responses were also drastically different in SYC and WOC. For 23 storm events, median runoff responses in WOC were characterized by 3x greater unit discharge, 2x greater runoff ratios (Q/P), 2x greater peak unit discharges, 2x shorter time lags from peak precipitation intensity to peak Q, and one third $Q_{q:t}$ relative to SYC.

While the difference in the timing and magnitude of runoff between SYC and WOC is clear, the cause of this disparity is more ambiguous. Potential explanations are differences in catchment size, landscape alterations from MTM/VF operations, and legacy disturbance from underground mining. The degree to which each of these factors is affecting hydrology in each catchment is uncertain but is discussed below.

Catchment size

While reconciling variable hydrologic responses across spatial scales remains unresolved in hydrology [*McGlynn et al.*, 2004], it has been generally accepted that hydrologic responses in small catchments are likely to be different than those in large catchments [*Pilgrim et al.*, 1982]. At the storm event scale, peak discharge tend to be greater and time to peak discharge tend to be shorter with decreasing catchment size [*Heerdegen and Reich*, 1974], though the relationship between runoff responses and scale are often unique to different regions [*Pilgrim et al.*, 1982].

Negley and Eshleman [2006] observed that disparity in catchment size can obscure or augment landcover differences in comparative studies of catchment runoff responses. SYC (25.5 km^2) is almost 4x the catchment area of WOC (6.5 km^2). While this discrepancy is short of the near order of magnitude difference in the forested and mined catchments studies by *Negley and Eshleman* [2006], it does represent a substantial disparity. The modeling work of *Robinson et al.* [1995] and the empirical work of *McGlynn et al.* [2004] suggest that the controls on catchment response transition from hillslope to channel network structure between scales of ~3 km^2 [*McGlynn et al.*, 2004] to ~20 km^2 [*Robinson et al.*, 1995]. If channel network structure is the dominant control in these systems, the more complex, dendritic channel network of SYC (length = 70.0 km; drainage density = 2.75 km km^{-2}) likely contributes to the delayed runoff responses compared to WOC (length = 21. Km; drainage density = 3.33 km km^{-2}), which increases the physical distance water must travel to the catchment outlet as well as its storage potential.

Anthropogenic changes to the drainage network in WOC add additional uncertainty to this relationship; over 1.5 km of stream length has been completely buried by contemporary VF and spoil piles associated with earlier contour mining in WOC (Figure 1). Equally significant are the two, 0.25 ha sediment ponds at the base of the VF located on the main stem of White Oak

Creek. Sediment retention ponds are important storage components capable of attenuating peak discharge and lengthening runoff response time [*Curtis*, 1977]. Manmade drainage channels on the mine surface and VF face also extend the drainage network. Modeling work by *Ritter and Gardner* [1993] shows that channel structure of reclaimed mine sites can be the major control of runoff response in landscapes dominated by infiltration excess overland flow. The extent of this anthropogenic network is relatively unknown in WOC due to restricted access by the mining company to all parts of the catchment and the perpetual evolution of the land surface during MTM operations. Thus, it is impossible to compare the drainage network between SYC and WOC based on length alone.

Some runoff variables in SYC and WOC deviate from the expected relationships observed between catchment area and outlet response. During the driest times of the growing season, volumetric discharge in WOC exceeded that in SYC. Larger catchments generally have greater volumetric discharges due to larger contributing areas. Additionally, hydrograph separations into quick flow (Q_q) and baseflow (Q_b) using PART and *Hewlett and Hibbert* [1967] methods reveal that runoff in SYC contains a greater fraction of Q_q during the study period. This contradicts the modeled responses of *Post and Jakeman* [1996] which showed Q_q to be inversely correlated to catchment area and positively correlated to drainage density. *Messinger* [2003] also observed runoff relationships in MTM catchments independent of catchment scale. The greater magnitude of responses in the smaller, heavily mined catchment compared to the larger, forested catchment was likely a function of landuse and catchment size. However, the downstream, partially-mined catchment exhibited similar, and at times greater, total unit discharge and peak discharge compared to the forested catchment, despite being nearly 4x larger. Therefore, it seems plausible that catchment area plays a role in the disparate runoff responses in SYC and WOC (particularly temporal metrics such as time lag), but that additional accounted for and unaccounted for factors are likely contributing to the observed relationship.

MTM/VF operations

Runoff responses observed in this study are similar to those reported in other studies examining the hydrologic impacts of surface mining at the headwater scale. Augmented baseflow in WOC is similar to the patterns observed downstream of VFs in other studies [*Green et al.*, 2000; *Messinger*, 2003; *Messinger and Paybins*, 2003; *Wiley et al.*, 2001]. While streamflow is sustained throughout the year in both catchments, volumetric discharge in WOC frequently exceeded that in SYC during the driest times of the growing season. We hypothesize that this is a function of the VF from active MTM operations in WOC as significant discharge was observed emanating from the base of this structure even during the driest times of the year.

The event scale runoff metrics in the surface mined catchment relative to the forested catchment in this study (3x greater total storm runoff, 2x greater peak runoff, and 2x greater runoff ratios) are nearly identical to those reported by *Negley and Eshleman* [2006] (3x greater total storm runoff, 2x greater peak runoff, and 2.5x greater runoff ratios). Increases in discharge in mined catchments are attributed to severely compacted mine soils which result in decreased rainfall abstraction and rapid routing of runoff to the stream channel via surface flowpaths [*Bonta et al.*, 1997; *Negley and Eshleman*, 2006; *Ritter and Gardner*, 1993]. While this is a possible explanation of the greater runoff responses in WOC, without direct knowledge of the soil conditions on the active and reclaimed mine surface it is difficult to make such a conclusion. Contrary to *Messinger* [2003], precipitation thresholds and double peaked hydrographs were not observed in WOC. This is likely a function of catchment area, as unique patterns of water fluxes generally attenuate downstream [*Wood et al.*, 1988], though extent of disturbance might also be a factor. *Messinger* [2003] did not observe these patterns at the downstream gaging station, which drained a larger but still substantially MTM disturbed catchment.

The substantially greater total unit discharge during the study period in a MTM-impacted catchment was also observed in the hydrologic studies of Ballard Fork [*Messinger*, 2003; *Messinger and Paybins*, 2003]. Greater unit discharge is thought to be related to reduced evapotranspiration due to the loss of vegetation of surface mining activities [*Messinger*, 2003] though *ET* was not directly measured in these studies. It is likely a factor in the increased runoff response in this study; approximately 10% of WOC has been completely devegetated due to surface mining activities and forest has been replaced by grassland in an additional 20% of the catchment. *Bosch and Hewlett* [1982] observed a deforestation threshold of 20% to detect measurable streamflow change related forest harvesting activities. Therefore, a 30% reduction in forest cover is likely to initiate a change in runoff response. However, it is likely that not all of the increased runoff is attributable to MTM/VF operations alone. WOC and the largest catchment from *Messinger* [2003] have similar sizes (6.5 km^2 and 5.7 km^2 respectively) and landcover characteristics (30.5% and 40.0% disturbance from MTM/VF, respectively). Yet, in a water year from 01 September to 31 August (a large storm event in [*Messinger*, 2003] prevented the use of the USGS water year), the runoff in WOC was over 4x greater than runoff in BF, despite BF receiving 52% more rainfall during the same time period. Thus, there likely is another control on runoff response in WOC beyond MTM/VF operations alone.

Underground coal mining

Extensive underground mining has occurred in both SYC and WOC. Approximately 19% of SYC has been undermined for coal with much of this development occurring in the southern and western ridges of the catchment (Figure 9). In WOC, nearly 85% of its catchment area is undermined, with the central valley of White Oak Creek being the sole area not underlain with abandoned underground mines. At least six different coal seams in the Kanawha formation have been mined within SYC and WOC. Underground mining operations in this region began in the 1930s and continued until 2008. The deepest seam of coal mined in SYC is the Eagle seam which has an approximate low point of 622 m within SYC (SYC outlet elevation is 333 m; SYC max elevation is 1013 m). Mining in WOC extends deeper into the Kanawha formation; the Ben's Creek and Glen Alum Tunnel (GAT) seams were mined as recently as 2008 (GAT low point in WOC is 483 m; WOC outlet elevation is 475 m; WOC max elevation is 991 m). Neither the mainstem of Sycamore Creek nor White Oak Creek are underlain with underground coal mines although several tributaries to White Oak Creek are. The strike and dip of coal seams generally runs from the southeast to the northwest at a slope of approximately 0.74° in SYC and 0.91° in WOC, though this varies somewhat between seams.

Underground coal mining that has taken place throughout much of this region has drastically altered the structure of this subsurface system [*Puente and Atkins*, 1989]. Subsidence associated with abandoned underground mines creates additional fractures which increase the hydraulic conductivity and hydrologic connectivity between surface and subsurface as well as between water-bearing subsurface geologic units [*Hawkins and Dunn*, 2007; *Hobba*, 1981]. Consequently, underground mines and associate subsidence fractures can become major conduits for subsurface water movement. Headwater drainage networks downdip and stratigraphically below mined coal beds can gain significant amounts of water while streams underlain by underground mines can lose water, especially during baseflow conditions [*Puente and Atkins*, 1989]. Substantial volumes of water can be transferred between basins at the headwater scale which increases the complexity of assessing hydrologic change in catchments undergoing both surface and surface mining [*Borchers et al.*, 1991]. While *Borchers et al.* [1991] examine the combined effects of deep mining and surface strip mining, no study has examined the interactions of contemporary MTM and VF operations and legacy deep mining.

The considerable difference in runoff ratio between WOC (0.62) and SYC (0.21) during the study period would indicate that an additional input of water contributes to discharge in WOC. Larger runoff ratios in surface mine impacted catchments compared to forested catchments were observed by *Dickens et al.* [1989] and *Messinger* [2003]. Both *Dickens et al.* [1989] and *Messinger* [2003] suggest that this is a result of the reduction of *ET* due deforestation related to surface mining activity although *ET* was not directly measured in either study. For this to be true in this study, the difference in runoff between SYC and WOC should be greatest during the growing season when the deciduous forest is actively intercepting rainfall and transpiring soil water. However, this was not the case as the greatest differences between SYC and WOC were observed during the dormant season, not the growing season (Table 7, Figure 11). For total unit discharge, *Q/P*, peak unit discharge, time lag, $Q_{q:t}$ at the event scale, and Q_b as determined by PART, the greatest difference occurred from November to April (Figure 12). Subsurface water movement via underground mines and subsidence fractures will be greatest during the more saturated conditions throughout the dormant season due to suppressed *ET*.

Analysis of maps documenting underground mining activity in SYC and WOC indicate that substantial amounts of water may be entering WOC from an adjacent catchment. Legacy underground mines in the Eagle and No.2 Gas coal seams to the southeast of WOC are likely conduits for subsurface routing of water into WOC (Figure 10). Flow direction of underground mine water is controlled by the dip direction of the coal seam [*Puente and Atkins*, 1989], therefore water in these abandoned mine will move from the southeast to the northwest. A thin (approximately 20-50 m) barrier of unmined coal divides mines on the approximate catchment boundary of WOC and the condition of this aquitard will greatly influence that rate at which water is transmitted into WOC. Even if this barrier is intact, coal is highly transmissive compared to surrounding sandstone and shale geology [*Hobba*, 1991] and would likely contribute water to WOC. However, given the age of the mines (1930 and 1962) and proximity of MTM activity above the No.2 Gas coal seams (100 m), it is quite possible that this barrier is not intact, thereby increasing interbasin transfer of water into WOC through these seams. It is plausible that deep mine drainage is responsible for the surprisingly small fraction of Q_q during storm events in WOC; the large volume of mine drainage, as well as delayed drainage from VFs, augments contributions from Q_b thereby masking the significance of Q_q in WOC.

It is also quite possible that some water in WOC is being lost to underground mines but without access to the mined portions of these catchments to trace subsurface water movement through monitoring wells and to sample end members for geochemical analysis, little can be done to confirm the nature of subsurface water movement in these systems. The movement of subsurface mine water can be predicted using underground mine maps and strike and dip data of coal seams (as above) and confirmed by identifying large seeps using high resolution aerial photography. However, in WOC, likely seepage points for mine water in the Eagle and No.2 Gas coal seams are covered by VFs within WOC and in adjacent catchments. Therefore, it is possible that VFs in WOC and the adjacent Horse Creek and Ewing Fork are being recharge by underground coal mines.

SYC appears to be less influenced by subsurface mining compared to WOC due to less underground mining activity within the catchment and in adjacent areas. Underground mining activity is limited to the southern and eastern ridges of SYC (Figure 9) and although there are potential for water gains and losses, it is less than in WOC. While the overall capacity for interbasin transfer of water appears reduced in SYC, underground mining likely exhibits a major control on the hydrology of SYC. A local resident of SYC with extensive knowledge of the catchment area reports massive, "room-sized" subsidence fractures that connect the catchment surface to abandoned subsurface mines (similarly sized subsidence fractures were described by *Hobba* [1981]). He also reports seeps that discharge underground mine water into the incipient drainage network of SYC on the eastern ridge. Even in areas not dramatically losing or gaining water, subsurface mining plays an important role in the runoff mechanisms of these catchments and likely the region.

