Comparison of Storm Response of Streams in Small, Unmined and Valley-Filled Watersheds, 1999–2001, Ballard Fork, West Virginia

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CONVERSION FACTORS

Multiply	By	To obtain
cubic feet per second (ft^3/s)	0.02832	cubic meter per second
cubic feet per second per square mile ($ft^3/s/mi^2$)	0.01093	cubic meter per second per square kilometer
foot (ft)	0.3048	meter
inch	25.4	millimeter
mile (mi)	1.609	kilometer
ounces per cubic inch	1.73	grams per cubic centimeter (g/cm^3)
square mile (mi^2)	2.590	square kilometer

VERTICAL DATUM

In this report, vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) and horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Historical data collected and stored as National Geodetic Vertical Datum of 1929 have been converted to North American Vertical Datum of 1988 (NAVD 88) for this publication.

Comparison of Storm Response of Streams in Small, Unmined and Valley-Filled Watersheds, 1999–2001, Ballard Fork, West Virginia

By Terence Messinger

ABSTRACT

During storms when rainfall intensity exceeded about 1 inch per hour, peak unit runoff from the Unnamed Tributary (surface-mined and filled) Watershed exceeded peak unit runoff from the Spring Branch (unmined) Watershed in the Ballard Fork Watershed in southern West Virginia. During most storms, those with intensity less than about 1 inch per hour, peak unit (area-normalized) flows were greater from the Spring Branch Watershed than the Unnamed Tributary Watershed. One storm that produced less than an inch of rain before flow from the previous storm had receded caused peak unit flow from the Unnamed Tributary Watershed to exceed peak unit flow from the Spring Branch Watershed. Peak unit flow was usually similar in Spring Branch and Ballard Fork. Peak unit flows are expected to decrease with increasing watershed size in homogeneous watersheds; drainage area and proportion of the three watersheds covered by valley fills are 0.19 square mile (mi^2) and 44 percent for the Unnamed Tributary Watershed, 0.53 mi^2 and 0 percent for the Spring Branch Watershed, and 2.12 mi^2 and 12 percent for the Ballard Fork Watershed.

Following all storms with sufficient rainfall intensity, about 0.25 inches per hour, the storm hydrograph from the Unnamed Tributary Watershed showed a double peak, as a sharp initial rise was followed by a decrease in flow and then a delayed secondary peak of water that had apparently flowed through the valley fill. Hortonian (excess overland) flow may be important in the Unnamed Tributary Watershed during intense storms, and may cause the initial peak on the rising arm of storm hydrographs; the water composing the initial peaks may be conveyed by drainage structures on the mine. Ballard Fork and Spring Branch had hydrographs with single peaks, typical of elsewhere in West Virginia.

During all storms with 1-hour rainfall greater than 0.75 inches or 24-hour rainfall greater than 1.75 inches during which all stream gages recorded a complete record, the Unnamed Tributary yielded the most total unit flow. In three selected major storms, total unit flow from the Unnamed Tributary during recessions exceeded storm flow, and its total unit flow was greatest among the streams during all three recessions.

Runoff patterns from the mined watershed are influenced by the compaction of soils on the mine, the apparent low maximum rate of infiltration into the valley fill compared to that in the unmined, forested watershed, storage of water in the valley fill, and the absence of interception from trees and leaf litter. No storms during this study produced 1-hour or 24-hour rainfall in excess of the 5-year return period, and streamflow during this study never exceeded a magnitude equivalent to the 1.5-year return period; relative peak unit flow among the three streams in this study could be different in larger storms. Rainfall-runoff relations on altered landscapes are site-specific, and aspects of mining and reclamation practice that affect storm response may vary among mines.

INTRODUCTION

Large-scale surface mining that uses valley-fill spoil disposal, including mountaintop removal, is an important method of extracting coal in the low-sulfur Central Appalachian coal field of southern West Virginia, western Virginia, and eastern Kentucky (fig. 1). During 1996-2000, more than 1.36 billion tons of coal, or 25 percent of all coal mined in the United States, were mined from this field (Energy Information Administration, 2002). In 2000, more than 258 million tons of coal were surface-mined in this coal field; this production accounts for 42 percent of the coal mined in the coal field and 10 percent of the coal mined in the United States. During the 1990s, production of the mostly low-sulfur coal from West Virginia has increased, a trend that is widely attributed to provisions in the Clean Air Act amendments of 1991 that were intended to reduce acid precipitation (Messinger and Hughes, 2000). Surface mining has increased steadily during the same period, because increases in the size and efficiency of earth-moving equipment made it profitable to mine multiple thin coal seams covered by hundreds of feet of rock. The rock is removed from the tops of mountains and dumped into adjacent headwater valleys, or valley fills.

Mountaintop-removal and other types of large-scale surface mining have become increasingly controversial in the central Appalachians since the mid-1990s (Loeb, 1997; BRAGG vs. ROBERTSON, Civil Action No. 2:98-636 [S.D. W.Va.]). As a condition of a partial settlement of Bragg vs. Robertson, Federal agencies with regulatory jurisdiction over coal mining were required to prepare a comprehensive Environmental Impact Statement (EIS) on the effects of valley fills. As part of that effort, the U.S. Geological Survey (USGS) began a study in cooperation with the Office of Surface Mining, Reclamation, and Enforcement in November 1999 of streamflow at three continuous-flow gaging stations in the Ballard Fork Watershed within the upper Mud River basin in southern West Virginia (fig. 2).

Following intense flooding in parts of the southern West Virginia coal region during July 2001 and May 2002, public concerns were raised that large-scale surface coal mining, particularly by mountaintop-removal methods, worsened flooding. Investigating and addressing these concerns is critical in light of the present economic importance of mountaintop-removal and other types of large-scale surface mining and the likelihood that the use of these mining practices will continue or increase if their environmental effects, including any changes in rainfall-runoff characteristics to mined areas, are judged to be acceptable.

Purpose and Scope

This report describes storm hydrographs measured at three small watersheds in the Ballard Fork Watershed in the upper Mud River Basin, in Boone County, WV, between November 1999 and September 2001. The discussion centers on the hydrologic effects of large-scale surface mining, along with possible mechanisms of water flow through the mine and valley fill compared to an unmined watershed.

Description of Study Area

The study area is in the Kanawha Section of the Appalachian Plateaus Physiographic Province (Fenneman, 1938). Surface rocks are sedimentary and of Pennsylvanian age (Cardwell and others, 1968). Madison, WV, the closest long-term climatography station, receives an average of 47.7 inches of precipitation annually (1971–2000) (National Oceanic and Atmospheric Administration, 2002). The study area receives about 17.5 inches of snow per year. May and July are the wettest months, with an average precipitation of 5.2 inches. Madison received 46.2 inches of precipitation in the first year of the study (November 1999–October 2000), and 40.2 inches in the second year (November 2000–October 2001).

