

Review

Mountaintop Removal Mining and Catchment Hydrology

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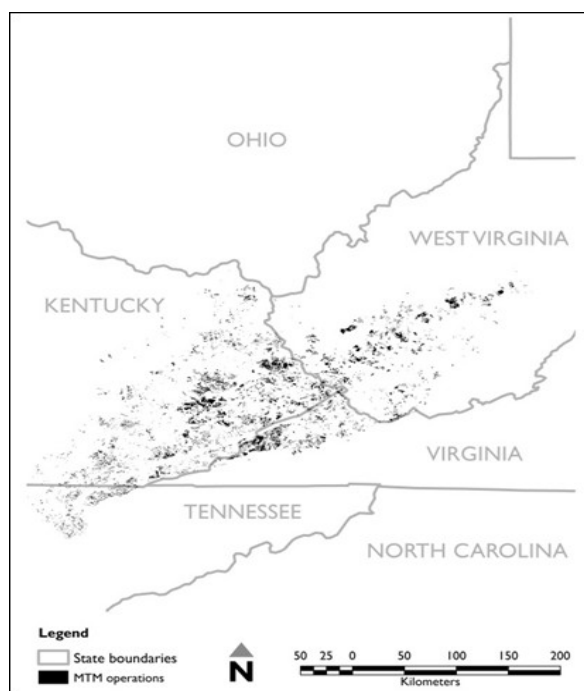
Abstract: Mountaintop mining and valley fill (MTM/VF) coal extraction, practiced in the Central Appalachian region, represents a dramatic landscape-scale disturbance. MTM operations remove as much as 300 m of rock, soil, and vegetation from ridge tops to access deep coal seams and much of this material is placed in adjacent headwater streams altering landcover, drainage network, and topography. In spite of its scale, extent, and potential for continued use, the effects MTM/VF on catchment hydrology is poorly understood. Previous reviews focus on water quality and ecosystem health impacts, but little is known about how MTM/VF affects hydrology, particularly the movement and storage of water, hence the hydrologic processes that ultimately control flood generation, water chemistry, and biology. This paper aggregates the existing knowledge about the hydrologic impacts of MTM/VF to identify areas where further scientific investigation is needed. While contemporary surface mining generally increases peak and total runoff, the limited MTM/VF studies reveal significant variability in hydrologic response. Significant knowledge gaps relate to limited understanding of hydrologic processes in these systems. Until the hydrologic impact of this practice is better understood, efforts to reduce water quantity and quality problems and ecosystem degradation will be difficult to achieve.

Keywords: mountaintop removal mining; valley fills; streamflow; hydrology; Appalachians; surface coal mining

1. Introduction

Mountaintop removal mining and valley fill (MTM/VF) coal extraction, practiced in the Central Appalachian region of the eastern United States, 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. While surface mining is used to mine metals, minerals, and oil, it is often associated with coal, accounting for 40% of coal mined globally and accounts for two-thirds of coal production in the US and Australia [1]. Surface mining represents the largest landuse/land cover change in the Central Appalachian region [2] and by 2012, the US Environmental Protection Agency (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 4000 km of headwater streams buried under valley fills [3] (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 [4]. Furthermore, the large-scale alterations of catchment structure (e.g., topography, slopes, organization, volume, *etc.*), water chemistry, and land cover are likely permanent, having important health implications for aquatic and human communities linked to these streams.

Figure 1. Mountaintop removal mining (MTM) operations of the Central Appalachian coalfields. The EPA [3] 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 valley fills. MTM boundaries remote sensed from aerial photography by SkyTruth [5].



Significant progress has been made in understanding the impacts of MTM/VF on downstream chemistry and ecological conditions. A recent review by Griffith *et al.* [6] provides a state-of-understanding about the physiochemical impacts of this practice and recent work by Lindberg *et al.* [7]

and Bernhardt *et al.* [8] show cumulative and regional impacts and significant biological impairment downstream of mountaintop mines and valley fills. By placing minespoil in the path of streams, contact time is forced between runoff and overburden chemistry potentially altering stream chemistry (e.g., alkaline or acid mine drainage). Notwithstanding the role hydrology plays on stream chemistry, aquatic ecology, and overall aquatic ecosystem health, and despite the scale, extent, and potential for continued development, the effects MTM/VF on hydrology is poorly understood. Much of our limited knowledge about the hydrologic impacts of surface mining is from only a handful of traditional surface mining (*i.e.*, strip, auger) studies whose numbers pale in comparison to other land use studies (e.g., forest harvesting). The number of MTM studies is considerably less making generalization and inference difficult between watersheds. While in certain respects MTM is similar to traditional surface mining, MTM generally differs in terms of its spatial extent and prolific use of valley fills, although valley fills are sometimes using in conjunction with contour mining. While valley fills have been described as acting like an unconsolidated aquifer that modulate runoff [9], the minespoil that forms the valley fill also develops preferential flow paths capable of storing and rapidly routing water [10–12].

Investigations into contemporary MTM/VF operations have involved hydrologic modeling or quantifying catchment outlet streamflow responses to precipitation inputs. These studies show an overall increase in baseflow in MTM/VF impacted catchment [11,13–15] and generally show increases in discharge for larger storm events [11,16]. However, results from these studies are variable, influenced by climate, geography location, and the stage/age of mining activities, underscoring the need for more hydrological studies.

MTM/VF has become an increasingly polarized issue nationally and particularly in the communities in which it is practiced. Local citizens, environmental advocacy groups, and regulators have expressed concerns over the long term impacts of MTM/VF on downstream water quality, public health, and safety. After several devastating floods in southern West Virginia, public concerns were raised about the potential of MTM 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 [17] and, more effectively, citing the absence of conclusive scientific evidence to support the MTM/VF operations' culpability in the alteration of downstream hydrology. Underscoring the critical knowledge gaps associated with MTM is the need for thorough scientific investigations to inform citizens, the energy industry, and policy makers about the potential environmental consequences of this practice.