The impacts of underground mining on hydrology in MTM-impacted systems have important implications for downstream water quality. Numerous investigations into the water quality in the Central Appalachian coalfields have reported the deleterious effects of VFs on downstream water chemistry [e.g., *Lindberg et al.*, 2011] and biology [e.g., *Pond et al.*, 2008]. However, the water quality impacts of underground mine drainage in the MTM region have received less attention. Most mine drainage in the southern coalfields of West Virginia are alkaline and don't have the dramatic water quality consequences of acid mine drainage (AMD) more prevalent in the northern part of the state, though discharge from underground coal mines in this region can significantly affect water chemistry in receiving streams [*Hobba*, 1981]. Given the scrutiny of surface water quality in the MTM region, understanding the linkages between legacy underground mining, hydrology, and water quality is needed.

WOC experienced substantially more variability in runoff response than SYC. For total unit flow, *Q/P*, and peak unit discharge the ranges and standard deviations of responses in WOC were generally 2x greater than those in SYC. Temporal metrics (i.e. time to peak and time lag from peak precipitation to peak discharge) show similar variability to SYC, however. This is mostly a function of several large dormant season storm events that produced considerably larger unit flows in WOC compared to SYC. Events 5, 8, 9, 10, and 12 produced discharge peaks greater than 0.3 mm hr^{-1}; this threshold was only exceeded twice in SYC. The large total and peak unit discharges observed in WOC compared to SYC is likely related to both catchment scaling and underground mining. Peak storm runoff is typically generally greatest during the dormant season in most Appalachian catchments, regardless of size and land disturbance due to larger precipitation inputs and reduced ET losses. If subsurface water from adjacent catchments is indeed draining into WOC via underground mines, then this will further augment peak flows as mine drainage is most active during the dormant season when soil moisture content is greatest. Therefore, WOC may be particularly prone to flooding during the winter months when larger volumes of precipitation are coupled with underground mine drainage.

5.2 Response time modeling

Given the paucity of process-level studies in the Central Appalachian coalfields, models can be used to generate hypotheses about catchment processes. A transfer function rainfall-runoff model was used to quantify median response time (RT_{med}), the median time for a catchment to discharge a volume of water equal to an input of effective precipitation. The model was calibrated using 100,000 Monte Carlo simulations and RT_{med} and parameters from the top 1% performing models were averaged and reported in Table 3.

Both catchments responded quickly to rainfall inputs, shown by the short RT_{med} and steeply sloping response curves, a time series of the fraction of P_{eff} discharged from the catchment based on the median of the top performing Monte Carlo simulations (Figure 13). Response curves in SYC in WOC reflect the TPLR model structure where the P_{eff} input is partitioned into a fast and slow draining reservoir; the steep sloped recession on the response curves in the first 20-30 hours represents the initial period when fast draining reservoir is active whereas the longer, more gradual recession beyond 30 hours after input is a function of the measured depletion of the slow draining reservoir. For 23 storm events, both SYC and WOC display variability in response during the first 20 – 30 hours of events. Because mean residence times in the fast draining reservoir (T_f) is relatively similar across events (Table 3), this is likely a function of Φ, the parameter that controls the fraction of input partitioned into the fast draining reservoir. Aggregating the response curves into a single, median response curve for each catchment results in two near identically shaped functions for SYC and WOC (Figure 13). However, there is greater variability in WOC than SYC during the early portions of the storm event which might be related to scaling and/or surface mining activities.

Predictably, RT_{med} is greater in both catchments during the dormant season when event durations are longer and reduced ET loses lead to prolonged runoff events. This is reflected in the model parameters, where the variables controlling rainfall abstraction (b_1, b_2, b_3) are greater (therefore, more P_{eff}) during the dormant season (Table 4). Additionally, the model routes more water through the slow reservoir during the dormant season, indicated by the smaller values of Φ for each catchment. The slow drainage of VFs and underground mines likely explain the greater

RT_{med} in WOC relative to SYC during the dormant season. That the inverse is true is possibly a function of landscape disturbance from MTM operations as well as WOC's smaller area. WOC exhibited more variability in RT_{med}, particularly during the growing season. The exact cause of this variability is unclear, however. During the study period, WOC was subjected to a broader range of storm intensities during the growing season (a trend common throughout Appalachia); WOC may be particularly sensitive to climatic variability as compared to SYC because it is 1) smaller and 2) deforestation and soil compaction related to MTM activities abate the natural modulation in the conversion of rainfall to runoff in forested systems. When combined with the highly variable hydrometric runoff responses, it appears that the moderating effects of MTM/VF operations described in other studies at broader spatial and time scales [*Larson and Powell*, 1986; *Zégre et al.*, 2013] are not applicable to WOC at the storm event time scale.

While model parameters in SYC and WOC varied seasonally, there was relatively little distinction between model parameters for each catchment. The inherent equifinality (i.e., an end result can be reached through countless methodologies) in complex hydrologic models is well known [*Beven*, 1993; *Beven and Freer*, 2001]. This elicits questions regarding the identifiability of each parameter: are effective models driven by a narrow range of viable parameters or can a multitude of parameter sets produce well-fit simulations? While this study stops short of formal uncertainty analysis (e.g. the generalized likelihood uncertainty estimation (GLUE) developed by *Beven and Binley* [1992]), the Monte Carlo simulations used in this study are used as a preliminary step towards charactering parameter identifiability. Dotty plots of Monte Carlo simulations were produced for each storm event in each catchment (a representative event is shown in Figure 14). In each plot, the unique value of each parameter for each realization is plotted against its efficiency (*NSE*). Parameter identifiability was consistently poor for b_2, b_3, T_f,

T_s, and Φ for all storm events in SYC and WOC. Only b_1, the parameter that controls the water balance between effective precipitation and observed runoff, showed some constraint. While this finding does not invalidate the results observed through the use of this model, it does reinforce the stated need to explore additional models and structures.

5.3 Isotope hydrograph separations

Successful isotope hydrograph separations were limited in this study. Reasonable separations for both δD and $\delta^{18}O$ between the two models used in this study (two-component and TRANSEP) were limited to a single storm though this event is only moderately successful (TRANSEP runoff model *NSE* = 0.59). The failure of the other 8 events stem from poor runoff and event tracer efficiencies in TRANSEP and two-component separations that produced unreasonable negative pre-event or event water fractions. The exact cause of the unsuccessful separations is unclear but it is worth noting that the methodology employed in this study to perform tracer based hydrograph separations are based on several assumptions [*Sklash*, 1990; *Sklash and Farvolden*, 1979; 1982]:

1. There is a significant difference between isotopic composition of event water and pre-event water;
2. rainfall volume is spatially uniform across the catchment area;
3. rainfall isotopic composition is spatially uniform across the catchment (and in steep catchments, elevation);
4. rainfall isotopic composition is temporally uniform (not assumed in this study);
5. rainfall isotopic composition is equal to throughfall isotopic composition;

6. event water isotopic composition doesn't change due to fractionation while in route to the catchment outlet;

7. pre-storm stream samples adequately represent pre-event water stored in the catchment;

8. pre-event water is spatially uniform throughout the catchment;

9. pre-event water only changes throughout the storm event due to mixing;

10. soil water contributions are negligible or have the same isotope composition as groundwater;

11. contributions to streamflow from surface storage are negligible; and

12. simplifying the reservoirs of water stored within a catchment into a single component is appropriate.

Several of these assumptions have already been proven invalid. Multiple studies have observed the spatial heterogeneity of the volume [e.g., *Goodrich et al.*, 1995; *Krajewski et al.*, 2003] and isotopic composition [e.g., *Lyon et al.*, 2009; *McGuire et al.*, 2005; *O'Driscoll et al.*, 2005] at small catchment scales. Isotopic composition of throughfall may considerably differ from direct precipitation due to additional evaporation that occurs while intercepted rainfall is temporarily stored in the tree canopy [*DeWalle and Swistock*, 1994; *Kendall*, 1993]. The temporal variability of the isotopic composition of rainfall is well documented [*Matsuo and Friedman*, 1967] and multiple methodologies have been developed to address this variability including those utilized in this study. Less information is available pertaining to the variability of pre-event water in space and time, though many have observed the spatial variability of both groundwater across area [*Buttle and Sami*, 1992] and depth [*Hill and Waddington*, 1993]. Using a three-component mixing model, *DeWalle et al.* [1988] showed that soil water in a central

Pennsylvania catchment was both isotopically different than groundwater and a significant source of stormflow, a finding that revealed the weakness of two-component separations.

Much of the error in these invalid assumptions can be addressed, or at least mitigated, through multiple sampling points to assess the spatial variability of the volume and isotopic concentration of model inputs. A robust sampling network in both catchments was not possible because access was limited to the small, stream-adjacent parcels of cooperative landowners where our gaging equipment was located. Thus, our ability to properly characterize the pre-event and event water inputs necessary for confident isotope hydrograph separation was limited from the outset. This reveals a challenging limitation in conducting hydrologic research in MTM systems: characterizing catchment-scale process requires catchment-scale access, a necessity not often realized.

In the context of this study, it is assumption 12 that is perhaps most tenuous. In WOC and to a lesser degree SYC, multiple reservoirs of water stored in the catchment likely contribute to streamflow during storm events. Groundwater, hillslope and riparian water, VF storage, underground mine storage, and surface retention ponds all have the potential to contribute runoff during storm events and such contributions may be non-linear. Hence, a model that simplifies multiple, unique reservoirs into a broad category such as “pre-event water” is likely insufficient to capture the complexity of these systems. Future research with unlimited catchment-wide access should utilize geochemical tracers in addition to isotope and hydrometric data to properly characterize these members in order to assess the geographic sources of runoff. Longer timescale studies are also needed to capture data over a wider range of climatic conditions and characterize the long term evolution of these systems from pre- to post-mining conditions. Quantifying the residence times of storage reservoirs in MTM systems using isotopic and geochemical tracers should also be a priority of future research.

In the context of poor model performance for other storm events, few conclusions can be drawn from the successful hydrograph separations of event 20. However, given the consistent results observed across isotopic tracers and mixing models, it is worth examining. Expectedly, both catchments reflect the widely observed dominance of pre-event water in storm hydrographs in forested catchments [*Bonell*, 1993]. However, the similarity between total event water compositions in both catchments is somewhat surprising. Many studies have documented the increase in surface runoff from surface mined catchments and therefore a higher composition of event water in WOC might be expected. It is important to stipulate that the partitioning of pre-event and event water are relative to each other. Therefore, there might be more event water in the storm hydrograph of mined WOC compared to forested SYC, but this larger volume is lost to the large baseflows of pre-event water from VFs and underground mine drainage.

Results from event 20 suggest that pre-event water constitutes a larger portion of peak flow in WOC (fraction of pre-event water averaged from models and tracers: 0.78). compared to SYC (fraction of pre-event water averaged from models and tracers: 0.63). Two possible explanations of this observation are that pre-event water stores (groundwater, soil water, VFs, and underground mine drainage) flush more rapidly in WOC than SYC and/or event water is detained and slowly released throughout the event. The response time of underground mine to precipitation input will largely depend on hydraulic conductivity within the mined area and the degree of connection with the catchment surface. VF controls on storm response to storm events are less clear, though *Wunsch et al.* [1999] showed that monitoring wells in VFs respond quickly to precipitation events, likely from rapid surface and subsurface recharge. Therefore, VFs might be an important source of water during storm events in addition to baseflow. Understanding how VFs collect, store, and release water is a critical knowledge gap that has hydrologic, geomorphic, and biogeochemical implications and should therefore be a priority in future MTM investigations.

6. Concluding remarks

MTM represents a dramatic change to the landscape, but land managers, regulators, scientists, and citizens are still contemplating the breadth its consequences. In spite of the scale of disturbance and potential for future growth of MTM operations, our understanding of its impacts on hydrologic processes in small headwater catchments where the majority of Appalachian coalfield communities are located is insufficient.

We examined runoff response in two headwater catchments for a 13 months study period using hydrometric data, rainfall-runoff modeling, and isotopic hydrograph separations. Both catchments responded rapidly to storm events. However, WOC, an extensively mined catchment, exhibited significantly greater total discharge, peak discharge, runoff ratios, and shorter time lags compared to SYC, a predominantly forested catchment. Similarly, rainfall-runoff modeling revealed that WOC exhibited a shorter median response time to inputs of precipitation. Based on hydrograph separations using PART and constant slope methodology, WOC experienced substantially greater baseflow at both event and annual time scales. The cause of this discrepancy is likely a combination of multiple factors. The 4x smaller catchment area of WOC likely amplifies storm responses as the magnitude and flashiness of runoff responses tend to attenuate downstream. Legacy underground mining appears to play a particularly important role in WOC where subsurface mines may be routing water from adjacent catchments into the study basin.