About 0.89 mi^2 (40 percent) of the Ballard Fork Watershed was permitted for mining, and about 0.26 mi^2 (12 percent) was covered in valley fills. Less than 40 percent of the Ballard Fork Watershed was actually mined; because regulations prohibit damage resulting from mining activities outside the permitted area, it is standard industry practice for permits to include a buffer area. All valley fills in the Ballard Fork Watershed were built by dumping overburden from trucks over the edge of the bench (or fill) into the valley. The sediment ponds for the mines were still in place during this study.

All mining in the Ballard Fork Watershed had been done under one permit, which was issued in 1989. The mine permit specified a post-mining land use of

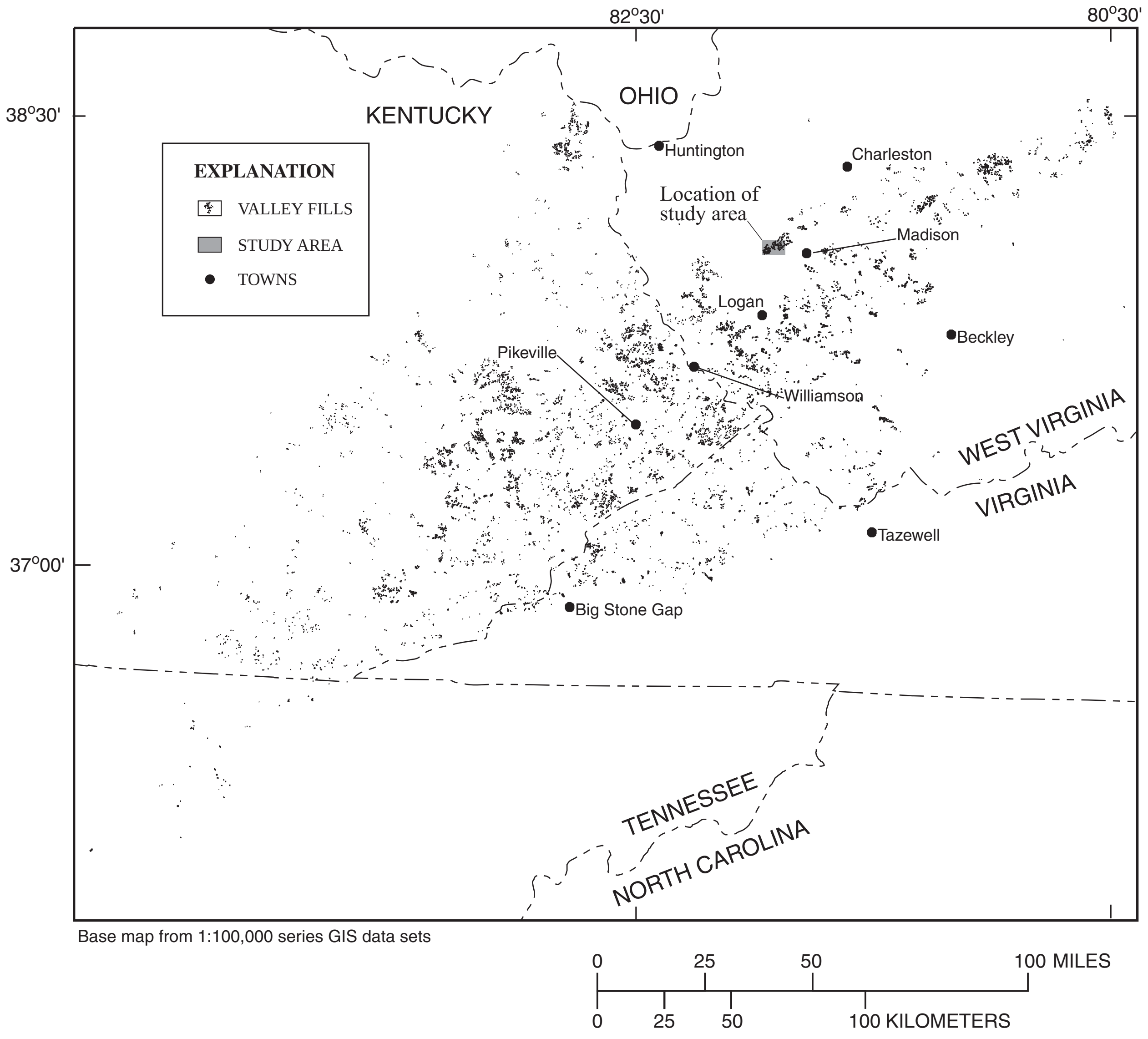
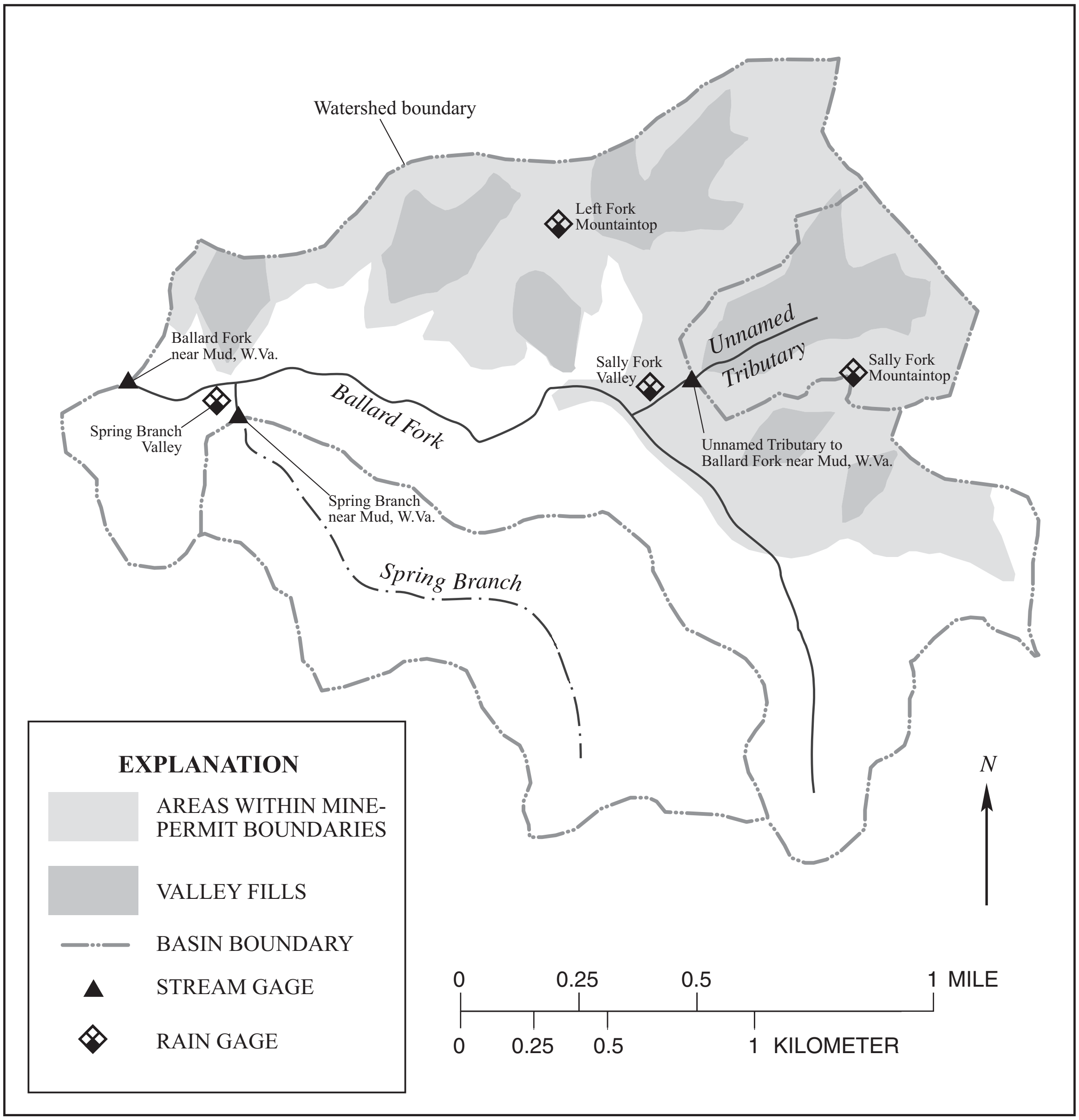