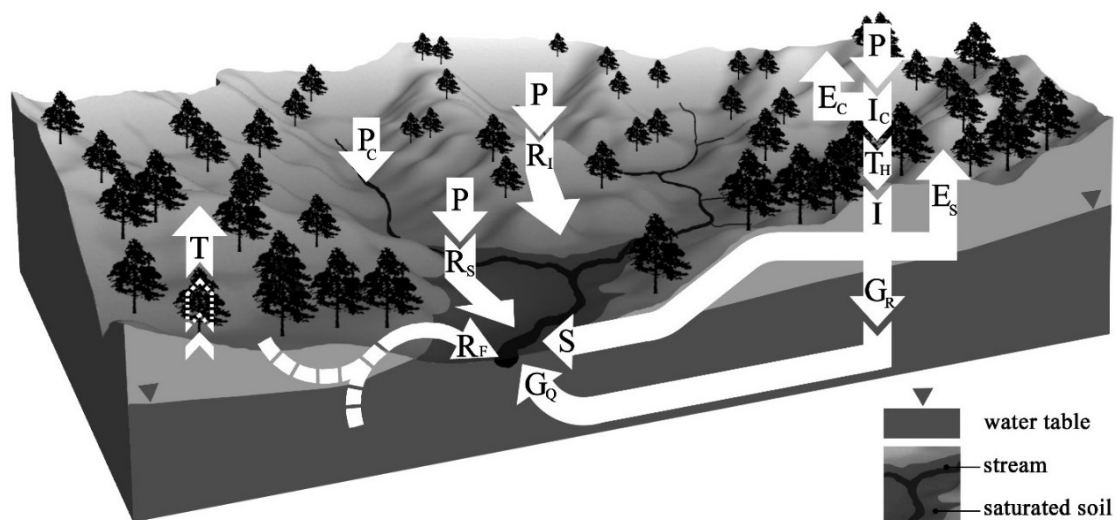
In short, there is a lack of data to inform our understanding of how hydrologic systems are responding to this drastic and permanent landscape-scale change. Thus, the overall objective of this paper is to aggregate the existing knowledge base of the hydrologic impacts of MTM/VF to identify areas where further scientific study is critically needed. The organization of this paper is as follows: Section 2 provides an overview of the catchment water balance, important processes that govern runoff, and impacts of land cover changes on streamflow to develop a conceptual understanding of potential impacts of MTM/VF on hydrology; Section 3 describes MTM/VF and traditional surface mining operations and reviews hydrologic impacts associated with each practice; and in Section 4 we identify critical hydrologic knowledge gaps based on our literature search to provide direction for future research.

2. Overview of Catchment Hydrology

2.1. Water Balance and Catchment Processes

Small catchments (<10 km²) and hillslopes are the primary experimental unit for many hydrologic studies because inputs and outputs (Figure 2) are relatively easier to measure at smaller scales. How catchments collect, store, and release water is largely a function of climate, morphology (including topography, soils, geology), and land cover. The storage and flow of water through a catchment affects a number of processes including the quantity and timing of runoff, soil erosion and sediment transport, downstream water chemistry and biology, and biogeochemical cycling.

Figure 2. Conceptualization of forest headwater catchment hydrologic processes. Water is added to the catchment as precipitation (**P**), some of which falls directly into the stream channel (**P_C**). Precipitation falling on forested hillslopes is intercepted by the tree canopy (**I_C**) and is either lost to evaporation (**E_C**) or falls to the forest floor as throughfall (**T_H**). On the forest floor, water is infiltrated (**I**) into the soil and is either lost to evaporation (**E_S**) and plant transpiration (**T**) or percolates to the water table and becomes groundwater recharge (**G_R**) which will be stored then discharged to the stream channel (**G_Q**) or to the adjacent riparian area as return flow (**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 (**R_I**). Precipitation falling on saturated soil becomes saturation excess overland flow (**R_S**).



The primary input to headwater catchments in the Central Appalachian region is precipitation primarily in the form of rain and a transient snowpack. Losses are from evaporation and transpiration (evapotranspiration, E_t), streamflow and groundwater. E_t in this region accounts for, on average, 47% of annual precipitation [18]. Canopy interception in this predominantly deciduous forests accounts for 10%–20% of precipitation [19–21].

Runoff can take a variety surface and subsurface flowpaths from the hillslope to the stream channel that ultimately control the timing and magnitude of runoff. Because of high hydrologic conductivity in

soil macropores [21,22], runoff generation in forested catchments is dominated by subsurface flow [23]. The biogeochemical composition of water discharged to the stream channel is a function of how long water remains in the catchment; longer residence times imply greater contact time for biogeochemical transformation [24,25]. Therefore, runoff flowpaths exert important controls on downstream aquatic ecosystems that extend beyond physical hydrology.

2.2. Landuse and Land Cover Changes

The consequences of landuse/land cover changes on streamflow have garnered much attention over the past few decades [26]. While significant research focuses on the impacts of forest harvesting on streamflow (e.g., [27–29]) studies also include agriculture (e.g., [30]), and urbanization (e.g., [31–33]).

Forest harvesting usually increases runoff by reducing canopy interception and transpiration (e.g., [34]). In addition, soil compaction from heavy machinery and logging roads reduces infiltration thereby increasing surface runoff (e.g., [35]). Logging roads cut into steep hillsides can intercept shallow subsurface flowpaths from upland hillslopes, thereby delivering this water to the stream channel as surface runoff [36]. Because vegetation is usually reestablished after logging operations and the catchment structure is relatively unaltered, the impact of harvesting on streamflow is generally thought to be short-lived, though dense and poorly constructed logging road networks can prolong the impact [37].

Agricultural practices and urbanization can have profound effects of streamflow. The conversion of mature forests to agricultural land changes the amount of water lost through E_t , increasing available water for runoff. Further exposure of bare soils and compaction can lead to rapid routing of runoff to stream channels, often as Hortonian overland flow [38] or through constructed drainage networks [39]. Urbanization generally increases runoff magnitude and volume. Impervious surfaces such as roads, parking lots, and roofs can greatly diminish infiltration resulting in reduced soil moisture, groundwater recharge and increased stormflow [32]. The conversion of forest to lawn or impervious surface can greatly reduce catchment E_t [40]. Runoff is often directly routed to streams through storm sewers and constructed channels. Consequently, urbanized catchments tend to quickly convert rainfall to runoff with flashy, high-magnitude storm hydrographs and limited baseflow compared to forested systems [31–33].

Similar to these landuse/land cover changes, surface mining alters the catchment water budget by altering flow paths. Ferrari *et al.* [41] described the impacts of traditional surface mining as being more similar to urbanization than forest harvesting. Confounding better understanding of the impacts of MTM/VF is that this practice causes structural changes in the catchment (*i.e.*, topography, drainage density) in addition to altering the water budget due to loss of forest and soil compaction during reclamation; MTM activities can result in major changes to headwater topography and drainage network but the implication of a wholesale alteration in catchment structure and land cover is not well understood.