Given the two aforementioned confounding variables, the degree to which MTM/VF operations effect WOC is difficult to quantify, though patterns were similar to other MTM studies. A successful isotope hydrograph separation of a single storm event suggests that total stormflow peaks in WOC have a higher concentration of pre-event water than SYC, but that storm hydrographs in both catchments are composed of similar amounts of total pre-event water. However, given the poor model performance and inherent assumptions of isotope based hydrograph separations, such results are preliminary at best.

This study reveals the complex hydrology of the Central Appalachian coalfields and the difficulty in conducting scientific research in this area. The footprint of underground mining overlaps much of the area now impacted by MTM operations. This study suggests that alterations to the subsurface geology in the past century are as significant to the hydrology of headwater catchments as more conspicuous MTM mining operations. Discerning the effects of these disturbances and quantifying their interactions will ultimately require more insight into the catchment processes that control the storage and movement of water in these complex systems. Our preliminary study demonstrates that process level measurements exclusively at the catchment outlet are too limited to provide meaningful results Therefore, researchers landowners, and mine operators in MTM-impacted areas must work collectively to overcome access restrictions that limit the collection of necessary data in disturbed catchments. Given the importance of hydrology in controlling downstream chemistry, biology, and flood generation, this step is critical to reducing the environmental and social consequences of this landscape scale disturbance.

7. References

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8. Tables and figures

Table 1. Catchment locations and topographic and landcover characteristics.

Watershed/Station	Station location	Drainage area	Station elevation	Elevation change	Mean slope (±SD)	Total surface mine disturbance	Legacy mining[a]	MTM surface[b]	VF[c]
	[Lat/Long]	[km^2]	[m]	[m]	[°]	[km^2 (%)]	[km^2 (%)]	[km^2 (%)]	[km^2 (%)]
Sycamore Creek (SYC)	37°56.47'/ -81°26.01'	25.5	333	680	60.4 (± 13.7)	0.5 (2.1)	0.5 (2.1)	0	0
White Oak Creek (WOC)	37°56.47'/ -81°19.93'	6.5	475	516	55.6 (± 19.2)	2.0 (30.5)	0.8 (10.4)	1.1 (17.3)	0.2 (2.9)

[a]Legacy surface mining in SYC constitutes highwall mining on the western ridge during the 1970s. The highwall and mining bench were not reclaimed, but natural succession of deciduous forest has occurred. Legacy surfacing mining in WOC constitutes contour surface mining during the 1990s. This area was reclaimed and is currently covered by herbacous grasses and some woody

[b]MTM surface in WOC consists of in preparation areas (0.3 km^2), active surface mining areas (0.7 km^2), and reclaimed areas (0.2 km^2). See text for description of landcover for each area.

[c]VFs in WOC consists of one large contemporary VF (0.1 km^2) and legacy VFs from legacy contour mining (0.1 km^2)

Table 2. Rainfall and runoff data for 23 storm events from 01 September 2011 to 30 September 2012 in SYC and WOC. Dormant season storms are shaded in gray.

			Sycamore Creek (SYC)									White Oak Creek (WOC)								
			Precipitation			Runoff						Precipitation			Runoff					
Event Number	Event Start[a]		Duration	Depth	Intensity	Total Unit Discharge	Q/P	Peak Discharge	Time to Peak[c]	Time Lag[d]	$Q_{q:t}$ [e f]	Duration	Depth	Intensity	Total Unit Discharge	Q/P	Peak Discharge	Time to Peak[c]	Time Lag[d]	$Q_{q:t}$ [e]
	Date	Time[b]	[hr]	[mm]	[mm hr^{-1}]	[mm]	--	[mm hr^{-1}]	[hr]	[hr]	--	[hr]	[mm]	[mm hr^{-1}]	[mm]	--	[mm hr^{-1}]	[hr]	[hr]	--
1	04 Sep 2011	1440	78.5	90.9	1.2	2.7	0.03	0.09	42.0	41.5	--	41.7	65.0	1.6	16.4	0.25	0.18	41.7	1.5	0.08
2	26 Sep 2011	1510	10.0	62.0	6.2	2.1	0.03	0.10	10.3	6.7	0.42	12.7	48.0	3.8	5.2	0.11	0.21	4.7	1.2	0.27
3	11 Oct 2011	1930	55.7	49.5	0.9	5.5	0.11	0.13	61.7	20.0	0.17	55.8	51.8	0.9	17.3	0.33	0.22	57.5	15.5	0.13
4	26 Oct 2011	1130	65.8	30.7	0.5	6.9	0.23	0.06	73.5	55.3	--	68.3	34.8	0.5	34.4	0.99	0.17	65.2	65.2	0.02
5	15 Nov 2011	0500	52.3	49.5	0.9	7.7	0.16	0.21	37.7	11.3	0.35	52.7	49.0	0.9	20.8	0.42	0.35	37.7	10.8	0.21
6	20 Nov 2011	1010	71.0	23.1	0.3	6.0	0.26	0.08	86.5	28.3	--	71.7	23.4	0.3	25.3	1.08	0.18	84.0	25.7	0.02
7	29 Nov 2011	0020	34.5	16.8	0.5	3.7	0.22	0.05	24.3	23.0	--	34.8	22.4	0.6	20.1	0.90	0.19	20.8	18.8	0.03
8	05 Dec 2011	1950	63.2	50.6	0.8	15.4	0.31	0.22	47.5	37.7	0.19	63.7	46.5	0.7	30.7	0.66	0.36	43.3	5.2	0.09
9	20 Jan 2012	1720	63.3	33.3	0.5	10.8	0.33	0.26	17.7	7.0	0.31	63.5	32.3	0.5	26.0	0.80	0.36	16.7	5.3	0.12
10	29 Feb 2012	0450	70.5	73.9	1.0	30.4	0.41	0.58	17.5	7.3	0.43	151.0	88.9	0.6	57.5	0.65	0.70	17.8	5.0	0.23
11	23 Mar 2012	1320	50.8	17.8	0.3	13.0	0.73	0.09	53.7	34.8	--	127.7	27.2	0.2	25.5	0.94	0.17	49.2	49.2	0.00
12	25 Apr 2012	1520	78.0	86.9	1.1	20.9	0.24	0.51	19.8	9.7	0.37	78.7	75.7	1.0	34.3	0.45	1.30	19.7	9.0	0.46
13	30 Apr 2012	2340	22.0	23.4	1.1	7.5	0.32	0.14	16.7	16.3	0.08	26.3	19.6	0.7	9.8	0.50	0.19	3.3	3.2	0.04
14	04 May 2012	2330	117.2	37.3	0.3	13.5	0.36	0.15	23.3	15.3	0.04	127.3	47.8	0.4	21.4	0.45	0.28	35.5	17.0	0.12
15	13 May 2012	1700	60.7	26.2	0.4	7.9	0.30	0.08	41.3	32.0	0.02	38.3	26.7	0.7	9.6	0.36	0.13	20.5	16.3	0.02
16	29 May 2012	1300	1.3	19.6	14.7	0.8	0.04	0.05	1.2	1.0	0.10	1.5	16.5	11.0	1.1	0.07	0.08	1.5	1.5	0.05
17	01 Jun 2012	0300	11.8	17.3	1.5	1.5	0.08	0.04	13.0	3.7	0.05	10.8	20.3	1.9	2.7	0.13	0.09	10.5	1.5	0.02
18	17 Jun 2012	2000	14.2	15.2	1.1	0.7	0.04	0.03	15.2	2.7	0.07	14.3	18.8	1.3	2.2	0.12	0.07	14.5	1.3	0.04
19	12 Jul 2012	2110	92.7	21.1	0.2	0.6	0.03	0.01	17.8	14.3	--	67.2	24.4	0.4	4.2	0.17	0.08	45.2	1.2	0.04
20	26 Jul 2012	2050	15.0	41.4	2.8	1.9	0.05	0.09	4.2	2.5	0.21	95.7	39.9	0.4	5.8	0.14	0.20	2.3	1.3	0.16
21	31 Jul 2012	1500	114.2	68.8	0.6	3.1	0.04	0.15	1.8	1.7	0.29	6.7	21.1	3.2	1.8	0.08	0.07	5.5	2.7	0.04
22	14 Aug 2012	1500	70.3	14.5	0.2	1.4	0.10	0.07	4.2	2.0	0.15	18.8	12.7	0.7	1.4	0.11	0.05	2.8	0.8	0.01
23	17 Sep 2012	1410	31.0	41.9	1.4	3.5	0.08	0.07	15.7	8.0	0.13	41.7	59.7	1.4	11.7	0.20	0.25	13.7	0.8	0.12
Average			**54.1**	**39.6**	**1.7**	**7.3**	**0.20**	**0.14**	**28.1**	**16.6**	**0.20**	**55.3**	**37.9**	**1.5**	**16.7**	**0.43**	**0.26**	**26.7**	**11.3**	**0.10**
Median			**60.7**	**33.3**	**0.9**	**5.5**	**0.16**	**0.09**	**17.8**	**11.3**	**0.17**	**52.7**	**32.3**	**0.7**	**16.4**	**0.36**	**0.19**	**19.7**	**5.0**	**0.05**
Max			**117.2**	**90.9**	**14.7**	**30.4**	**0.73**	**0.58**	**86.5**	**55.3**	**0.43**	**151.0**	**88.9**	**11.0**	**57.5**	**1.08**	**1.30**	**84.0**	**65.2**	**0.46**
Min			**1.3**	**14.5**	**0.2**	**0.6**	**0.03**	**0.01**	**1.2**	**1.0**	**0.02**	**1.5**	**12.7**	**0.2**	**1.1**	**0.07**	**0.05**	**1.5**	**0.8**	**0.00**
Range[g]			**115.8**	**76.5**	**14.5**	**29.8**	**0.70**	**0.57**	**85.3**	**54.3**	**0.41**	**149.5**	**76.2**	**10.8**	**56.4**	**1.02**	**1.25**	**82.5**	**64.3**	**0.46**
Std. Dev.			**32.3**	**23.4**	**3.1**	**7.4**	**0.17**	**0.14**	**23.4**	**15.1**	**0.14**	**40.7**	**20.4**	**2.3**	**14.2**	**0.33**	**0.27**	**22.8**	**16.3**	**0.11**

[a]Start times defined as start of precipitation in SYC

[b]Time listed in Eastern Standard Time (EST)

[c]Time to peak defined as time from start of precipitation to peak discharge

[d]Time lag defined as time from maximum instantaneous storm intensity to peak discharge

[e]$Q_{q:t}$ represents the ratio of quickflow to total flow using the methodology described by *Hewlett and Hippert* [1967] at a constant slope of 0.002 mm hr^{-1}

[f]Hydrograph sepereation in SYC was unsuccessful for events 1,4,6,7,11,19 due to the separation slope being greater than the rising limb of the hydrograph

[g]Range = Max - Min

Table 3. RT_{med} and model parameter sets in SYC and WOC for 23 storm events from 01 September 2011 to 30 September 2012. Model parameters and RT_{med} are based on the average of the top 1% best performing models from 100,000 Monte Carlo simulations of a transfer function rainfall-runoff model. Dormant season storms are shaded in gray.