Figure 1. Valley fills in the Central Appalachian coal field, and location of the Ballard Fork Watershed, West Virginia.

rangeland. Coal was not mined in the watershed during this study. The mine was still under reclamation in October 1999, although mine-inspection forms showed that inspectors had estimated that no more than 10 acres were unreclaimed by November 1997 (West Virginia Department of Environmental Protection, 2002a). The mine received a partial ("Phase 1") bond release in August 2000, when backfilling and grading had been satisfactorily completed. Revegetation was ongoing but incomplete during the rest of the study period. Unlike most nearby mined areas, the study area has no recorded deep mines, which are often a confounding factor in studies of surface mining.

Coal seams at the base of the Allegheny Formation were mined in the Ballard Fork Watershed, so the overburden was rocks of that formation and the Conemaugh Group (Cardwell and others, 1968). The Allegheny Formation and Conemaugh Group are both Pennsylvanian-aged. The Allegheny Formation is mixed sandstone, shale, and coal, and the Conemaugh Group is predominantly shale with some interbedded sandstone. The sandstones of both these units are typically soft and crumbly, and weather rapidly when exposed. Mine spoil from these rocks is likely to produce abundant fine particles, which would in turn fill some of the void space in the fill and lead to



Modified from U.S. Environmental Protection Agency and
West Virginia Department of Environmental Protection digital data

Figure 2. Stream-gaging stations, rain gages, valley fills, and areas permitted for mining in the Ballard Fork Watershed, West Virginia.

channelized flows of the type observed in other valley fills. Rocks beneath the base of the Allegheny Formation, which make up the bottoms of mountains and underlie the valley floor, are of the Kanawha Formation, predominantly hard, massive sandstone with some interbedded shale.

Soils in the unmined part of the basin are well drained, on steep slopes, and formed in material weathered from siltstone, shale, and sandstone (Wolf, 1994). Ridgetop soils are of the Gilpin–Wharton association. In the Gilpin unit, the average depth to bedrock is 36 inches, and the permeability is 0.6–2.0 inches per hour. In the Wharton unit, the average depth to bedrock is 44 inches, and the permeability is 0.6–2.0 inches per hour in the top 2 inches, and 0.06–0.6 inches per hour in subsoil. Hillslope soils are of the Berks-Shelocta association. In the Berks unit, the average depth to bedrock is 23 inches and the average permeability is 0.6-6.0 inches per hour. In the Shelocta unit, the average depth to bedrock is 65 inches and the average permeability is 0.6–2.0 inches per hour. Valley soils are of the Sensabaugh-Lobdell association. In both valley soil units, the average depth to bedrock is 65 inches. In the Sensabaugh unit, the average permeability is 0.6–6.0 inches per hour. In the Lobdell unit, the average permeability is 0.6–2.0 inches per hour in the top 27 inches, and 0.6–6.0 inches in the subsoil.

The Ballard Fork Watershed had not been mined when the soil survey was completed and so soils of its mined areas were not classified in the published report. Soils on nearby surface-mined areas were classified as belonging to the Kaymine series. These soils were described as strongly sloping to very steep (dominant slope 35 to 80 percent), well drained, very stoney (35 to 80 percent rock fragments by volume) soils that formed from material weathered from siltstone, shale, and sandstone. These mine soil units are very deep (65 or more inches to bedrock or mine spoil), well drained, and permeability is moderate or moderately rapid (0.6–6.0 inches per hour). In some cases, the A horizon of these soils is partly material that was stockpiled during mining and spread over the surface during reclamation.

In the mined parts of the Ballard Fork Watershed, vegetation included broomsedge (actually a grass) and other grasses, crown vetch, and other herbaceous vegetation typical of dry and disturbed land, as well as scattered woody vegetation such as autumn olive, tree of heaven, and white pine. Forest in Spring Branch and the rest of Ballard Fork was second- or third-growth. Common tree species of the canopy in the unmined parts of the watershed included white and red oak, several hickory species, sycamore, and tulip poplar. The forest understory included dogwoods, redbuds, and young oaks, hickories, and beech. No large forest fires took place during the study period, and leaf litter was present on the forest floor.

The Ballard Fork Watershed had no human residents during the study period, and the unmined parts were predominantly forest; however, the unmined areas in the watershed were not pristine. Several roads passed through this area, and many or most of these had rills and gullies that would be important in rainfall-runoff relations. Natural gas wells and pipelines were also present in the watershed, and some of the pipeline rights-of-way along steep slopes have been used as all-terrain vehicle trails, which has caused extensive gullying and erosion, as on steep all-terrain vehicle trails in the mined part of the watershed.