3. Impacts of Mountaintop-Removal Mining and Valley Fill on Hydrology

3.1. Overview of MTM/VF Operations

MTM/VF 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 (Figure 3). While MTM/VF is broadly categorized as surface mining and synonymous with traditional strip and contour mining, MTM is distinct in terms of its scale and management of overburden [6]. As much as 300 m of overburden is removed from ridge tops to access underlying coal seams [42]. Because the volume of displaced minespoil precludes it being replaced to the ridge tops, much of this excess material is placed in adjacent valleys burying headwater streams and springs, creating valley fills (Figure 4). Valley fill construction techniques vary; the sorting and placement of spoil material, management of water through or on top, and soil conditions of the valley fill face are often site-specific and vary considerably across the region.

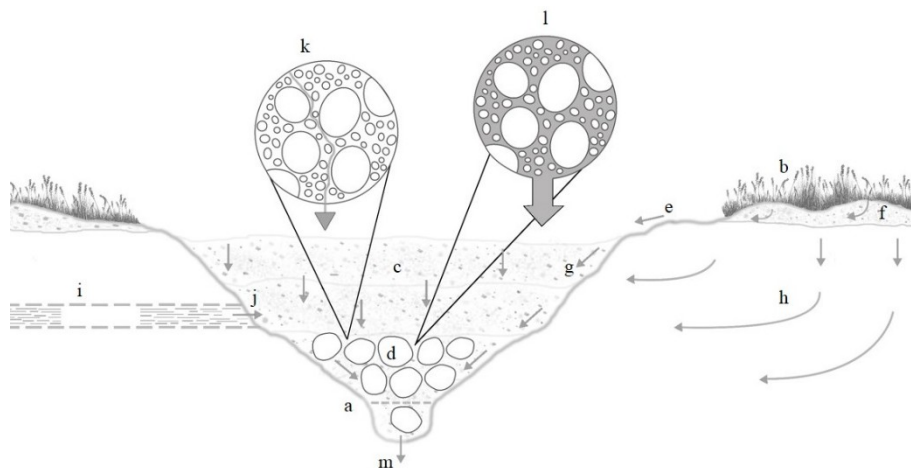
Figure 3. The process of MTM removes vegetation, soil, and uses explosives and heavy machinery to gain access to deeper coal seams. Overburden is placed in adjacent headwater stream valley creating valley fills. The picture below shows the critical elements of a MTM/ valley fill (VF) operation in a headwater catchment in southern West Virginia (WV): (a) Pre-mining forest; (b) forest and soils cleared in preparation of blasting; (c) Explosives are used to remove overburden geology changing ridgelines (d) and altering topography; (e) Overburden material is placed in stream valleys creating valley fills (f) in lifts altering catchment storage; (g) post-mining landscape is reclaimed under the Surface Mining Control and Reclamation Act (SMCRA). Post-mining vegetation is often herbaceous.



MTM is permitted under the Surface Mining Control and Reclamation Act (SMCRA) of 1977 [43]. 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 [43]. 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 valley fill structures.

Figure 4. Conceptual model of runoff flow paths in a MTM/VF headwater catchment: (a) original stream channel; (b) MTM surface reclaimed with herbaceous cover; (c) valley fill material and lifts; (d) larger overburden material sort to fill bottom; (e) rapid Hortonian overland flow; (f) infiltrating water hits less permeable mine pavement facilitating horizontal flow; (g) percolation of water through valley fill and along original valley slope; (h) groundwater flow; (i) subsurface flow paths along coal seams and abandoned deep mines; (j) groundwater contributions to fill from (i); (k) steady state matrix flow through tortorous flow paths sustains streamflow exiting valley fill (m) during non-storm periods; (l) runoff through connected saturated pores and large voids during storm conditions rapidly routes water through valley fill; (m) runoff exiting valley fill to surface channel.



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 [44]. To achieve this, mine soils are heavily compacted using heavy machinery and fast growing (often exotic) 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 [45]. The Forestry Reclamation Approach (FRA) advocated by the Appalachian Region Reforestation Initiative (ARRI) has shown that loose dumped spoil is an effective growing medium for Appalachian hardwood tree species [46]; while this method of surface mine reclamation has become more commonplace, it does not represent the predominant reclamation practice on surface mines in the region.

Because MTM/VF operations create two distinct landforms, each with unique physical and hydrologic impacts, the following sections discuss the impacts of traditional surface mining and the individual and combined hydrologic impacts of the MTM/VF (Table 1).

Table 1. Hydrologic impact studies of surface mining and MTM/VF in the eastern US.

Reference ^a	Year ^b	Location	Mining Method	# of catchments	Spatial Scale ^c	Time scale/ study duration	Key hydrologic observations
[47]	1965	Indiana	pre-SMCRA surface mining	2	HW to MS: 55.4 & 111.4 km ²	3 months	Show that spoil piles act as reservoirs for groundwater storage.
[48]	1966	Indiana	pre-SMCRA surface mining	2	HW: 55 & 111 km ²	12 months	Surface mine impacted watersheds maintained flows while forested catchments went dry during extreme draught conditions.
[49]	1970	Kentucky	pre-SMCRA strip mining	3	HW: 0.67–2.2 km ²	4 years	Greater flow variability, less storage, larger peakflows in mined catchments.
[50,51]	1972	Kentucky	pre-SMCRA strip mining	4	HW: 0.66–1.8 km ²	Single storm event	During a major storm event, surface mined watersheds had smaller peak discharges than adjacent, undisturbed catchments.
[52]	1972	Kentucky	pre-SMCRA surface and underground mining	1	BA: 2442 km ²	25 years	Streamflow is maintained during extended dry periods in mined catchments after streams in unmined catchments have ceased flowing, which the authors attributed to storage of water in underground mines, spoil piles, and strip pits.
[53]	1981	Kentucky	pre-SMCRA strip mining	6	HW: 0.70–1.5 km ²	4 years	Storm flow volumes were unchanged but peak flows increased by 36% in mined catchments. This effect was most prominent during smaller events; higher magnitude peaks were unaffected.
[54]	1987	Pennsylvania	post-SMCRA surface mining	-	PS: 78 Infiltration tests on 5 reclaimed surface mines	30 minutes tests on reclaimed mines 1–4 years old	Infiltration rates on newly reclaimed mine soil were an order of magnitude lower than undisturbed soils. Infiltration rate recovered through time the extent of which appeared to be controlled by overburden lithology.
[9]	1989	Tennessee	pre- and post-SMCRA contour mining; small scale MTM operations	5	HW: 1.74–11.2 km ²	8 years	Total flow increased in mine-impacted catchments, particularly during low flow conditions. Authors attributed this to decreased ET losses from deforestation and the storage and slow release of runoff from mine spoil.
[55]	1989	West Virginia	pre-SMCRA strip and underground mining	5	HW: 4.66–20.07 km ²	3–5 years	Synoptic discharge measurements revealed the importance of underground mining in rerouting subsurface water. A rainfall-runoff model indicated increased ET losses and decreased runoff in surface mined catchments.