	Sycamore Creek (SYC)							White Oak Creek (WOC)						
Event Number	b_1	b_2	b_3	T_f	T_s	Φ	$\boldsymbol{RT_{med}}$	b_1	b_2	b_3	T_f	T_s	Φ	$\boldsymbol{RT_{med}}$
				[hr]	[hr]		**[hr]**				[hr]	[hr]		**[hr]**
1	0.01	3.95	0.35	11.2	117.2	0.37	**40.4**	0.01	3.73	0.36	11.6	120.0	0.31	**26.6**
2	0.00	3.49	0.39	11.1	111.5	0.44	**13.8**	0.01	3.45	0.39	11.3	106.2	0.43	**12.4**
3	0.01	3.99	0.40	12.0	116.7	0.26	**40.0**	0.02	3.86	0.39	12.9	111.4	0.30	**27.4**
4	0.04	4.89	0.44	10.3	136.0	0.11	**68.4**	0.11	4.74	0.42	10.4	145.5	0.11	**76.8**
5	0.02	5.09	0.47	13.3	106.7	0.27	**28.4**	0.04	4.78	0.49	12.9	112.6	0.18	**32.2**
6	0.03	4.84	0.44	11.7	121.4	0.14	**53.0**	0.06	4.75	0.45	11.3	122.2	0.11	**45.8**
7	0.01	3.56	0.29	11.3	111.9	0.36	**42.0**	0.02	4.03	0.34	12.1	109.6	0.23	**33.2**
8	0.05	4.47	0.46	13.9	100.2	0.23	**30.2**	0.04	4.23	0.41	14.7	97.0	0.38	**25.0**
9	0.01	4.80	0.48	14.2	102.3	0.35	**22.8**	0.02	4.92	0.48	14.4	102.8	0.36	**23.2**
10	0.03	4.94	0.45	13.9	106.3	0.26	**28.2**	0.03	4.96	0.48	12.9	119.5	0.20	**42.6**
11	0.08	5.35	0.48	10.5	130.0	0.09	**60.6**	0.02	4.02	0.34	11.1	125.5	0.17	**57.4**
12	0.01	4.69	0.48	12.1	109.8	0.39	**21.4**	0.01	5.47	0.47	14.0	99.1	0.53	**12.8**
13	0.01	4.06	0.28	11.5	109.2	0.39	**21.0**	0.01	3.81	0.28	11.6	108.9	0.38	**19.4**
14	0.02	4.64	0.41	13.3	104.1	0.27	**30.2**	0.02	4.90	0.40	12.8	109.9	0.22	**29.2**
15	0.02	3.81	0.42	11.7	115.7	0.21	**37.8**	0.01	3.50	0.35	12.5	110.3	0.33	**24.6**
16	0.01	4.23	0.28	11.7	108.5	0.43	**9.2**	0.01	4.06	0.21	11.1	109.0	0.46	**5.6**
17	0.01	3.40	0.40	11.2	112.9	0.42	**13.0**	0.01	3.28	0.39	11.1	106.7	0.45	**8.6**
18	0.01	4.03	0.30	11.3	111.0	0.40	**17.4**	0.00	3.99	0.36	11.0	111.2	0.43	**9.2**
19	0.01	2.61	0.38	10.8	112.8	0.39	**40.4**	0.01	2.63	0.39	11.1	108.6	0.37	**24.6**
20	0.01	3.51	0.33	11.1	111.6	0.40	**17.0**	0.01	3.58	0.31	11.1	112.4	0.40	**16.6**
21	0.00	4.70	0.36	11.4	112.4	0.39	**20.4**	0.01	3.37	0.34	11.0	108.7	0.47	**9.4**
22	0.01	3.53	0.30	11.4	110.9	0.39	**23.4**	0.01	3.41	0.30	11.1	107.1	0.43	**9.8**
23	0.01	3.50	0.39	12.0	115.9	0.31	**34.0**	0.01	3.69	0.40	11.7	113.5	0.37	**33.2**
Average	0.02	4.18	0.39	11.9	112.8	0.32	**31.0**	0.02	4.05	0.38	12.0	112.1	0.33	**26.3**
Median	0.01	4.06	0.40	11.5	111.6	0.36	**28.4**	0.01	3.99	0.39	11.6	109.9	0.37	**24.6**
Max	0.08	5.35	0.48	14.2	136.0	0.44	**68.4**	0.11	5.47	0.49	14.7	145.5	0.53	**76.8**
Min	0.00	2.61	0.28	10.3	100.2	0.09	**9.2**	0.00	2.63	0.21	10.4	97.0	0.11	**5.6**
Range[a]	0.08	2.74	0.21	3.9	35.8	0.34	**59.2**	0.10	2.85	0.28	4.3	48.6	0.42	**71.2**
Std Dev	0.02	0.69	0.07	1.1	8.1	0.10	**15.2**	0.02	0.69	0.07	1.2	9.9	0.12	**17.1**

[a]Range = Max - Min

Table 4. Modeling parameters and RT_{med} for 23 storm events measured in SYC and WOC catchment between 01 September 2011 and 30 September 2012 separated into growing and dormant seasons. Model parameters and RT_{med} are the average of the top 1% best performing models from 100,000 Monte Carlo simulations. RT_{med} in WOC is longer than SYC during the dormant season, likely due to the slow drainage of VFs and underground mines. The inverse of this relationship is true during the growing season, possibly because the smaller catchment area and MTM operations of WOC.

Summary Statistics	Sycamore Creek (SYC)							White Oak Creek (WOC)						
	b_1	b_2	b_3	T_f	T_s	Φ	$\boldsymbol{RT_{med}}$	b_1	b_2	b_3	T_f	T_s	Φ	$\boldsymbol{RT_{med}}$
				[hr]	[hr]		**[hr]**				[hr]	[hr]		**[hr]**
Growing Season[a]														
Average	0.01	3.88	0.37	11.5	114.1	0.34	**29.0**	0.02	3.73	0.36	11.5	112.9	0.36	**22.4**
Median	0.01	3.88	0.38	11.3	112.6	0.39	**26.8**	0.01	3.63	0.37	11.1	110.1	0.39	**20.6**
Max	0.04	4.89	0.44	13.3	136.0	0.44	**68.4**	0.11	4.90	0.42	12.9	145.5	0.47	**76.8**
Min	0.00	2.61	0.28	10.3	104.1	0.11	**9.2**	0.00	2.63	0.21	10.4	106.2	0.11	**5.6**
Range[c]	0.04	2.28	0.16	3.0	31.9	0.33	**59.2**	0.10	2.27	0.21	2.6	39.3	0.37	**71.2**
Std Dev	0.01	0.61	0.05	0.7	7.2	0.10	**15.9**	0.03	0.58	0.06	0.8	10.0	0.10	**18.2**
Dormant Season[b]														
Average	0.03	4.64	0.42	12.5	110.9	0.28	**34.2**	0.03	4.55	0.42	12.8	110.8	0.28	**32.4**
Median	0.02	4.80	0.46	12.1	109.2	0.27	**28.4**	0.02	4.75	0.45	12.9	109.6	0.23	**32.2**
Max	0.08	5.35	0.48	14.2	130.0	0.39	**60.6**	0.06	5.47	0.49	14.7	125.5	0.53	**57.4**
Min	0.01	3.56	0.28	10.5	100.2	0.09	**21.0**	0.01	3.81	0.28	11.1	97.0	0.11	**12.8**
Range[c]	0.08	1.79	0.21	3.7	29.9	0.30	**39.6**	0.06	1.66	0.21	3.6	28.5	0.42	**44.6**
Std Dev	0.02	0.55	0.08	1.4	9.4	0.11	**14.4**	0.02	0.55	0.08	1.3	10.1	0.14	**14.2**

[a]growing season from 01 May to 31 October; n = 14

[b]dormant season from 01 November to April 30; n = 9

[c]Range = Max - Min

Table 5. Results of storm hydrograph separations using a two-component mixing model and TRANSEP in SYC and WOC showing event water fractions for each event where separation was possible. Dashes (--) indicate that no isotopic data was collected or there was an incomplete isotopic or hydrometric record in one of the catchments. Unsuccessful separations are indicated by *e* and the source of error is footnoted. The only successful hydrograph separations using both tracers and models, event 20, is shaded in gray.

Event	SYC				WOC			
	Two-component[a]		TRANSEP[b]		Two-component[a]		TRANSEP[b]	
	δD	δ^{18}O	δD	δ^{18}O	δD	δ^{18}O	δD	δ^{18}O
1	--	--	--	--	--	--	--	--
2	e^{g}	0.68	e^{t}	e^{t}	0.39	e^{g}	$e^{t,p}$	$e^{t,p}$
3	--	--	--	--	--	--	--	--
4	--	--	--	--	--	--	--	--
5	0.19	e^{g}	0.28	e^{t}	e^{g}	e^{g}	e^{t}	e^{t}
6	--	--	--	--	--	--	--	--
7	--	--	--	--	--	--	--	--
8	--	--	--	--	--	--	--	--
9	--	--	--	--	--	--	--	--
10	--	--	--	--	--	--	--	--
11	--	--	--	--	--	--	--	--
12	--	--	--	--	--	--	--	--
13	e^{g}	e^{g}	e^{t}	e^{t}	e^{g}	e^{g}	e^{t}	e^{t}
14	e^{g}	e^{g}	e^{t}	e^{t}	e^{g}	e^{g}	e^{t}	e^{t}
15	e^{g}	e^{g}	e^{t}	e^{t}	e^{g}	e^{g}	e^{t}	e^{t}
16	--	--	--	--	--	--	--	--
17	e^{g}	e^{g}	e^{t}	e^{t}	e^{g}	e^{g}	$e^{r,t}$	$e^{r,t}$
18	--	--	--	--	--	--	--	--
19	--	--	--	--	--	--	--	--
20	0.24	0.23	0.23	0.22	0.21	0.23	0.21	0.28
21	0.27	0.21	e^{r}	e^{r}	0.06	0.05	e^{r}	e^{r}
22	--	--	--	--	--	--	--	--
23	0.06	e^{g}	0.16	e^{t}	e^{g}	0.30	e^{t}	e^{t}

[a]Two-component mixing model incrementally weighted by precip intensity

[b]The TPLR transfer function utilized in rainfall-runoff and tracer modules.

[g]Fraction of Q_{pe} or Q_e greater than Q_t

[r]Rainfall-runoff model $NSE < 0.50$

[t]Event tracer model $NSE < 0.50$

[p]Pre-event tracer model $NSE < 0.50$

Table 6. The fraction of event water in total runoff and peak runoff for event 20 in SYC and WOC. Runoff in both catchments is dominated by pre-event water, a common observation in forested catchments. Both catchments show a similar fraction of total event water, though peak runoff in WOC contains a greater fraction of event water than SYC.

Method	Tracer	SYC		WOC	
		total Q_e:Q_t	peak Q_e:Q_t	total Q_e:Q_t	peak Q_e:Q_t
Two-component[a]	δD	0.24	0.36	0.21	0.22
	$\delta^{18}O$	0.23	0.36	0.23	0.17
TRANSEP[b]	δD	0.23	0.43	0.21	0.26
	$\delta^{18}O$	0.22	0.35	0.28	0.23

[a]Two-component mixing model incrementally weighted by precip intensity as described by *McDonnell et al. (1990)*

[b]The TPLR transfer function utilized in rainfall-runoff and tracer models.

Table 7. Seasonal differences between runoff responses in SYC and WOC.

Summary Statistics	Sycamore Creek (SYC)									White Oak Creek (WOC)								
	Precipitation			Runoff						Precipitation			Runoff					
	Duration	Depth	Intensity	Total Unit Discharge	Q/P	Peak Discharge	Time to Peak[a]	Time Lag[b]	$Q_{q:t}$[c]	Duration	Depth	Intensity	Total Unit Discharge	Q/P	Peak Discharge	Time to Peak[a]	Time Lag[b]	$Q_{q:t}$[d]
	[hr]	[mm]	[mm hr^{-1}]	[mm]	--	[mm hr^{-1}]	[hr]	[hr]	--	[hr]	[mm]	[mm hr^{-1}]	[mm]	--	[mm hr^{-1}]	[hr]	[hr]	--
Growing Season[e]																		
Average	52.7	38.3	2.3	3.7	0.11	0.08	23.2	14.8	0.15	42.9	34.8	2.0	9.7	0.25	0.15	22.9	9.1	0.08
Median	58.2	34.0	1.0	2.4	0.06	0.08	15.4	7.3	0.13	40.0	30.7	1.1	5.5	0.16	0.15	14.1	1.5	0.05
Max	117.2	90.9	14.7	13.5	0.36	0.15	73.5	55.3	0.42	127.3	65.0	11.0	34.4	0.99	0.28	65.2	65.2	0.27
Min	1.3	14.5	0.2	0.6	0.03	0.01	1.2	1.0	0.02	1.5	12.7	0.4	1.1	0.07	0.05	1.5	0.8	0.01
Range[g]	115.8	76.5	14.5	12.9	0.33	0.14	72.3	54.3	0.40	125.8	52.3	10.6	33.3	0.92	0.23	63.7	64.3	0.26
Std. Dev.	39.5	22.9	3.9	3.6	0.11	0.04	22.8	17.0	0.12	36.9	17.2	2.8	9.7	0.24	0.08	21.9	17.3	0.07
Dormant Season[f]																		
Average	64.1	46.2	6.1	6.1	0.17	0.08	34.7	25.0	0.29	74.4	42.8	0.6	27.8	0.71	0.42	32.5	14.7	0.13
Median	55.5	36.2	3.1	3.7	0.11	0.08	23.0	15.9	0.33	63.7	32.3	0.6	25.5	0.66	0.35	20.8	9.0	0.09
Max	117.2	90.9	14.7	13.5	0.36	0.15	73.5	55.3	0.43	151.0	88.9	1.0	57.5	1.08	1.30	84.0	49.2	0.46
Min	1.3	14.5	0.2	0.6	0.03	0.01	1.2	1.0	0.08	26.3	19.6	0.2	9.8	0.42	0.17	3.3	3.2	0.00
Range[g]	115.8	76.5	14.5	12.9	0.33	0.14	72.3	54.3	0.35	124.7	69.3	0.7	47.7	0.66	1.13	80.7	46.0	0.46
Std. Dev.	45.2	30.6	6.7	5.6	0.14	0.05	30.6	23.8	0.13	40.8	24.9	0.3	13.1	0.23	0.37	24.2	14.9	0.15

[a] Time to peak defined as time from start of precipitation to peak discharge

[b] Time lag defined as time from maximum instantaneous storm intensity to peak discharge