The Unnamed Tributary flows generally southwestward (fig. 2); its watershed has a maximum length of 3,250 ft, and a maximum width of 2,500 ft. Spring Branch flows generally northwestward, and the maximum length of its watershed is 7,500 ft, and maximum width is 3,000 ft. Ballard Fork flows generally westward. The maximum length of its watershed is 10,500 ft, and maximum width is 9,500 ft. Storms in the region typically move from west to east, so that the downstream parts of the watersheds receive precipitation before the upland areas, and streamflows begin to rise more quickly and recede more slowly than in watersheds in which storms move from the headwaters downstream. Basin relief at the time of the study was 680 ft in the Spring Branch Watershed and 700 ft in the Ballard Fork Watershed, both measured from a topographic map. Post-mining basin relief in the Unnamed Tributary Watershed is about 450 ft, from altimeter readings taken at some of the highest points in the watershed.

WATER STORAGE IN AND MOVEMENT THROUGH A WATERSHED

Differences in hydrograph shape and runoff characteristics among the three streams in the Ballard Fork Watershed can be better understood in light of other information on how water flows through a watershed and where and how it is stored. A great deal is known about how water is stored, and moves through, vegetation and soils. Less is known about movement of water through mine spoil.

Vegetation

Water is stored on vegetation as intercepted precipitation. Some rainfall is needed to wet leaves before any rain reaches the forest floor. In a forest with a canopy and understory, such as that in the Spring Branch Watershed, leaves in both layers need to become wetted before water begins to drip to the forest floor. Leaves initially intercept rain, although this is highly dependent on wind, which shakes water off the leaves and increases throughfall during a storm. About 10 percent of rain from a given storm during the growing season is thought to be intercepted and evaporated in eastern hardwood forests; this estimate is based on a regression equation of Throughfall = 0.901(Precipitation)-0.031 (Helvey and Patric, 1965; 1988). Water intercepted by the forest canopy evaporates while rain continues to fall so long as relative humidity in the canopy is less than 100 percent. Intercepted precipitation that evaporates is not available for wetting soil and thus is not available for either recharge to ground water or runoff. Timing of the storm affects the amount of evaporation; more intercepted water evaporates during a daytime storm than a nighttime storm, and more water evaporates in summer storms than in winter storms.

Leaf litter, at the interface between vegetation and soil, can intercept a substantial amount of rain, depending on antecedent moisture conditions. Helvey (1964) reports that leaf litter becomes fully saturated with water only after about 1 inch of throughfall, but estimates that leaf litter in a study site at Coweeta, in a southern Appalachian hardwood forest, intercepted between 2–4 inches of rain annually, or about 2–5 percent of annual precipitation. Black (1996) states that with a thick litter layer under Eastern hardwoods, as much as 0.5 inches of rain may be needed before any water reaches the soil.

Interception of rain by either the canopy or litter of hardwood forests differs seasonally. Interception by the canopy is much greater during the growing season, although some precipitation is intercepted by bare branches. Precipitation intercepted during the dormant season is more likely to flow down tree trunks and recharge ground water than is precipitation intercepted by leaves (Black, 1996). Litter interception in Eastern hardwood forests is greatest in autumn, in the first months following leaf fall, while leaves are still intact (Helvey, 1964). Evaporation of water from litter is greatest during the dormant season, when more solar radiation reaches the forest floor. Water evaporates from litter most rapidly for the first three days of drying; early drying is most rapid during the dormant season, and after about 12 rainless days, moisture loss from litter is essentially complete (Helvey, 1964).

Soil

Water is stored on soils in surface depressions, and in soils in detention and retention storage (Black, 1996). Depression storage is water stored, usually temporarily, in puddles, and this water usually either evaporates or gradually seeps into the soil. Detention storage is water temporarily detained in the soil in non-capillary pores, or those soil pores that are large enough so that gravity exerts a greater force on water in them than do capillary forces. Water in detention storage typically flows out of the soil within 24 hours. Retention storage is water retained in soil by capillary forces—a combination of cohesion, or attraction among water molecules, and adhesion, attraction of water molecules to soil particles. The amount of water that can be held in retention storage is a function of soil-particle size; smaller particles provide a greater surface area in a given volume of soil than do larger particles, and thus provide more soil area for water to adhere to. Clays retain the most water, and sands the least water, among soils. Water in retention storage is decreased over time by evaporation and transpiration. Water moves easily between depression and detention storage, and from both depression and detention storage into retention storage, but not from retention storage into detention storage.

Water that is introduced to a partially dried soil will move to the area of greatest tension, the driest area, with the smallest pores and the greatest number of small pores (Black, 1996). Following rain or snowmelt, water moves first into retention storage and continues to do so until that type of storage is full before any water is available to fill detention storage. When detention storage is full, the soil is saturated, and if no further infiltration takes place, water runs off the surface.

The maximum rate at which water can move into soils is called the infiltration capacity. Infiltration capacity is related to soil porosity, texture, organic content, land cover, and antecedent moisture conditions. Precipitation's path to a stream, or water table, is related to infiltration capacity and the soil properties that determine it. The mechanisms by which precipitation moves into a stream are complex and still not fully understood. The first mechanism proposed for the origin of runoff (Horton, 1933), excess or Hortonian overland flow, was originally proposed as a general mechanism but has long been recognized to apply only as a special case. In Hortonian overland flow, the precipitation rate exceeds the soil's infiltration capacity, depression storage is filled, and then water moves downslope under laminar flow as a thin sheet. In the Eastern United States, Hortonian flow generally is limited to urban or other highly disturbed areas (Hibbert and Troendle, 1988).

The observations that streamflow increases under conditions when not only depression storage but detention storage remain unsaturated, and that sheet flow is never observed in deep forest soils, led to the concept of the Variable Source Area of streamflow origin (Hewlett and Hibbert, 1967). According to the Variable Source Area concept, water seeps downhill through soils until it reaches a confining layer. Streams form in saturated areas above the soil surface. The area of saturated soil that contributes to streamflow is variable through time; this area increases when precipitation is received and decreases when water runs off or is evaporated and transpired from soils. Water is delivered to the stream both through translatory flow, the lateral throughflow of "old" water that is displaced from near-bank areas into the channel by precipitation inputs (Hewlett and Hibbert, 1967), and macropore flow, the rapid movement of "new" water through large conduits in the soil (Whipkey, 1965). These mechanisms can also be combined, and "old" water may be rapidly displaced into and delivered to the stream through soil cracks and pipes (McDonnell, 1990). If an effective connection exists, source areas for stormflow may include saturated upslope areas in addition to near-bank areas (Buttle, 1998).