Table 1. Cont.

Reference ^a	Year ^b	Location	Mining Method	# of catchments	Spatial Scale ^c	Time scale/ study duration	Key hydrologic observations
[56]	1991	West Virginia	pre- and post-SMCRA strip mining; underground mining	4	HW: 12.6–21.8 km ²	3 years	Peak stream discharges from mined basins were smaller than those from unmined areas, and mined basins had lower high flows and higher low flows than the unmined basins.
[57]	1993	Pennsylvania	post-SMCRA surface mining	3	HW: 0.11 & 0.32 km ²	3 & 11 years in each catchment	The extent of infiltration rate recovery of reclaimed surface mines will control the storm hydrograph and drainage network evolution. Where recovery occurs, saturation excess overland flow becomes primary runoff mechanism.
[58]	1995	West Virginia	Unclear	-	PS: 8 ha spoil pile	14 years	The spoil pile contained highly permeable spoil channels that are variably oriented and interconnected which created a pseudo-karst hydrologic setting.
[59]	1997	Ohio	post-SMCRA contour-area and haul-back mining	3	HW: ~0.12–0.2 km ²	5–6 years	Mining and reclamation activities caused more frequent higher daily flow volumes. Peak flows on mined lands decreased with reclamation but were still greater than pre-mining flows.
[12,60,61]	1999	Kentucky	VF	1	HW: 4.1 km ² mine spoil area with 2 VFs	multiple scales/ 4 years	Identified 3 distinct but interconnected zones of water stored in mine spoil: slow moving water in the spoil interior and more rapidly moving water in the valley fills at lower elevations.
[62]	2001	Pennsylvania	post-SMCRA surface mining	1	HW: 0.32 km ²	4 years	In spite of an increase in infiltration rate, little change is observed in total runoff from a reclaimed surface mine indicating contributions through throughflow and return flow. Dye tracing revealed a developed macropore network.
[63]	2002	West Virginia	MTM (VFs not considered in model)	3	HW: 9.9–26.1 km ²	3 modeled storm events	Peak runoff increased 3%–21% in surface mined and timbered catchments based on hydrologic modeling. This significance of this additional input was lessened downstream.
[11]	2003	West Virginia	MTM/VF	3	Headwater: 0.49–5.67 km ²	storm event/ 2 years	During larger storm events, the mined catchment produced more unit runoff than the forested catchment. Double peaks were observed in the heavily mined catchment during intense storms.
[14]	2003	West Virginia	MTM/VF	3	3 catchments: 0.49–5.67 km ²	daily & monthly/ 2 years	Total unit flow in mined catchment was approximately 2× greater than forested catchment, with greatest differences occurring dry periods. Unit flow during high flows was similar between the mined and forested catchment.

Table 1. Cont.

Reference ^a	Year ^b	Location	Mining Method	# of catchments	Spatial Scale ^c	Time scale/ study duration	Key hydrologic observations
[16]	2003	West Virginia	MTM/VF	5	HW: 0.49–3.03 km ²	single storm event	Return interval in forested catchment varied from 10–25 years compared to <2 to >100 years in mined catchments.
[64]	2004	Kentucky	MTM/VF	4	HW: 1.4–6.5 km ² (theoretical catchments)	2 storms; summer 2001	Highly variable model outcomes, with surface mining either increasing or decreasing flood potential. However, the author concludes that, on balance, MTM/VF is likely to increase flood potential.
[65]	2006	Maryland	post-SMCRA strip mining	2	Headwater: 0.03 & 2.7 km ²	event-annual/ 3 years	Mined/reclaimed catchment show 2.5× higher storm runoff coefficients, 3× greater total runoff volume, and 2× higher peak hourly runoff rates than the forested catchment.
[41]	2009	Maryland	pre- and post-SMCRA strip mining	1	MS: 187.5 km ²	310-year periods: 1971–1981, 1982–1992, 1994–2004	Estimations of flood response showed that the rate at which flood magnitude increases due to increased mining is linear, a response synonymous with urbanization rather than deforestation.
[66]	2009	Maryland	pre- and post-SMCRA strip mining	2	Meso-scale: 127.2 & 187.5 km ²	multiple scales / 57 years	Floods in the mined catchment showed higher peak runoff and shorter centroid lag than the forested catchment but less total stormflow volume due to water lost through underground mine workings.
[67]	2009	Kentucky	loose dumped mine spoil	-	PS: 6 test cells: ~ 1 acre	12 storm events / 15 month study period	Loose-dumped spoil of varying composition generally produced low discharge volumes (12% of rainfall), small peak discharge rates (between 2.5×10^{-5} and 3.0×10^{-3} m ³ /s), and long discharge durations (6 days on average).
[68]	2011	Maryland	pre- and post-SMCRA strip mining	4	Headwater: 3.0–27.1 ha	15–61 storm events /3–8 years	Calculated curve numbers (range: 68–92) for three mined watersheds were generally higher than estimates from engineering methods (range: 65–79).
[69]	2013	West Virginia	MTM/VF	1	BA: 1011 km ²	annual /16 years	Statistically significant mean annual streamflow change not detected
[70]	2014	West Virginia	pre-SMCRA surface mine to MTM/VF	2	HW to BA: 6.4 & 1011 km ²	storm event to annual/ 41 years	Characterized streamflow changes over lifetime of MTM/VF practice (1969–2010). Significant changes in streamflow variability and baseflow at different spatial & temporal scales.

Notes: ^a References based on streamflow, runoff, hydrologic response, water balance, and watershed studies only; ^b publication year; ^c PS-plot scale; HW-headwater: up to 10¹km²; MS-meso-scale: 10¹ - 10³ km²; BA- basin-scale: >10³ km².

3.2. Traditional Surface Mining

Surface mining for coal in the Appalachians began in the mid-20th century and continues today. Much of the mining in the early part of this period constituted small contour and strip mine operations that disturbed areas less than 400 hectares. In contrast, MTM in the coalfields of southern West Virginia, southwestern Virginia, and eastern Kentucky, and Tennessee in the 1980s disturbed areas on the scale of thousands of hectares [64]. 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 [71], many areas were left untouched after extraction causing prolific water chemistry, 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 [44]. To achieve this goal, regulators emphasized heavily grading minespoils to achieve AOC and the use of quick growing herbaceous grasses and legumes to prevent soil erosion. This methodology resulted in heavily compacted soils often lacking organic matter and competitive groundcovers that prevented natural succession, growth, and survival of native trees species [45,72]. Natural succession from adjacent forest land has occurred, but the overall basal area and species diversity lagged behind natural forests, even after decades [73]. Thus, the predominant state of reclaimed surface mines across Appalachia is grasslands with heavily compacted soils with limited to no tree growth.