[c] $Q_{q:t}$ represents the ratio of quickflow to total flow using the methodology described by *Hewlett and Hippert* [1967] at a constant slope of 0.002 mm hr^{-1} ; due to several unsuccessful separations, n = 17, n = 11 during growing season, and n = 6 during dormant season

[c] $Q_{q:t}$ represents the ratio of quickflow to total flow using the methodology described by *Hewlett and Hippert* [1967] at a constant slope of 0.002 mm hr^{-1}

[e] growing season from 01 May to 31 October; n = 14 except where noted

[f] dormant season from 01 November to April 30; n = 9 except where noted

[g] Range = Max - Min

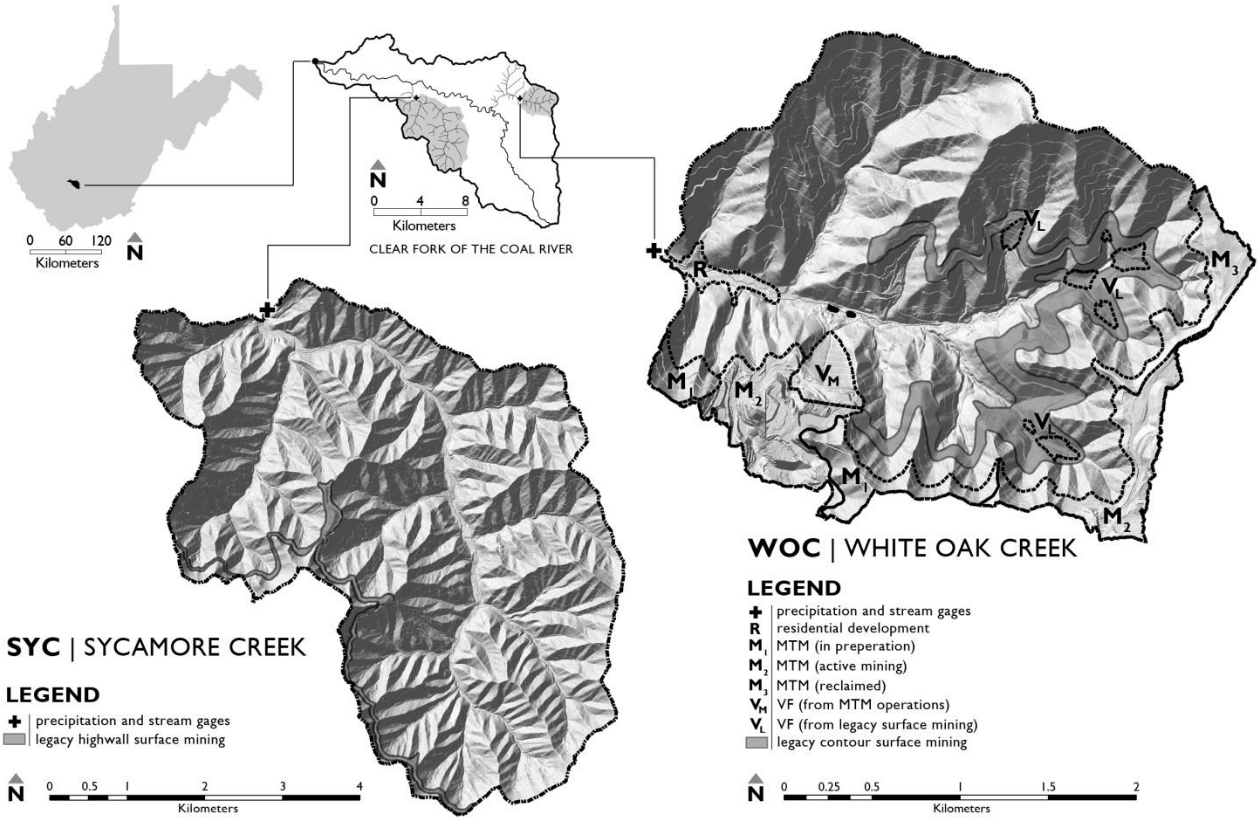

Figure 1. Locations of the Sycamore Creek (SYC) and White Oak Creek (WOC) catchments of the Clear Fork of the Coal River in southern West Virginia. Hillshades and catchment boundaries were derived from a 1 m DEM derived from LiDAR flown and processed by Natural Resource Analysis Center (NRAC) in April of 2010. Landuse boundaries were digitized from 1 m aerial imagery collected in 2011 National Agriculture Imagery Program (NAIP). Note that SYC and WOC are displayed at different

scales.

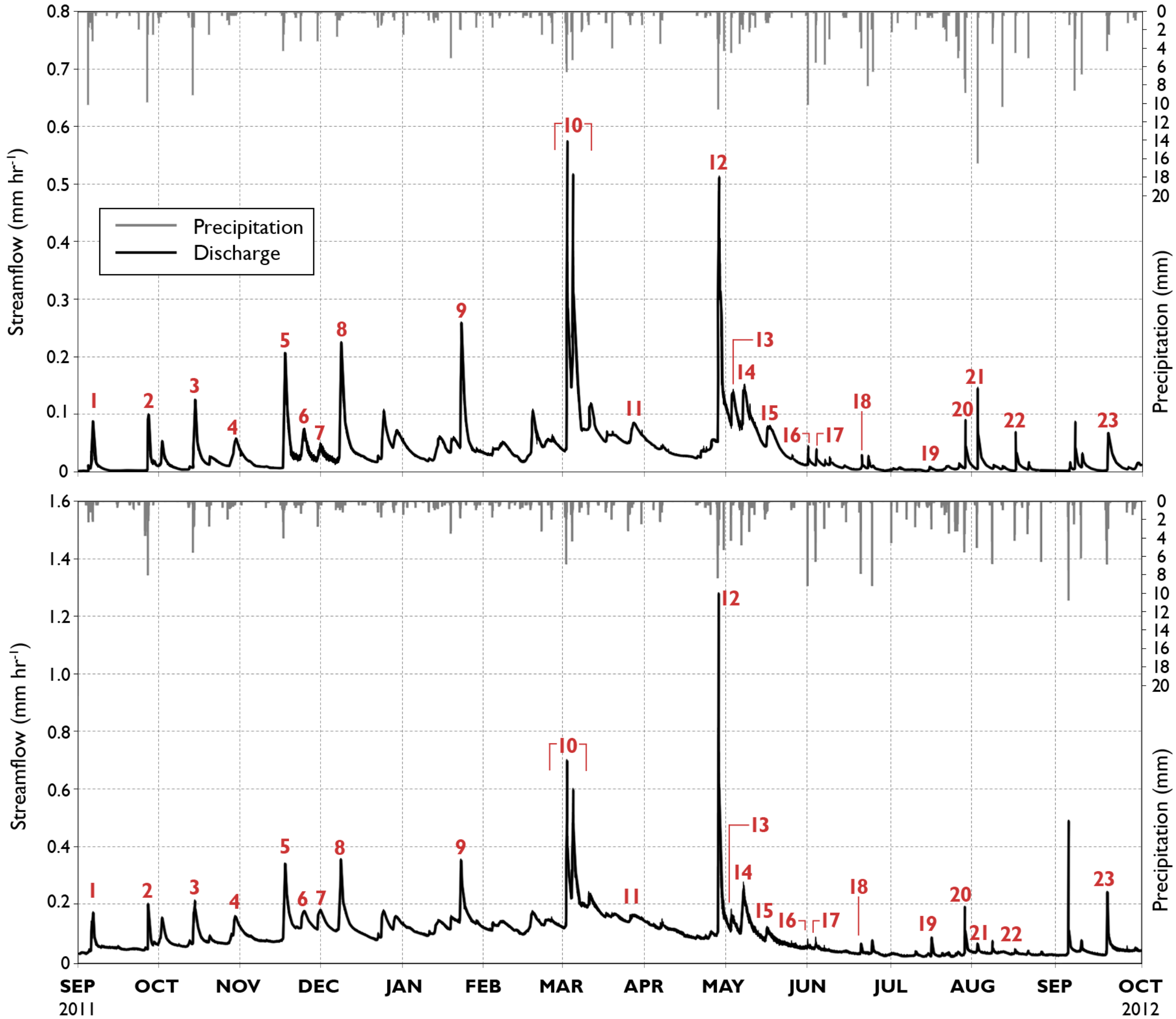

Figure 2. Hydrographs and hyetographs for SYC (a) and WOC (b) for the study period from September 2011 – October 2012. Storm events included in hydrometric analysis are marked sequentially at discharge peaks. Note the different scales for discharge in SYC and WOC.

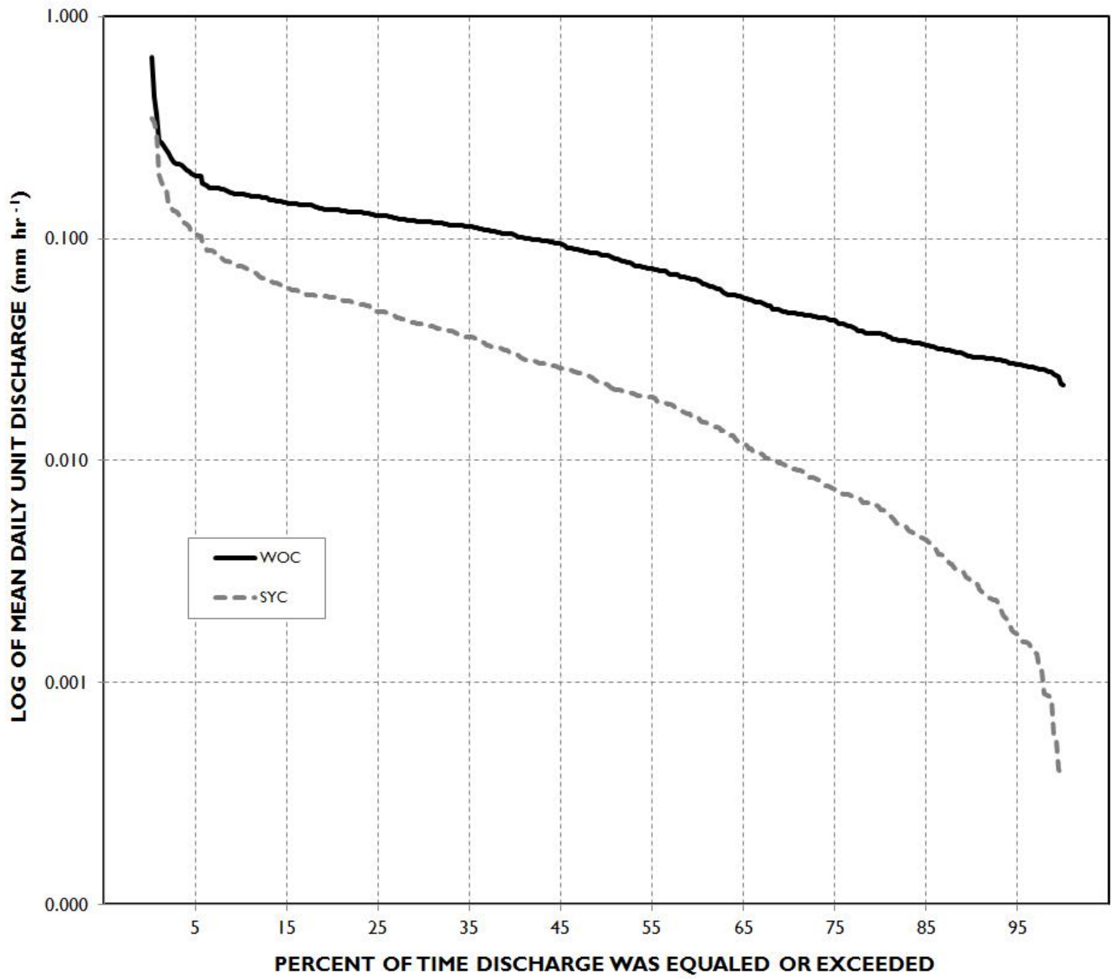

Figure 3. Flow duration curves for SYC and WOC from 1 September 2011 to 30 September 2012. Note that y axis is in log scale. Low exceedance flows represent the largest flows during the study period whereas high exceedance flows represent baseflow during the driest times of the year. This figure demonstrates the different flow regimes in SYC and WOC; runoff in WOC is greater than SYC during all times of the study period, particularly during baseflow conditions where flow is well sustained in WOC compared to SYC.