Mine Spoil

Ground-water flow in the backfill of a surface mine in central West Virginia was highly channelized and was not observed until a randomly located channel was intercepted (Hawkins, 1998). Lithology of the native rock that becomes mine spoil can influence the hydraulic conductivity in reclaimed mines. Hydraulic conductivity and void space in mine spoil are directly related to the proportion of sandstone and inversely related to the proportion of shale in the spoil. Sandstone-rich spoil zones tend to have larger rock fragments than do shale-rich zones, which causes larger voids and greater hydraulic conductivity. Shales tend to break into smaller fragments during mining and to weather and break down to silt- and clay-sized particles more readily; both processes fill void spaces and decrease hydraulic conductivity. Clay and silt accumulate toward the base of the spoil, and are commonly observed in monitoring wells that are pumped or bailed infrequently. This observation is consistent either with breakdown of mine spoil or with settling of fine particles to the bottom of the fill.

At a large surface mine with valley fills in eastern Kentucky, two distinct saturated zones were present, one in the spoil on the bedrock layer exposed during mining, and one in the spoil in valley fills (Wunsch and others, 1996). Water flowed much faster through the saturated zones in valley fills than through the spoil interior. Water infiltrated the spoil through disappearing streams, ground-water infiltration, and along the contact between the spoil and the bedrock highwall; direct infiltration of rainfall through the surface of the spoil was minor and was only appreciable through macropores, usually near boulders protruding through the graded fill surface. The same processes controlled infiltration to the valley fill, except that an experimental infiltration basin had also been built to direct rainfall into a valley fill; this basin was thought to contribute a negligible amount of water compared to the water infiltrating through the spoil-highwall contact. Water movement inside the spoil and valley fills was controlled by the buried topography and the interaction of recharge and discharge zones with low-permeability zones. Spoil settled around the casing of the observation wells during the study at a rate as high as 0.28 ft/yr; the greatest settlement was observed in recently mined areas.

STUDY METHODS

Three stream-gaging stations were sited to address the effects of large-scale surface mining and valley-fill spoil disposal (fig. 2). One gaging station was located on an Unnamed Tributary to Ballard Fork, directly downstream from a valley fill, and upstream from the sediment pond. The entire area (0.19 mi^2) drained by this stream was within the area permitted for mining, and 0.084 mi^2 (44 percent) was valley fills. A small area (less than about 2 acres) immediately uphill from the Unnamed Tributary was not disturbed by mining. The second was near the mouth of Spring Branch, which drains an unmined watershed. Spring Branch drains a larger area (0.53 mi^2) than does the Unnamed Tributary. The third gaging station was located on the main stem of Ballard Fork, about 0.3 mi downstream from the confluence with Spring Branch; Ballard Fork drains 2.19 mi^2 at the gaging station. All mine runoff flowing past the Ballard Fork gaging station had previously flowed through a sediment pond, which is the normal condition for streams receiving runoff from active or incompletely reclaimed mines.

Stream gages were operated and rated, and records were prepared according to standard USGS methods (Rantz and others, 1982). Stage was recorded at 10-minute intervals. Gages were equipped with air-pumping systems and pressure transducers. Erroneous measurements caused by sedimentation on gage orifices were deleted from data used to prepare the hydrographs in this report; hydrographs do not necessarily include all the measurements from 10-minute intervals.

Four tipping-bucket rain gages located away from trees were used during this study to collect precipitation data at 10-minute intervals. Two rain gages were operated on mountaintops of mined areas, and the other two were on the valley floor. One of the mountaintop rain gages was within the Unnamed Tributary Watershed. No rain gages were within the Spring Branch Watershed, because no site could be found that was not affected by trees or other obstructions.

Watershed boundaries were delineated on a 1:24,000-scale USGS topographic map for the unmined part of the watershed. Within the mine, a field crew visually determined the topographic perimeter of the watershed and made Global Positioning System (GPS) readings at the highest points. Between GPS readings, the topographic perimeter was delineated on a 1:24,000-scale topographic map in the field. The topographic perimeter of the watershed might not represent the actual watershed perimeter where it crosses valley fills. The area of valley fills shown on the mine-permit map outside the topographic perimeter of the watersheds is 0.04 mi^2 (21 percent of the apparent present area) for the Unnamed Tributary to Ballard Fork, and 0.11 mi^2 (5 percent of the apparent present area) for Ballard Fork. The actual drainage area for Ballard Fork and the Unnamed Tributary could be somewhat greater if some precipitation drains from the mine bench into valley fills that drain into these streams. On the other hand, the topographic perimeter of the watershed may be the actual watershed boundary if soils on the valley fills outside the topographic perimeter are impermeable enough to prevent infiltration into the valley fill. In any case, if peak unit runoff were calculated on the basis of the original drainage areas of these watersheds, the relations among sites with respect to peak unit runoff discussed later in this report would remain the same.

STORM PRECIPITATION

The greatest 1-hour total precipitation during the study period was received between 3:30 p.m. and 4:30 p.m. on July 26, 2001, when the four rain gages recorded an average of 1.63 inches (table 1). The 1-hour, 1-year precipitation for this part of West Virginia is about 1.1 inches; the 1-hour, 2-year precipitation is about 1.3 inches; and the 1-hour, 5-year precipitation is about 1.7 inches (Frederick and others, 1977; National Oceanic and Atmospheric Administration, 1961). Average 1-hour precipitation exceeded 1.1 inches one other time during the study, on June 6, 2001 (table 1).

The greatest 24-hour total precipitation during the study was received between 1:00 a.m. July 26, 2001, and 1:00 a.m. July 27, 2001. For this storm, 24-hour total precipitation ranged from 2.91 inches at Sally Fork Mountaintop to 3.49 inches at Left Fork Mountaintop, with an average of 3.16 inches and a standard deviation of 0.24 inches for the four rain gages (table 2). The 24-hour, 1-year rainfall for this part of West Virginia is between 2.0 and 2.5 inches; the 24-hour, 2-year rainfall is between 2.5 and 3.0 inches; and the 24-hour, 5-year rainfall is about 3.5 inches (National Oceanic and Atmospheric Administration, 1961). Average 24-hour rainfall exceeded 2.0 inches during one other storm, on November 26, 1999 (table 2).