The post-SMCRA reclaimed surface mine is characterized by herbaceous grasses and groundcovers growing on heavily compacted mines soils [73]. 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 [74,75]. 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 and storage capacities in grasslands are less than forested canopies, though the rates of evaporation from each are similar [76]. Losses to E_t are generally less for grasslands compared to forests [77]; therefore, a larger proportion of precipitation is converted to runoff [9,57].

During the mining process (Figure 3), soils are removed, stockpiled, and then replaced during reclamation, though variances may be granted that excuse this requirement [78]. The reconstructed post-mining soil structure is drastically altered from pre-mining condition [78,79]. Minesoils [80] are heavily compacted soils with high bulk density and low porosity near the soil surface [72,81,82]. But due to the presence of large rock fragments [83], porosity may increase with depth [80,84]. Excessive surface compaction limits root penetration and growth [78,85] and lowers the available water holding capacity [82,86]. While the conditions described above are nearly ubiquitous for reclaimed surface mines in the region, variation in soil structure and properties result from different machinery and techniques used for reclamation [79,85] as well as the pre-mining overburden lithology [54].

Infiltration rates of minesoil can be an order of magnitude lower than undisturbed forest soils [54,57,65] that cause the initiation of infiltration excess overland flow which dominates storm runoff in mined areas [54,57]. 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 [87] that originate from the mine surface during the period immediately following reclamation [88]. However, Ritter and Gardner [57] observed variability in the infiltration rate of mine soils through time; some minesoils maintain low infiltration rates with minimal recovery, while other minesoils return to near pre-mining rates in as little as four years. Jorgensen and Gardner [54] 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 bulk density of shallow minesoil [54,89,90]. This dissonance is explained by Guebert and Gardner [62], who show the increase in infiltration rate is due to the development of an extensive macropore structure. As the macropore structure develops, subsurface flow paths will become more significant which causes a reduction in the peak discharge during storm events.

While impact of surface mining and reclamation on streamflow has been explored for nearly as long as the practice of surface mining in Appalachia, studies are relatively few in number. Early investigations on the impact of surface mining used a paired catchment approach (e.g., [49]) where change through time was measured in a pre-SMCRA mined catchment and a reference catchment. Collier *et al.* [49] investigated changes in the Beaver Creek Basin of Kentucky from 1955 to 1966 and found that a surface mined catchment had dampened peak stormflow and greater baseflow compared to the undisturbed catchment. They were unable to link the modulated runoff response to surface mining due to an inadequate pre-mining calibration period, but other early studies observed similar effects [47,48,52]. Curtis [50] observed a marked increase in the peak flow volume in pre-SMCRA surface mined catchments in West Virginia, but later noted that such an increase only occurred during active mining and may be ameliorated by reclamation [91], particularly the use of sediment retention ponds [51]. In Kentucky, Bryan and Hewlett [53] observed a 36% increase in 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 and summer peak flows, Bryan and Hewlett [53] 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 Tennessee from 1972 to 1985, Dickens *et al.* [9] elaborated on the mechanisms that control runoff modulation observed in prior studies. Significant baseflow increases (10×) in mined catchments was a result of infiltration, storage, and slow release of water stored in minespoil. Using monitoring wells, total spoil storage was estimated to be $4 \times 10^6 \text{ m}^3$ (44% of annual catchment yield) in Indian Branch, a catchment mined in the 1950s–1960s. However, the authors observed differences in water storage in spoil banks due to mining and reclamation practices. Minespoil in a catchment reclaimed under Tennessee's partial backfill reclamation standards [80], stored $1 \times 10^5 \text{ m}^3$ of water (11% of annual catchment yield). Contrary to earlier studies, Dickens *et al.* [9] observed an increase in the total catchment water output which was attributed to reduction in E_t from deforestation and water storage in minespoil.

More recent studies of surface mining following the implementation of SMCRA observed different results than the aforementioned studies. In a study of three headwater catchments undergoing surface mining in Ohio, Bonta, *et al.* [59] observed increases in peak stormflow from undisturbed to reclaimed conditions with no consistent pattern in baseflow response to mining. In western Maryland, Negley and Eshleman [65] 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 (2.5×), greater total storm runoff (3×), and higher hourly peak runoff rates (2×). 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 an infiltration excess overland flow driven storm response in the mined catchment and poorly sustained baseflows during the winter and spring due to insufficient subsurface flow contributions. Negley and Eshleman [65] also analyzed storm responses using unit hydrograph theory [92]. 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 landcover change. The authors stress the importance of selecting catchments with similar size, shape, and physical characteristics because confounding variables may obfuscate or exacerbate effects of disturbance.

Few studies attempt to assess the impacts of surface mining at the basin scale (>100 km²). McCormick *et al.* [66] explored runoff responses in the mined George's Creek basin (188 km²) and unmined Savage River basin (127 km²) in Maryland. Results showed that George's Creek had higher peak runoff and shorter lag times 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 can be complicated by legacy subsurface mining. Ferrari *et al.* [41] modeled runoff responses in the George's Creek basin under increasing mining scenarios. Results show that runoff magnitude increases linearly with increasing 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 disturbance.

3.3. The Valley Fill

Few studies explore the role that valley fills play on controlling water storage and release. Much of our understanding of contemporary valley fill behavior comes from studies of unconsolidated spoil piles associated with pre-SMCRA surface mining operations. While limited inference about valley fill hydrology can be made, the scale and construction methods of contemporary valley fills drastically differ from spoil piles from early surface mining operations. The size of modern valley fills varies, but the largest have volumes of over 150 million m³ and are >3 km in length [93]. In the period 1985–2001 the US EPA found that average valley fill area was increasing through time in the southern coalfields of West Virginia [93].

Multiple methods exist for constructing valley fills but the predominant technique used in the rugged topography of Appalachia is the durable rock fill technique where spoil is end-dumped from the mine surface in lifts (Figure 3). Valley fills 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 valley fill construction techniques require that an underdrain be built prior to fill material placement 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 valley fill and large rock and boulders fall to the valley floor. In a study by the Office of Surface Mining and the Kentucky Division of Mine Reclamation and Enforcement, over half of 44 valley fills studied were constructed with less than 80% durable material and that gravity formed underdrains are often poorly formed or even nonexistent [94].