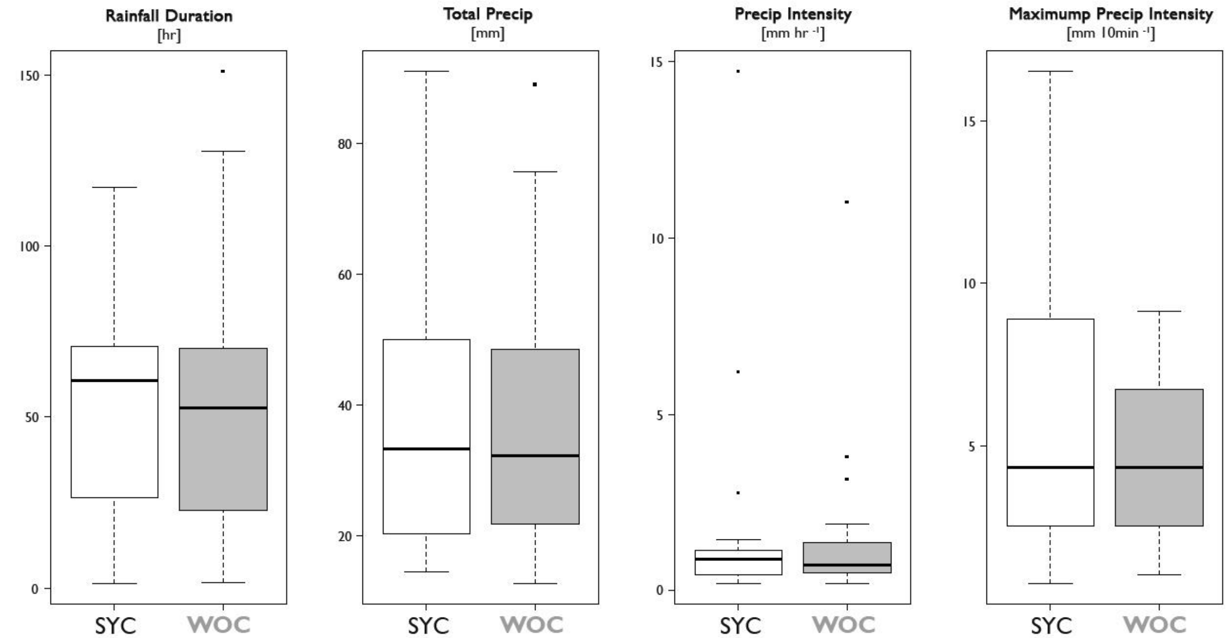

Figure 4. Boxplots of precipitation data from SYC and WOC for 23 storm events where dashed whisker bars represent the 95% confidence limit of the median, boxes represent the upper (75th) and lower (25th) percentiles, black bars are the median, and dots outside the whisker bars are outliers. No statistically significant differences in rainfall metrics were observed between SYC and WOC using a Wilcoxon signed rank test.

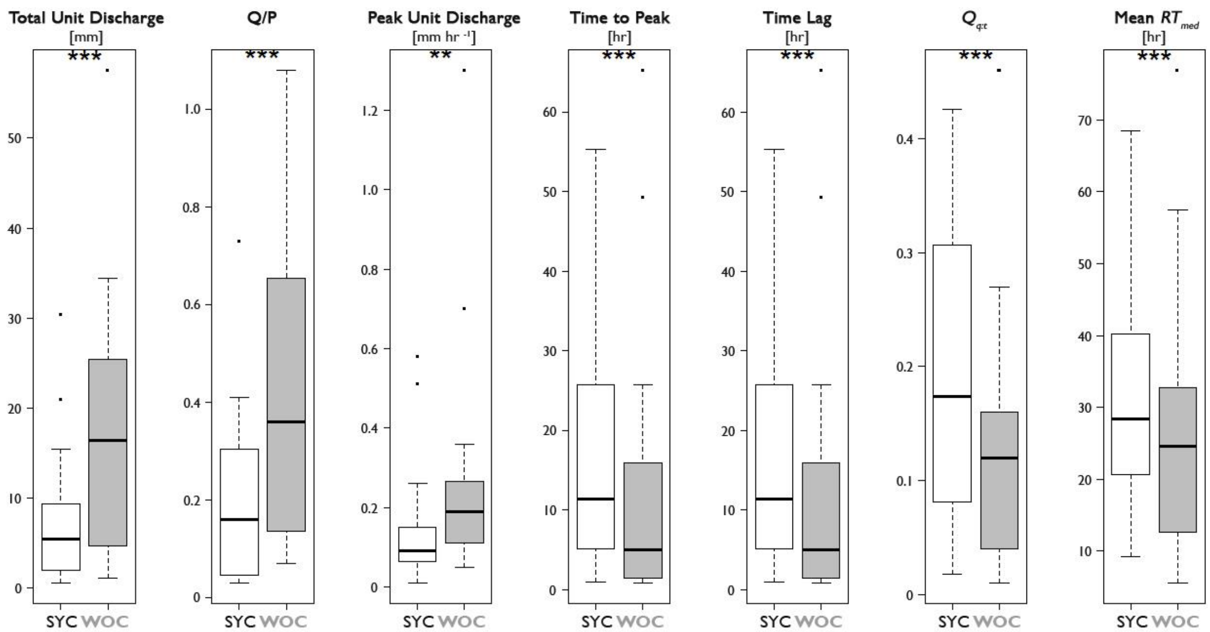

Figure 5. Boxplots of runoff data from SYC and WOC where dashed whisker bars represent the 95% confidence limit of the median, boxes represent the upper (75th) and lower (25th) percentiles, black bars are the median, and dots outside the whisker bars are outliers. Triple starred plots indicate statistically significant differences at the 99% confidence level using the Wilcoxon signed rank test. Double starred plots indicate 95% confidence level. Q/P represents the ratio of stormflow to precipitation. $Q_{q:t}$ is the fraction of quickflow to total flow using methods described by *Hewlett and Hibbert* [1967]. RT_{med} represents the median hydrologic response time derived using a transfer function rainfall-runoff model.

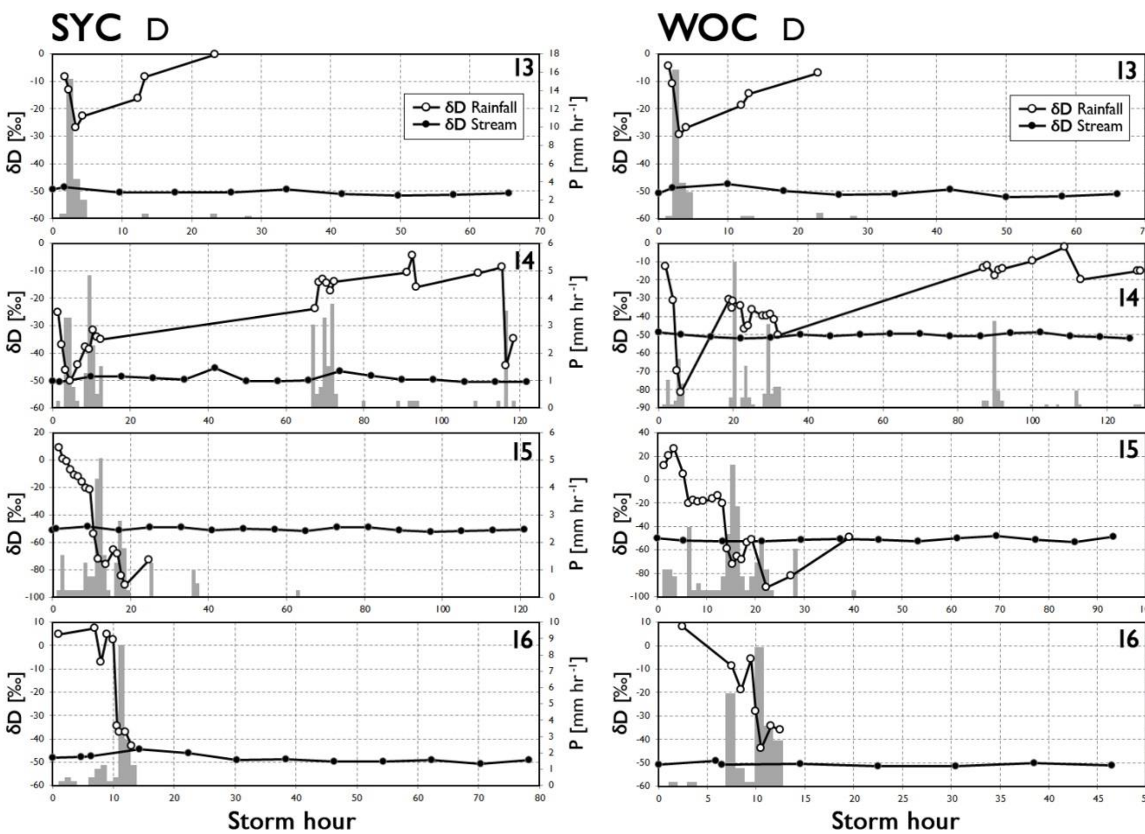

Figure 6. Plots of δD of rainfall and stream for events 13 – 16 in SYC and WOC. Precipitation in mm $hr^{-1}$is shown in gray. $\delta^{18}O$ displayed similar patterns for the same events. The isotopic composition of precipitation varies considerably throughout the storm event, often "crossing" the stream water isotopic composition. For these storm events, stream isotopic composition showed little response to rainfall input and were difficult to separate into event and pre-event water.

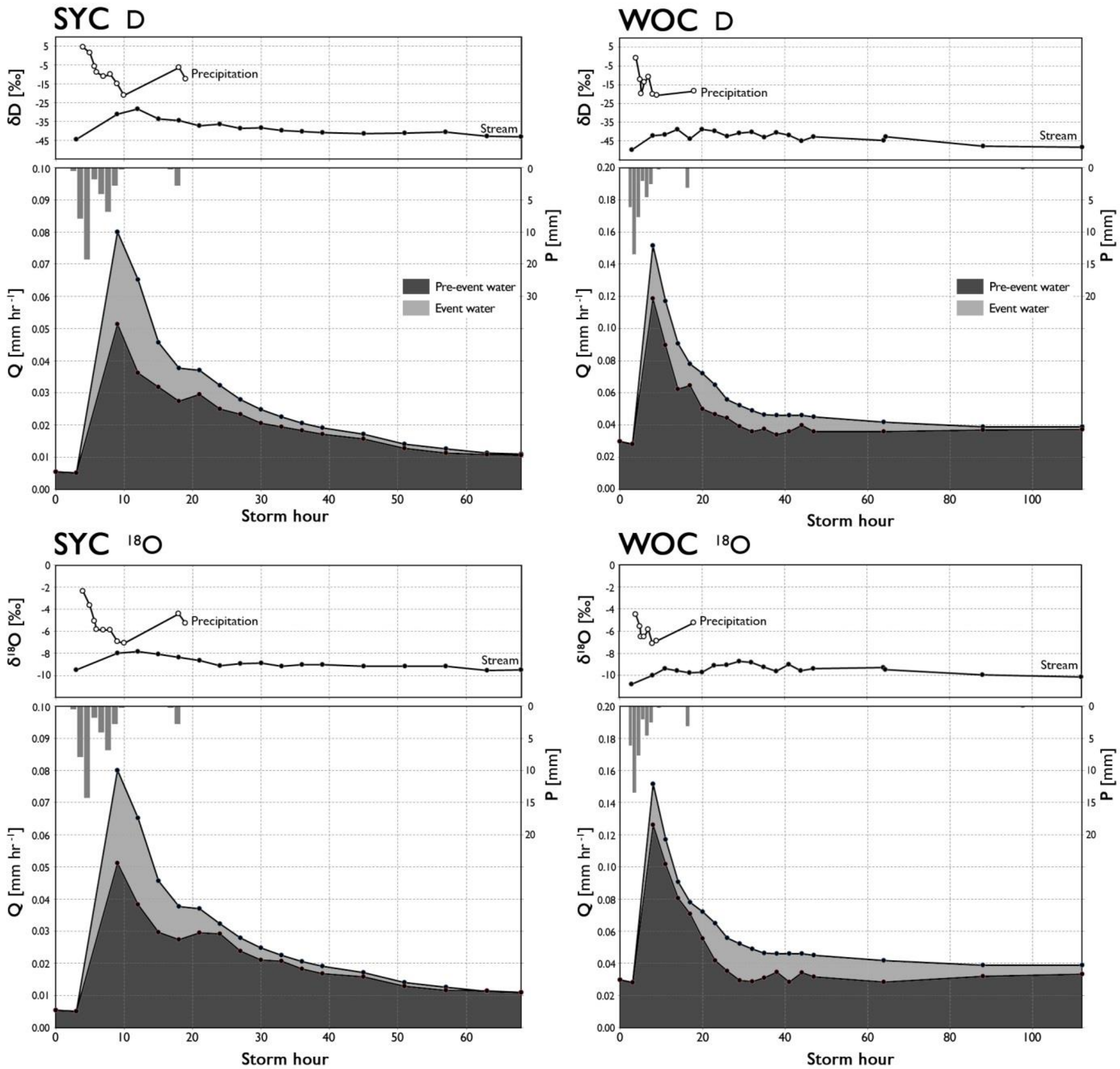

Figure 7. Isotope hydrograph separation of runoff from SYC and WOC using a two-component mixing model. Runoff in both catchments is dominated by pre-event water, a common observation in forested catchments. Both catchments show a similar fraction of total event water, though peak runoff in WOC contains a greater fraction of event water than SYC. Note that y axis for Q are in different scales for SYC and WOC.