Most of the intense rainfall recorded in the Ballard Fork Watershed fell during summer thunderstorms; 18 of the 20 largest 1-hour average rainfalls were during May through September, and 11 of these storms were during June and July (table 1). Of the 20 storms with the highest 1-hour rainfall, the 12 highest standard deviations were for storms during May through August, which illustrates the spotty nature of rainfall from thunderstorms. Rain gages even closer together than those used in this study commonly record rainfall varying as much as among these four rain gages (Black, 1996)

Table 1. Largest 1-hour precipitation recorded during this study, with means and standard deviations, Ballard Fork Watershed, West Virginia

[Times shown are ending times for the 1-hour periods. --, no data]

Date	Time	1-hour precipitation (inches)					
		Sally Fork Valley	Spring Branch Valley	Sally Fork Mountaintop	Left Fork Mountaintop	Mean	Standard deviation
July 26, 2001	4:40 p.m.	1.63	1.56	1.55	1.79	1.63	0.11
June 6, 2001	11:20 a.m.	1.22	1.15	1.02	1.55	1.24	.23
June 21, 2000	8:00 p.m.	1.07	1.14	.92	.99	1.03	.10
August 12, 2001	11:40 p.m.	1.15	1.00	.89	.77	.95	.16
February 18, 2000	9:50 p.m.	1.02	.95	.83	.92	.93	.08
May 27, 2000	5:20 p.m.	.87	.97	.68	.84	.84	.12
September 10, 2000	4:40 p.m.	.90	.81	--	.81	.84	.05
July 10, 2000	10:00 p.m.	.85	.78	.81	.86	.83	.04
July 29, 2001	12:00 p.m.	.82	.81	.75	.91	.82	.07
June 17, 2000	8:40 p.m.	.85	.55	.83	.63	.72	.15
May 27, 2000	11:30 a.m.	.67	.75	.62	.74	.70	.06
July 17, 2001	3:30 p.m.	.76	.50	.71	.70	.67	.11
June 17, 2000	8:30 p.m.	.80	.47	.78	.59	.66	.16
July 14, 2000	8:30 p.m.	.92	.75	.26	--	.64	.34
July 26, 2001	5:40 p.m.	.63	.78	.50	.55	.62	.12
August 8, 2000	2:40 p.m.	.62	.59	--	--	.61	.02
May 17, 2001	12:50 a.m.	.66	.28	.56	.72	.56	.19
July 28, 2001	5:00 p.m.	.52	.55	.54	.52	.53	.02
May 18, 2001	6:40 a.m.	.77	.16	.42	.69	.51	.28
December 13, 2000	9:40 p.m.	.56	.54	.37	.52	.50	.09
September 1, 2001	3:50 a.m.	.51	.58	.42	.46	.49	.07

Table 2. Largest 24-hour precipitation recorded during this study, with means and standard deviations, Ballard Fork Watershed, West Virginia

[Times shown are ending times for the 24-hour period.]

Date	Time	24-hour precipitation (inches)					
		Sally Fork Valley	Spring Branch Valley	Sally Fork Mountaintop	Left Fork Mountaintop	Mean	Standard deviation
July 27, 2001	12:50 a.m.	3.18	3.07	2.91	3.49	3.16	0.24
November 26, 1999	5:40 a.m.	2.17	2.19	1.87	2.17	2.10	.15
May 28, 2000	7:10 a.m.	1.98	2.21	1.69	1.99	1.97	.21
July 11, 2000	11:50 a.m.	2.02	1.96	1.85	1.40	1.95	.28
May 17, 2001	1:50 a.m.	2.08	1.86	1.49	2.19	1.91	.31
July 29, 2001	11:50 a.m.	1.94	1.97	1.78	1.90	1.90	.08
June 18, 2000	1:40 p.m.	2.02	1.76	1.89	1.80	1.87	.12
May 19, 2001	1:30 a.m.	2.13	2.13	1.17	1.99	1.86	.46
June 22, 2000	1:20 a.m.	1.82	1.86	1.67	1.74	1.77	.08
February 19, 2000	12:10 a.m.	1.75	1.68	1.52	1.62	1.64	.10
June 7, 2001	6:10 a.m.	1.60	1.54	1.28	1.92	1.59	.26
January 19, 2001	9:40 p.m.	1.59	1.61	0.65	1.53	1.35	.46

Because of this spottiness, in this report rainfall totals at the watershed scale are assumed to be the same throughout the Ballard Fork Watershed; and average rainfall for the four rain gages was assumed to have fallen on all three streams, rather than attributing rainfall from one gage to a particular watershed. In general, rainfall recorded in the Sally Fork Mountaintop rain gage, within the Unnamed Tributary Watershed, was less than that recorded at the other three gages; for the 20 storms with the highest 1-hour rainfall, the Sally Fork Mountaintop rain gage reading was less than the average for 13 storms (table 1). The largest 24-hour total rainfalls were generally recorded in the spring and summer, as well; 9 of the 12 highest 24-hour rainfall totals were recorded during May, June, or July (table 2).

STORM RESPONSE OF STREAMS

Maximum instantaneous flow during the study period was 8.9 ft^3/s for the Unnamed Tributary (July 26, 2001), 87 ft^3/s for Ballard Fork (May 18, 2001), and 34 ft^3/s for Spring Branch (February 19, 2000) (Ward and others, 2001; 2002). The only instantaneous flow recorded during the study period that exceeded the 1.1-year return magnitude was for Spring Branch on February 19, 2000 (table 3).

Peak flows with unit discharge greater than 20 ft^3/s/mi^2 were recorded 5 times at the Unnamed Tributary, 11 times at Spring Branch, and 9 times at Ballard Fork (table 4). All three gages recorded flows in this range during four of the five storms, which raised unit discharge in the Unnamed Tributary above 20 ft^3/s/mi^2 (the Spring Branch gage was not operating during one of these storms on May 18, 2001).

Response of the mined and reclaimed Unnamed Tributary to different types of storms was distinctly different than responses of Spring Branch and Ballard Fork. More peaks with unit discharge greater than 20 ft^3/s/mi^2 were recorded in Spring Branch and Ballard Fork than in the Unnamed Tributary. Flows in Spring Branch and Ballard Fork generally peaked about the time rainfall ended, and quickly receded, similar to the typical pattern for storm hydrographs from forested watersheds.