The storage and slow release of water from surface minespoil described by Dickens *et al.* [9] has been shown to apply to valley fills, as multiple studies have observed longer flow durations and augmented baseflow downstream of valley fills [11,15]. However, this conceptualization of minespoil as a storage reservoir may not capture the complexity of water movement in valley fills. Caruccio *et al.* [58] and Caruccio and Geidel [10] described flow through minespoil as pseudokarst [87], a term more often associated with glacial or pyroclastic sediments that have multiple, rapid responding flow paths [88]. Hawkins and Aljoe [95] showed that pseudokarst was a dominant flow path in minespoil during transient, unsteady conditions but during steady state conditions, flow was dominated by matrix flow.

The most complete picture of valley fill hydrology comes from a series of investigations of water movement and storage in a large minespoil area at the Star Fire Mine in eastern Kentucky [12,61]. Using groundwater monitoring wells, dye tracers, measured discharge from valley fill outflows, and structural and topography maps, the authors present a conceptual model of minespoil hydrology with distinct but interconnected saturated zones. Water stored on the former mining bench is slow moving but eventually drains towards two surrounding valley fills where water movement is rapid [12]. Recharge to the valley fills occur from streams, adjacent bedrock and coal aquifers, and surface water that infiltrates into the minespoil from the bedrock-spoil interface [12]. While hydraulic conductivity within the minespoil varied, there was no discernible difference between the spoil interior and the valley fills. Therefore, the discrepancy between water movement in the spoil interior and valley fills was a function of topographic gradients and continued recharge to the valley fills 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 start of mining.

3.4. Mountaintop Mining and Valley Fill—A Two Part System

Assessing the hydrologic impacts of MTM/VF 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, valley fills appear to act as storage reservoirs that dampen storm responses and sustain baseflow but the physical processes controlling runoff generation in these systems is not clear.

The U.S. Geological Survey's (USGS) study of extensively mined (0.5 km²; 44% MTM/VF), partially mined (5.7 km²; 40% MTM/VF), and forested (1.4 km²; no MTM/VF) subcatchments of Ballard Fork in southern West Virginia offers the most complete picture of hydrologic impacts of MTM. Messinger and Paybins [14] investigated differences in water balance components, namely precipitation and daily and monthly mean flow, for three watersheds from 1999 to 2001. Total unit flow in the extensively mined catchment was nearly twice that of the partially mined and forested

catchments. The greatest flow differences between the catchments occurred during low flow when the forested catchment went dry compared to sustained year round streamflow in the extensively mined catchment. This corroborates the findings of Wiley *et al.* [15] who show that 90% flow duration was $6\times-7\times$ greater downstream of valley fills. High flows were similar between the extensively mined and forested catchments. Messinger and Paybins [14] attribute the increased runoff responses to a reduction in E_t in the heavily mined catchment due to the removal of soil and vegetation from mining operations.

Messinger [11] examined storm responses in this same catchments and study period and found varying outlet responses 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 catchments. For storm events with sufficient intensity ($>6\text{ mm hr}^{-1}$), hydrographs from the extensively mined catchment showed a distinct double peak, which Messinger [11] attributed to infiltration excess overland flow causing the first peak and delayed discharges from valley fills contributing to the second peak, 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 recession limb of the storm hydrograph. Messinger [11] noted 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 [15,16] 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 6–7 July 2001. Peak discharge was indirectly calculated for six catchments using the slope-area method [91]. Three of these catchments were undisturbed and three had varying degrees of MTM/VF development. Flood recurrence intervals were calculated for the storm event for each catchment. The three undisturbed catchments had recurrence intervals between 10 and 25 years. The disturbed catchments showed greater variability with return intervals ranging from <2 years to >100 years. Variability is likely due to differing extents of valley fill development within each watershed; the lowest return interval occurred in a watershed with one large, reclaimed valley fill while the largest occurred in a catchment with active MTM and an un-reclaimed valley fill. Understanding how the stage of mining and reclamation affects runoff response is important to mitigating the flood risk to communities downstream of MTM/VF reclamation. If flooding is indeed more likely to occur during the mining process, then additional steps are necessary to protect downstream communities during this period.

Due to the dearth of gaged headwater catchments in the MTM region, several studies used hydrologic models to explore the impacts of MTM. In response to extreme flooding in May and July of 2001, the Governor of West Virginia created the Flood Advisory Technical Taskforce (FATT) to investigate the possible impacts of logging and surface mining. Using Natural Resource Conservation Service curve number approach, the study found that surface mining (including MTM) and harvesting 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 [63]. McCormick and Eshleman [68] calculated curve numbers for surface mined and reclaimed catchments in western Maryland using rainfall-runoff data and found that their curve numbers were greater than if estimated from prevailing engineering methods. Therefore, modeled runoff in mined catchments in the FATT [63] study likely

underestimates the magnitude of discharge. This reinforces the need for empirical studies of catchment hydrology. Predicting runoff responses to larger precipitation events will require hydrologic models tested and applied in the coalfields region. Phillips [64] examined runoff and surface and subsurface flow detention using hydrologic models that considered differences in runoff producing conditions in mine and unmined catchments in eastern Kentucky. Results from this study show that runoff production was likely to increase in MTM-impacted catchments compared to unmined catchments but with considerable variability attributed to local geologic, topographic, and pedologic conditions, and to differences in the stage and method of valley fill construction and mine reclamation. Zégre *et al.* [70] modeled the hydrologic response times of four storms in a MTM/VF-impacted headwater catchment in West Virginia and observed steep response curves indicating a rapid translation of rainfall to runoff, large baseflow ratios, and little variability between events but the absence of an unmined reference catchment makes placing these results in context to other catchments difficult.

Few studies have addressed the hydrologic impact of MTM at larger scales. Long term studies of the Tug Fork watershed (4040 km²) in West Virginia, Kentucky, and Virginia from 1947 to 1978 [96] and sub-watersheds (~225 km²) of the Russell Fork River in Virginia from 1927 to 1980 [97] show general trends in increased flood magnitudes and increased baseflows but the extent of MTM in those basins during the respective study periods is unclear and likely limited. More recently, Zégre *et al.* [69] characterized MTM-driven land cover changes and annual streamflow from 1994 to 2010 in the 1011 km² Big Coal River watershed in southern West Virginia. Despite that land cover changes show a general conversion of forest to mineland, significant streamflow changes were not detected. Zégre *et al.* [70] expanded the study in the Big Coal River by quantifying MTM/VF-driven land cover changes over the lifetime of this practice (1973–2010) and evaluated for changes across the hydrologic regime at multiple temporal and spatial scales. Significant decreases in maximum streamflow and variability and significant increases in baseflow ratio were detected since the start of MTM/VF in the 1970's. These changes were attributed to the influence of valley fills and to unaccounted-for water from deep abandoned underground coal mines [70]. Increased baseflow from surface and underground mine drainage raises significant water quality concerns for these receiving rivers; the degree to which mineral and metal laden discharge from mining-impacted catchments aggregate downstream will have major impacts on water quality (see Lindberg *et al.* [7]). Additionally, altered flow regimes will impact the mid- to long-term geomorphic evolution of these rivers. This is particularly relevant in the Central Appalachian coalfields where communities are often located directly adjacent to streams and rivers.