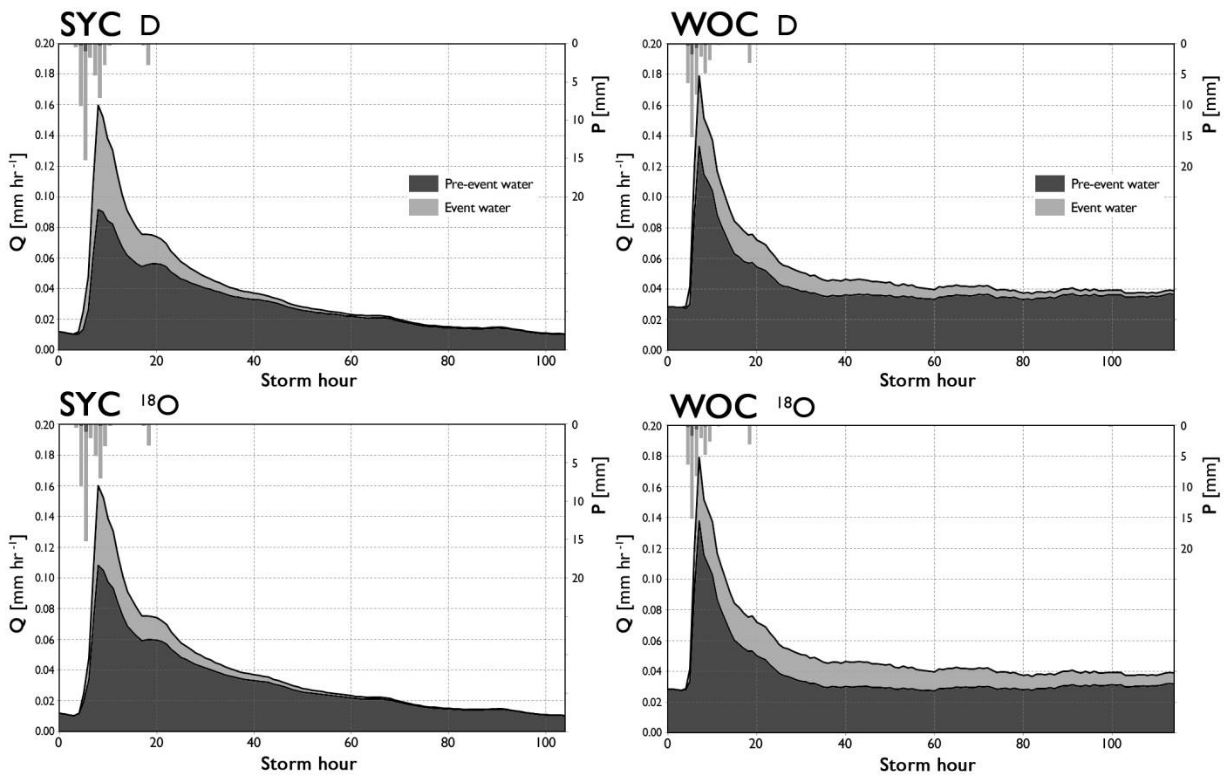

Figure 8. Isotope hydrograph separation of runoff from SYC and WOC using TRANSEP. Pre-event water is shaded in dark gray and event water is shaded in light gray. P_{eff} is shaded dark gray in hyetographs. Both catchments show a similar fraction of total event water, though peak runoff in WOC contains a greater fraction of event water than SYC. Note that y axis for Q are in different scales for SYC and WOC.

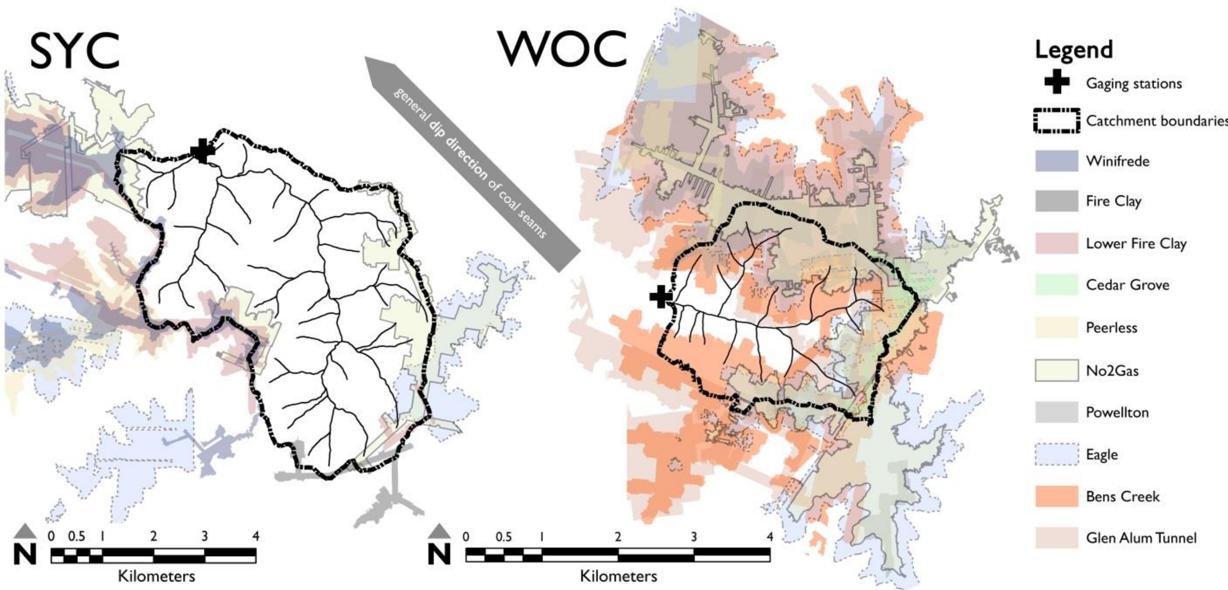

Figure 9. Underground mining activity in SYC and WOC. Coal seams are listed in stratigraphic order in the legend and dip direction is to the northwest. Mean dip in SYC is 0.74° and 0.92° in WOC. Approximately 85% of the catchment area in WOC is underlain by underground mining.

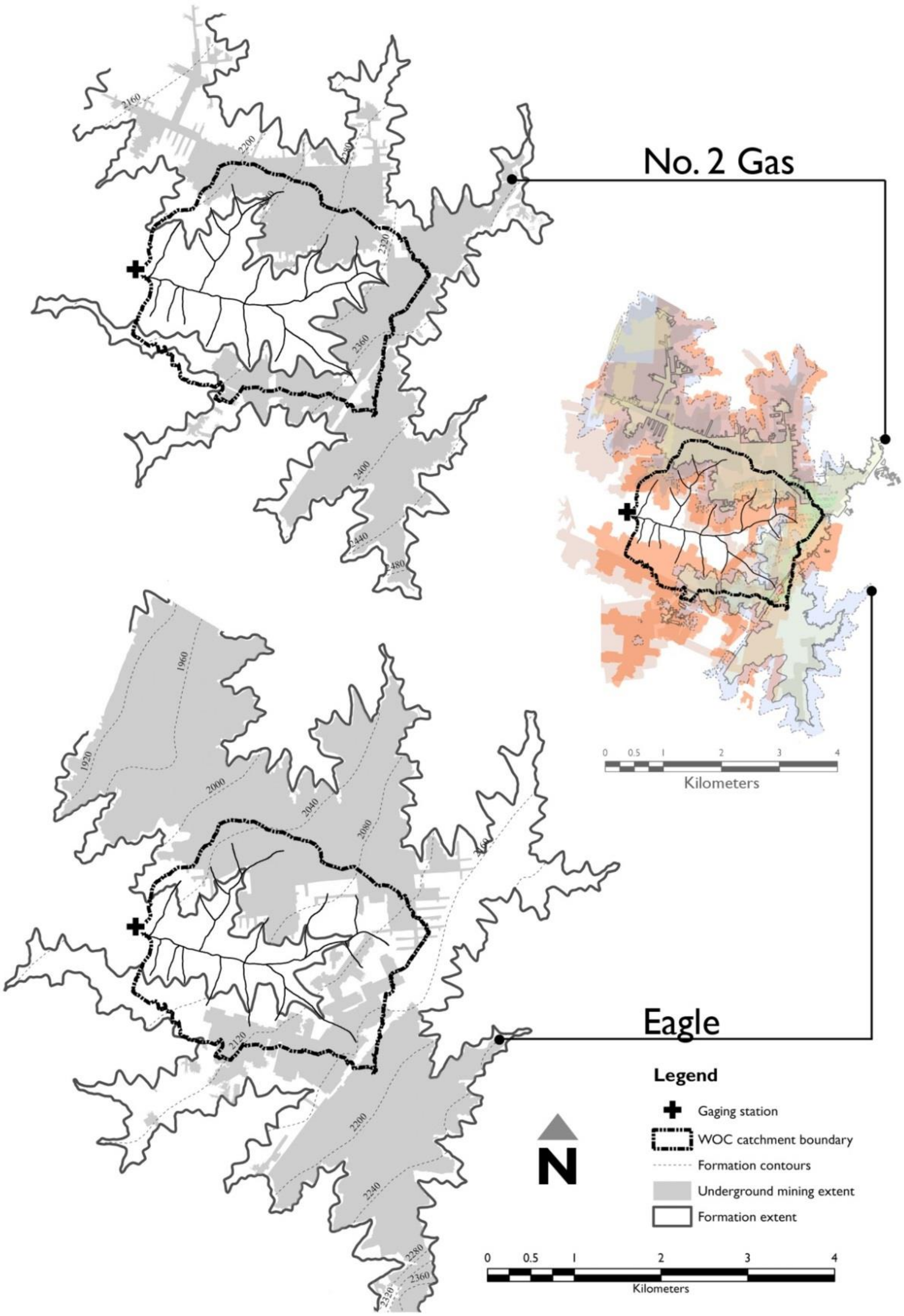

Figure 10. Map of the No.2 Gas and Eagle coal seams within WOC. There is potential interbasin transfer of water from underground mines into WOC on the southeastern edge of the catchment boundary. Water losses in WOC might also be occurring in the northeastern corner of the catchment. Underground mining likely exerts considerable influence on the hydrology in WOC and the MTM region.

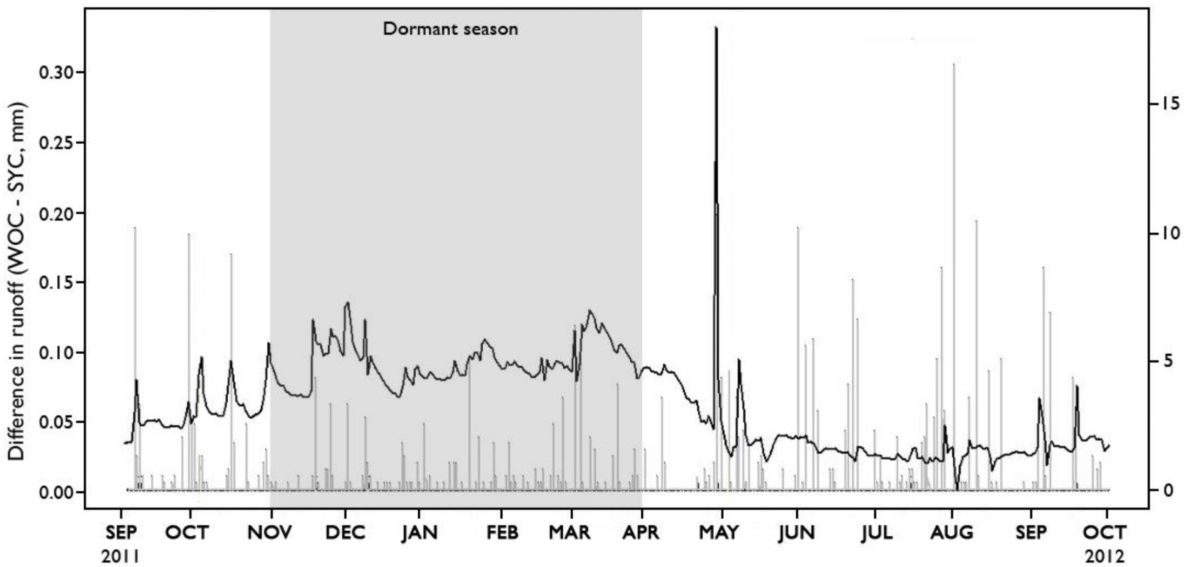

Figure 11. Differences runoff (WOC – SYC) during the study period. The dormant season from November – April is shaded in gray. The greatest differences in runoff between SYC and WOC were observed during the dormant season. This is contrary to the observations in other studies and is likely due to interbasin transfer of water into WOC through underground mine drainage .