The May 16–20, 2001, storms followed a period of dry weather; less than 0.10 inches of rain had been recorded in the Ballard Fork Watershed since May 1, and less than an inch of rain since April 15, so the initial rain did not cause an immediate rise (fig. 3). The forest canopy, leaf litter, and soils were saturated by 1.35 inches of rain on May 16 and 0.84 inches of rain on May 17. When hard rain began about 2:00 a.m. on May 18 and the watershed received over an inch of rain in the next four hours, Ballard Fork quickly

Table 3. Published peak discharges, and calculated discharges at selected return periods, for the three study sites in the Ballard Fork Watershed, West Virginia

[Discharges at selected return periods are calculated using equations from Wiley and others (2000) and Wiley and Atkins (2002). mi^2, square miles; ft^3/s, cubic feet per second]

Site	Drainage area (mi^2)	Annual peak flow			
		2000		2001	
		Date	Discharge (ft^3/s)	Date	Discharge (ft^3/s)
Unnamed Tributary near Mud, WV	0.19	May 27	5.3	July 26	8.9
Spring Branch near Mud, WV	.53	Feb. 19	34	May 22, July 26	17
Ballard Fork near Mud, WV	2.12	June 21	77	May 18	87

Site	Calculated discharge at selected return period (ft^3/s)				
	1.1 year	1.5 year	2 year	5 year	10 year
Unnamed Tributary near Mud, WV	12.3	20.4	25.9	42.5	55.2
Spring Branch near Mud, WV	28.2	45.9	58.0	93.7	121
Ballard Fork near Mud, WV	85.8	137	172	273	350

Table 4. Dates, times, and discharges for all peak flows at all three sites with runoff greater than 20 cubic feet per second per square mile, Ballard Fork Watershed, West Virginia

[$ft^3/s/mi^2$,cubic feet per second per square mile]

Date	Time	Discharge ($ft^3/s/mi^2$)
Unnamed Tributary		
May 18, 2001	6:40 a.m.	25.3
June 6, 2001	11:40 a.m.	40.9
July 26, 2001	4:40 p.m.	46.9
July 29, 2001	12:00 p.m.	38.4
Spring Branch		
Dec. 14, 1999	3:50 a.m.	26.3
Feb. 18, 2000	11:50 p.m.	63.4
May 27, 2000	5:50 p.m.	24.6
June 22, 2000	1:00 a.m.	29.4
Feb. 17, 2001	1:30 a.m.	20.5
May 22, 2001	3:30 p.m.	31.7
May 23, 2001	3:30 a.m.	22.6
June 6, 2001	11:40 a.m.	24.0
July 26, 2001	5:50 p.m.	31.3
July 28, 2001	5:30 p.m.	20.2
Ballard Fork		
Nov. 26, 1999	1:00 a.m.	28.8
Dec. 14, 1999	2:40 a.m.	26.9
Feb. 19, 2000	12:30 a.m.	34.2
May 27, 2000	9:00 p.m.	21.1
June 21, 2000	11:10 p.m.	36.3
May 18, 2001	7:40 a.m.	41.0
June 6, 2001	1:00 p.m.	20.4
July 26, 2001	6:00 p.m.	32.2

responded, reaching peak flow at 7:40 a.m., about an hour after the most intense rainfall. This flow receded in a few hours, although not to previous base flow, and rose slightly in response to scattered rain during May 19–20.

In contrast, the storm hydrograph of the mined Unnamed Tributary typically showed a double peak. The peak of November 26–27, 1999, shows this pattern clearly (fig. 4). Total rainfall for this storm exceeded 3 inches, and much of it fell as a slow, soaking rain; the maximum 1-hour rainfall recorded at any rain gage was 0.48 inches. Antecedent conditions were dry; the rain of November 24 was the first since November 2. Although the rain fell in two major bursts, the storm hydrograph had the shape typical of storms in which rain fell in only one major burst. About 0.73 inches of rain fell on November 25–26 between 9:30 p.m. and 3:30 a.m. Although the flow of Unnamed Tributary rose slightly about 12:30 a.m. on November 26, much of the water apparently percolated into the valley fill. By about 1:00 p.m. on November 26, a delayed rise in flow had begun, from rain received the previous night. Showers continued through the afternoon and evening, caused small spikes of surface runoff, and added to the larger delayed peaks. When rain was received with an intensity of about 0.3 inches per hour at about midnight on November 26, a sharp peak of stormwater ran off. This peak quickly receded when rainfall intensity decreased, but the stream continued to rise relative to its previous level, peaking at 2:00 p.m. on November 26, 8 hours after the last rain fell that exceeded 0.10 inches/hour. Streamflow had not receded to the previous base flow on December 1.

During most storms, peak unit discharge from Spring Branch and Ballard Fork exceeded peak unit discharge from the Unnamed Tributary, despite the effects of interception on runoff in forested parts of those watersheds. In the two most intense storms during the study period, however, on June 6, 2001 (maximum average 1-hour rainfall of 1.24 inches), and July 26, 2001 (maximum average 1-hour rainfall of 1.63 inches), peak unit discharge from the Unnamed Tributary exceeded peak unit discharge in the forested watersheds. In the third most intense storm during the study period, June 21, 2000, instruments at the gaging station on the Unnamed Tributary malfunctioned and the record for this storm was lost.

During the storm of July 26, 2001, intense rain exceeded interception and infiltration capacity of the Unnamed Tributary Watershed and led to a sharp peak that exceeded unit discharge from the other two watersheds by more than twofold (fig. 5). Antecedent conditions were fairly wet; the Ballard Fork Watershed received nearly 0.50 inches of rain the afternoon of July 22. The initial substantial rain (maximum rainfall intensity was 0.25 inch per hour) that began about 7:00 a.m. on July 26 did not cause a runoff response from any stream, but did wet the canopy, litter, and soils in the forested watersheds, as did additional rain early that afternoon. The most intense rainfall recorded during this study was received between 3:50 p.m. and