A review of existing literature highlights significant variability in the hydrologic responses of MTM/VF-impacted watersheds at the headwater and downstream scales. Despite mixed results, it is evident that individually and collectively, mountaintop mines and valley fills exert important controls on catchment hydrology, namely in runoff altering flow paths. Figure 4 shows a conceptual model for runoff flowpaths in this two-part system. Our hypothesis, based in part on the work by Hawkins and Aljoe [95] for surface mine minespoils, is that flow within the valley fill is controlled by matrix flow during non-storm conditions and by large preferential flowpaths during storm conditions. Elevated baseflow downstream of valley fills is the result of water flowing through torturous flowpaths through small pores (matrix flow), while the larger, air-filled pores remain hydrologically inactive. This results in transient storage and release of water overtime, sustaining baseflows compared to ephemeral nature of natural headwater streams. Prolonged forced contact time with overburden geology placed in the fill

results in elevated solutes downstream of valley fills. During storm conditions, small pores and voids created by large rock fragments are saturated, activating rapid runoff flowpaths, resulting in increased peakflows downstream of valley fills.

4. Knowledge Gaps and Future Research 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 also reveals considerable variability in hydrologic responses to storm events, extent 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-impacted catchments? How do these processes change with increasing disturbance from MTM? How do these processes change with differing reclamation techniques? How do contemporary valley fills store, route, and release water? What variability exists within forested catchments in the Central Appalachian coalfields? What are the effects of legacy disturbances such as timber harvesting and underground coal mining?*

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 expands on the knowledge gaps identified by Zegre *et al.* [70] and our review of the literature.

4.1. Streamflow Generation Processes in MTM-Impacted Catchments

At present, all investigations into the hydrologic impacts of MTM have been measured at the catchment outlet or have relied on hydrologic models in gaged and ungaged catchments. The limitations of conducting controlled scientific investigations in drastically disturbed areas (see Bonta [98]) have made these approaches appropriate and valuable information about the variability associated with MTM has been garnered from this work. But the inherent constraints of black box studies limit our understanding of streamflow generation processes. Significant data is required to quantify variability and inform models to extend information across the MTM region. Differences in 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 not yet known.

In order to understand the full range of hydrologic consequences 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, reclamation techniques, and alteration to catchment structure and organization 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 (e.g., [31,99]), but have seen little use in catchments impacted by surface mining (e.g., [100]). This will ultimately require cooperation between industrial landowners, researchers, and agencies as quantifying catchment wide streamflow generation processes will require access to all

reaches of the catchment, not just the outlet. This has been an obstacle to past research in these systems [70] and must be bridged in order to understand and ameliorate the environmental problems associated with this mining practice.

4.2. Hydrology of Non-MTM Catchments in the Central Appalachian Coalfields

As Wiley and Brogan [16] demonstrated, different hydrologic responses to large storm events are seen in adjacent, forested, similarly sized catchments. Wiley and Brogan [16] attribute the large variability to heterogeneous and patchy precipitation patterns within the study region, though the complex and heavily fractured geology of the Central Appalachian coalfields likely exerts some control on the observed runoff variability in adjacent catchments.

The hydrologic impact of MTM operations in the context of the heterogenous landscape of the region remains uncertain. 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 in the Central Appalachian coalfields. While the MTM region lies between long-term forested experimental catchments at the Fernow Experimental Forest (northern WV) and the Coweeta Hydrologic Laboratory (NC), the information gained from those sites is limited due to differing climatology, geology and historical and current land use in the Central Appalachian coalfields. Work in the greater Central Appalachian region has shown that stormflow is dominated by subsurface flow [101]. In the Central Appalachian coalfields, groundwater movement is predominantly controlled by a complex network of stress relief fractures in hillslopes and valley bottoms [102,103]. However, a long history of underground coal mining throughout much of this region has drastically altered the structure of the subsurface system [104]. Subsidence associated with abandoned underground mines creates additional fractures which can increase hydrologic connectivity between the surface and subsurface as well as between water-bearing subsurface geologic units [89,105]. Consequently, underground mines and associated subsidence fractures can become major conduits for subsurface water movement. Headwater drainage networks downdip (at the lower end of the sloped coal seam) and below the mined coal beds can receive significant amounts of water while streams underlain by underground mines lose water, especially during baseflow conditions [55]. 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 [56]. While Borchers *et al.* [56] examined the combined effects of deep mining and surface strip mining, no study we are aware of examines the interactions between contemporary MTM/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.

4.3. Valley Fill Hydrology

How do valley fills store and release water? Wunsch *et al.* [12] began to address this question of their study of a large spoil pile from a MTM operation in eastern Kentucky. Their research provides valuable insight into the complexity of valley fill hydrology but uncertainty remains regarding the processes involved in the movement and storage of water in valley fills. Little is known about the geographic sources of water that supply valley fills; the spatial distribution and residence time of water within valley fills; or how water is released during lowflow and storm conditions (Figure 4). Heterogeneity in the surrounding geology coupled with legacy land disturbance (*i.e.*, underground mining) and the multitude of different valley fill construction techniques creates additional complexity. Insights into these uncertainties extend beyond physical hydrology as valley fills 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 aquatic ecosystems downstream of MTM/VF (e.g., [7,104,105]). While the work of Hawkins and Aljoe [95] and Wunsch *et al.* [12] are starting point for understanding, future research should address valley fills that differ in size, construction and reclamation techniques, age, and geologic and topographic settings to represent the range of conditions present across the region. In addition, isotopic and geochemical tracers should also be used to discern the origin and flowpaths of water in valley fills (e.g., [100]).

4.4. MTM/VF Reclamation Techniques

The Forestry Reclamation Approach has gained traction as a potentially viable reclamation technique amongst industry and regulators [46]. In the FRA, minespoil and in some cases topsoil or amended topsoil, is dumped and loosely graded to create a minimally compacted growing medium for high value native hardwood tree seedlings [106]. This technique has shown to be an effective method for establishing forests in on mine lands [44], but its effect on catchment hydrology is not fully understood. Taylor *et al.* [67] describe plot-scale runoff of loose dumped soil to have low runoff ratios, small peak discharges, and long flow durations. Due to the high infiltration capacities of loose dumped minespoil [107], the broad application of the FRA to large surface mines would likely result in the establishment 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 forested hillslopes of the coalfields region that are generally thought to have thin soils with little storage capacity [108]. 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 reclamation practice.