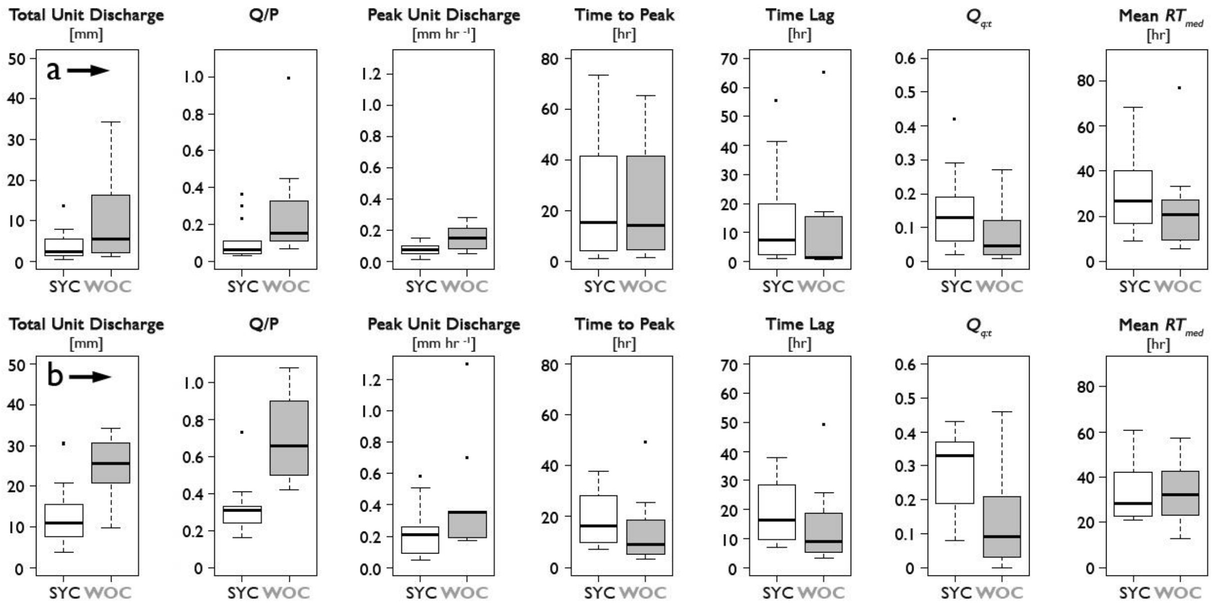

Figure 12. Boxplots of hydrometric broken down by a) growing season from May – October and b) dormant season from November – April. Greater differences between most runoff metrics in SYC and WOC are observed during the dormant season. This is contrary to the observations in other studies and is likely due to interbasin transfer of water into WOC through underground mine drainage. Q/P represents the ratio of stormflow to precipitation. $Q_{q:t}$ is the fraction of quickflow to total flow using methods described by *Hewlett and Hibbert* [1967]. RT_{med} represents the median hydrologic response time derived using a transfer function rainfall-runoff model.

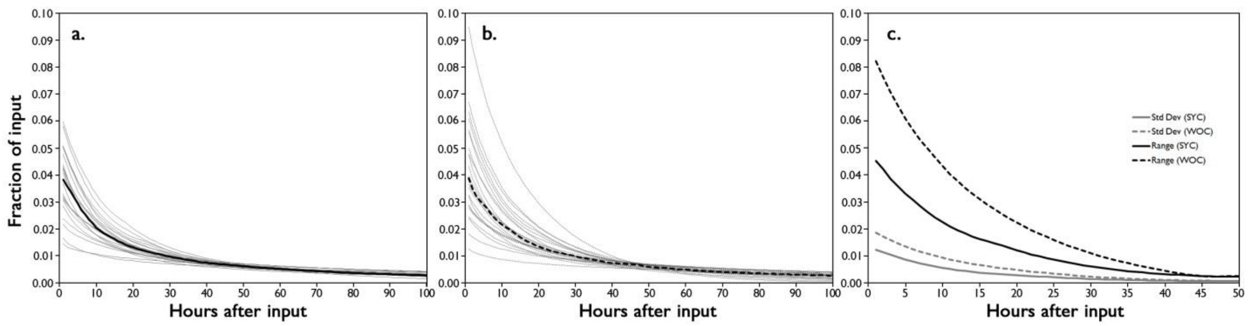

Figure 13. Response curves of rainfall-runoff models where fractions of input are discharge from the catchment through time in SYC (a) and WOC (b). Median response curves for the 23 storm events are shown bolded in a and b. In panel c, the ranges (black) and standard deviations (gray) for the first 50 hours of storm events are shown for SYC (solid line) and WOC (dashed). WOC exibits more variability than SYC in the first 40 hours of storm responses.

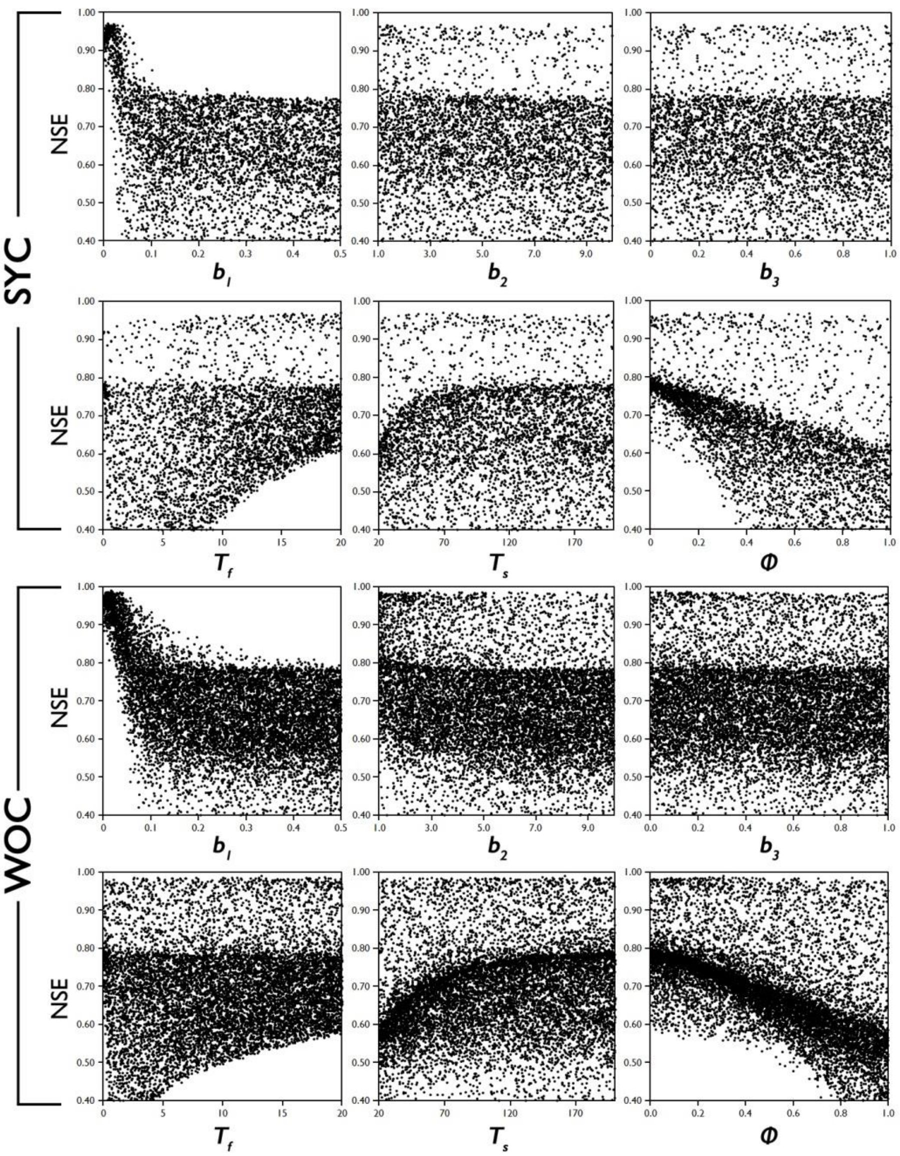

Figure 14. Dotty plots of rainfall-runoff parameters for event 1 in SYC (upper) and WOC (lower). *NSE* values closer to 1.0 represent optimum model efficiency. Dotty plots in this figure are derived from 10,000 Monte Carlo simulations in order to best visually represent the patterns observed in the 100,000 simulations used in this study. Parameter identifiability for all parameters except b_1 is poor.

4. Conclusions

Mountaintop mining (MTM) and valley fill (VF) coal mining represents a dramatic change to the landscape at local and regional scales. In spite of the scale of this practice, little is known about its impact on the storage and movement of water in headwater catchments that dominate the region where it is practiced. To address this knowledge deficit, we characterized runoff responses in two headwater catchments using hydrometric analysis, rainfall-runoff modeling, and isotopic tracers. Sycamore Creek (SYC) is a predominately forested catchment with no active surface mining disturbance and White Oak Creek (WOC) is undergoing MTM operations that impact 30% of its area including a large, partially reclaimed VF.

In spite of similarities in the precipitation inputs to SYC and WOC, the catchments demonstrated different runoff responses. At the annual timescale, total runoff was 3x greater in WOC than SYC and displayed less seasonal fluctuation due to sustained baseflows. This augmented baseflow appeared to be a result of delayed drainage of VFs and underground surface mines which appear to route water from adjacent catchments into WOC. At the storm event timescale, WOC displayed significantly greater total unit discharge, runoff ratios, and peak runoff. Median response time (RT_{med}), the median time for a water input to leave the catchment from the moment it hits the ground, was modeled using a transfer function rainfall runoff model. RT_{med} was shorter in WOC than SYC during the growing season from May – October. However, analysis of the 100,000 Monte Carlo simulations used to calibrate the model revealed poor parameter identifiability and the necessity of future research using multiple model structures.

The greater magnitude of runoff responses in MTM-impacted catchments in this study correlate with other work by *Negley and Eshleman* [2006] in surface mined areas of western Maryland and by *Messinger* [2003] and *Messinger and Paybins* [2003] in the MTM-impacted headwaters of the Mud River in southern West Virginia. However, the degree to which MTM operations in WOC contribute to the disparate runoff responses in the two study catchments is difficult to quantify. Discharge from an extensive underground coal mine network that extends beyond the catchment topographic divide likely contributes significant amounts of runoff to WOC. Thus, MTM's impact on hydrology is likely be confounded by legacy underground mine drainage in catchments where both are present. Additionally, WOC's smaller area (4x smaller than SYC) might contribute to its higher magnitude, flashier response compared to SYC, though the relations between catchment area and runoff response are regional and difficult to generalize [*Pilgrim et al.*, 1982].

The results of this study reveal the complexity of hydrology in disturbed landscapes of the Central Appalachian coalfields. This study, as well as the work of *Borchers et al.* [1991] and *Puente and Atkins* [1989], suggests that disturbance to the subsurface geology by underground mining operations in the past century are as significant to the hydrology of headwater catchments as more conspicuous MTM mining operations. Similarly, *Merriam et al.* [2011] conclude that impacts to downstream aquatic ecosystems from surface mining and residential development are additive physically, chemically, biologically. While initial research into the hydrologic impacts of MTM should seek to minimize confounding variables from other landuses, extrapolating our understanding of the hydrologic impacts of MTM to the entire Appalachian coalfields region ultimately requires investigating this mining practice in the context of a legacy of land disturbance. Discerning the effects of these disturbances and quantifying their interactions necessitates insight into the catchment processes that control the storage and movement of water in these complex systems. Understanding hydrologic processes is also critical for addressing the downstream geochemical and biological impacts of MTM/VF operations.

To initiate process-level studies in the Central Appalachian coalfields, we conducted preliminary isotope hydrograph separations of event responses into the temporal sources of runoff, but this technique ultimately proved unsuccessful for all but one event. For this event, total runoff in both catchments was dominated by pre-event water; however at peak runoff, WOC showed a substantially greater fraction of pre-event water than SYC. The explanation for this observation is not clear without more information, but it does correspond with the importance of water storage reservoirs (i.e. VFs, underground mines) in WOC's runoff response suggested by hydrometric and modeling analysis. However, given the poor performance of multiple hydrograph separation models (two-component, TRANSEP) for other events, it is difficult, if not impossible, to draw conclusions about the temporal sources of runoff in these systems.

The restricted access in both catchments required precipitation and pre-event water to be measured at single points at the catchment outlet. This sampling methodology necessitated inherent assumptions about the spatial uniformity of event and pre-event water inputs, many of which have already proven to be invalid [*Kendall and McDonnell*, 1993]. Given the number of pre-event water reservoirs in WOC that can contribute to runoff during events, such as groundwater, soil water, underground mine water, and retention ponds, simplifying water stored in the catchment prior to the onset of rain into a single reservoir is inappropriate. Future research should explore multiple-component mixing models using geochemical tracers to discern the geographic sources of runoff in MTM-impacted catchments. Therefore, researchers, landowners, and mine operators in MTM-impacted areas must work collectively to overcome access restrictions that limit the collection of necessary data in disturbed catchments. Given the importance of hydrology in controlling downstream chemistry, biology, and flood generation, this step is critical to reducing the environmental and social consequences of this landscape scale disturbance.

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