4.5. Thresholds

Disturbance thresholds to detect measurable changes in streamflow have not been established for MTM or traditional surface mining. Forest harvesting studies suggest that 15%–20% of a catchment needs to be disturbed to detect changes in streamflow [34,109]. Bernhardt *et al.* [8] showed that as

little as 2% of contributing area impacted by mining results in significant losses of intolerant macroinvertebrate taxa and at >5%, biological impairment occurs. Messinger [11] observed large differences in runoff responses in a heavily MTM-impacted catchment (44% MTM/VF) and moderately MTM-impacted catchment (12% MTM/VF) across storm events indicating that extent of mining and catchment size are likely important factors influencing outlet responses. However, the question of How much mining does it take to alter hydrology? remains unanswered.

Runoff thresholds for precipitation depth, duration, and intensity, and valley fill/catchment moisture conditions would also aid in understanding the hydrologic response of MTM-impacted catchments (Figure 4). Messinger [11] observed a precipitation intensity threshold of 25 mm hr^{-1} that dictated whether unit peak flow was greater in a MTM-impacted catchment ($>25 \text{ mm hr}^{-1}$) or the forested catchment ($<25 \text{ mm hr}^{-1}$). Understanding the conditions and the type of storms likely to produce flash flooding in MTM-impacted (as well as forested) catchments is critical to limiting the destructive events that have ravaged communities in the Central Appalachian coalfields.

4.6. Multiple Spatial and Temporal Scales

Investigations into the hydrologic impacts of MTM predominantly occur at the headwater scale. While this scale is an appropriate experimental unit and represents the scale of disturbance, it is also necessary to understand the downstream consequences of this practice. Zégre *et al.* [70] provides one of the first multiple spatial and temporal scale studies showing scale-invariant dampening of hydrologic variability, decreases in maximum flows, and increases in baseflow ratio thought to be related to valley fill control and unaccounted-for deep mine drainage. However more research is necessary to understand if this trend is consistent across watersheds in the coalfields region. Flow regime changes at headwater and downstream scales has important flood, geomorphology, and water quality implications to communities dependent on ecosystems derived from mountainous watersheds.

To the extent of our knowledge and extensive literature search, longitudinal studies of catchments undergoing MTM-related disturbance do not exist. Such studies are necessary to understand how hydrology changes in response to ongoing mining and reclamation. In addition, long-term (e.g., decades) studies are needed to assess how reclaimed landscapes, including morphology and vegetation, and hydrologic processes evolve over time. For example, Ritter and Gardner [57] observed differences of the infiltration rate recovery of surface mines in Central Pennsylvania during a decade long study. This elicits questions about the hydrologic evolution of valley fills and reclaimed MTM surfaces, and at a broader scale, the stability of the new topographic structure imposed on MTM/VF-impacted catchments. Surface mines reclaimed under the protocols of the FRA also warrant long-term study as these dynamic landscapes will rapidly change from their initial condition. Long-term studies will also capture infrequent large storm events which are critical to elucidating the role of MTM/VF in flood generation in the Central Appalachian coalfields.

4.7. Altered Topography

MTM/VF displaces as much as 300 m of overburden from Appalachian ridge tops to access deeper coal seams and therefore represents a substantial change to the size, shape, organization, slope, and drainage network of the catchments where it occurs. To date, quantifications of the change to

catchment topography from MTM/VF operations remains scarce and, to the authors' knowledge, no study connects this structural reorganization to hydrologic change.

The importance of catchment topography and drainage structure in controlling hydrologic response has been a focus in contemporary literature. McGlynn *et al.* [110] investigated the role of catchment size in hillslope and riparian runoff dynamics. McGuire *et al.* [111] explored the dominant physical controls on the residence time of catchment water. Among their findings were the importance of the headwater riparian zone and flow path gradient in generating runoff in headwater catchments. Given MTM/VF's potential to drastically reduce catchment slope (especially in instances where variances to AOC are granted) and bury headwater riparian areas, framing hydrologic change in the Central Appalachian coalfields as a result of "landcover disturbance" may be insufficient. The residence time and rate of runoff in MTM/VF-impacted catchments will, at least in part, be a function of the new topographic structure created by the coal mining and reclamation process.

This issue is confounded by the addition of drainage structures such as rock-lined channels from the mine surface to the valley bottom or sediment retention ponds at the base of valley fills. Therefore, discerning the hydrologic effect of topographic reorganization from other impacts of MTM will be difficult. This process must begin with a quantification of the extent and magnitude of topographic and drainage network change in MTM/VF-impacted areas. The proliferation of high resolution LiDAR-based topographic models of Central Appalachian coalfields will be critical in this step.

5. Concluding Remarks

MTM represents a dramatic and likely permanent landscape-scale disturbance with important local and regional impacts. Despite its scale, extent, and potential of continued use, key knowledge gaps regarding hydrologic consequences of this practice exist. Water storage and movement in these disturbed landscapes exert important controls on the well documented downstream water quality issues associated with MTM/VF. 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/VF play a critical role in elucidating the consequences of this mining practice.

Most investigations into the hydrologic impacts of surface mining involve traditional contour and strip mining techniques that occur at smaller scales and do not consider the role that valley fills have on hydrology, presenting additional uncertainties. Studies to date demonstrate that since the enactment of SMCRA, heavily compacted mine surfaces have decreased infiltration capacity and tree growth and consequently produce flashier, higher magnitude runoff responses to storm events. While minespoil studies provide insight into the potential hydrologic controls of valley fills, no studies specifically address valley fill hydrology. Previous studies dealing with hydrologic impacts of MTM operations have been successful in establishing a range of possible responses of this practice, but these studies underscore catchment heterogeneity and response variability limiting understanding of the downstream consequences and warranting further investigation through controlled experiments.

MTM's expected proliferation in the coming decades coupled with the adjacency of communities to streams and rivers in the Central Appalachian coalfields makes understanding the hydrologic consequences of this practice necessary. The observed hydrologic effects of MTM/VF present

landowners, policy makers, engineers, and water resource managers with many difficult questions about how to manage the altered landscapes created by this mining progress. Such progress will ultimately depend on expanding the number of hydrologic studies in the Central Appalachian coalfields region and concentrating research efforts on the physical processes that control hydrologic response in these disturbed systems.

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Conflicts of Interest

The authors declare no conflict of interest.

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