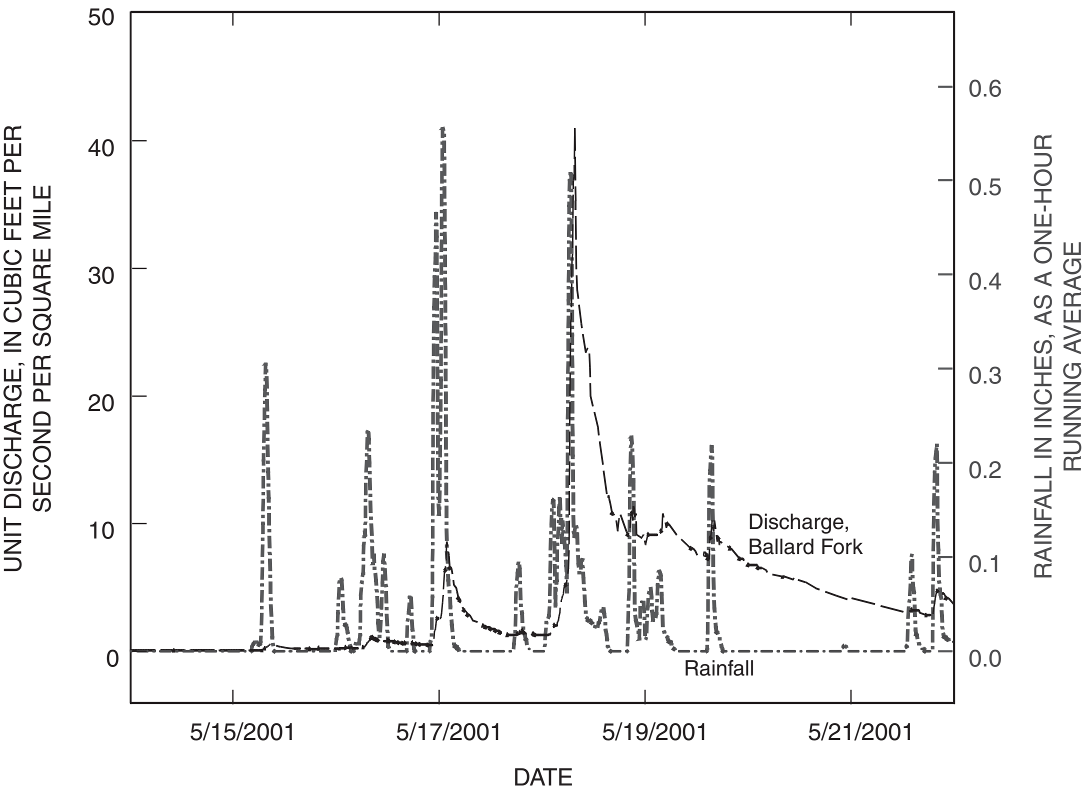


Figure 3. Storm hydrograph for Ballard Fork near Mud, West Virginia, and rainfall as a 1-hour running average for four rain gages in the Ballard Fork Watershed, West Virginia

4:30 p.m. on July 26, when more than 1.3 inches fell. Flows in the Unnamed Tributary rose sharply during this rain, and peaked at 4:40 p.m., while rain was still falling, but after intensity had decreased. Maximum unit discharge for the Unnamed Tributary was 46.9 $ft^3/s/mi^2$. Although flows in Spring Branch and Ballard Fork responded to this burst of rain, their peaks (31.3 and 32.2 $ft^3/s/mi^2$, respectively) were later in the evening, at about 6:00 p.m., at the end of a final spate of rain of 0.63 in/hr. The Unnamed Tributary responded less strongly to the final rain than it had to the earlier, more intense rain, with a maximum unit discharge on the second peak of 21.8 $ft^3/s/mi^2$. This initial peak on the Unnamed Tributary receded as quickly as the peak at Spring Branch and more quickly than the peak at Ballard Fork. At about 8:30 p.m., however, the Unnamed Tributary began to rise again in response to water that had apparently passed through the valley fill. This attenuated secondary peak reached a maximum unit discharge of 19.1 $ft^3/s/mi^2$ at 6:20 a.m. on July 27, several hours after Spring Branch and Ballard Fork had largely receded.

The delayed peak contributed to the other occasion when peak unit discharge from the valley fill exceeded peak unit discharge from the forested watersheds. Rain on July 28 caused small initial rises on all three streams (fig. 6). When a hard rain fell on the afternoon of July 29, the peaks on Spring Branch

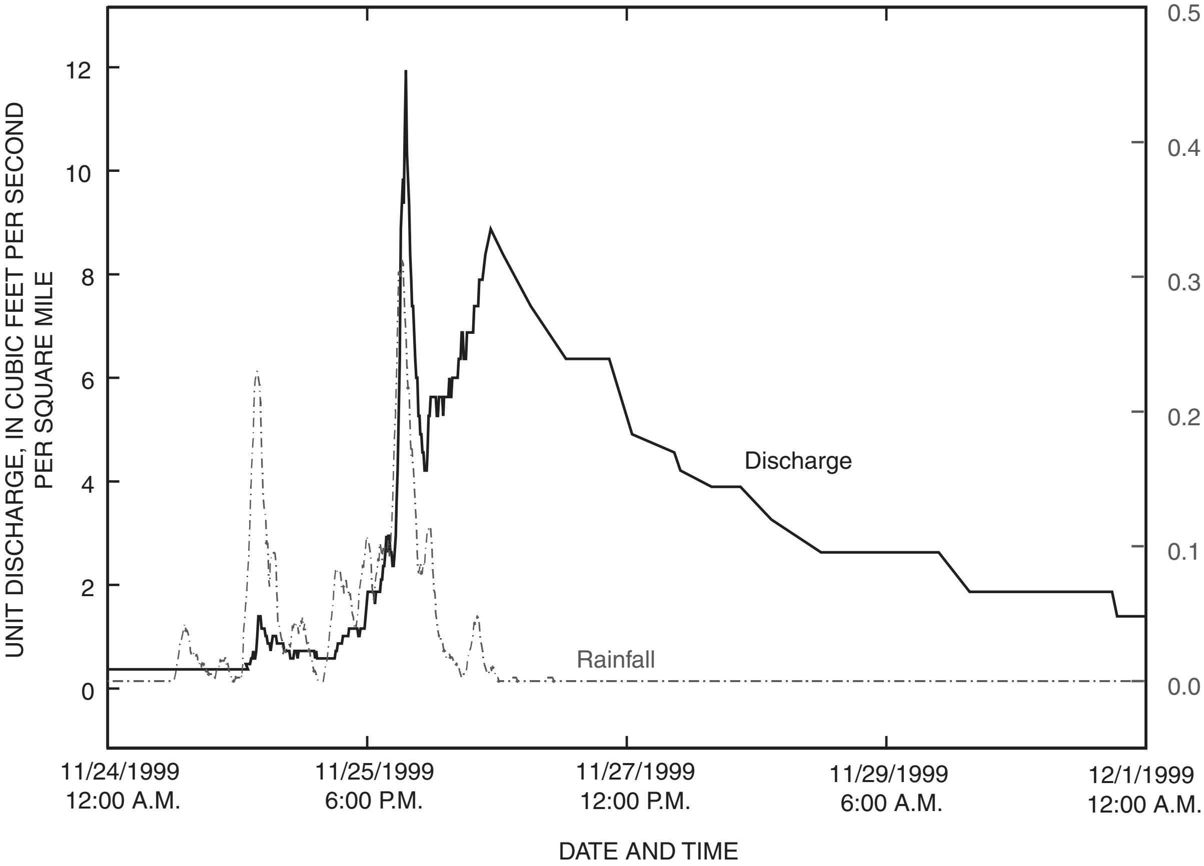


Figure 4. Storm hydrograph for November 24–December 1, 1999, for Unnamed Tributary of Ballard Fork near Mud, West Virginia, and rainfall as a 1-hour running average for four rain gages in the Ballard Fork Watershed, West Virginia.

and Ballard Fork had receded, but the Unnamed Tributary was still rising from delayed flow, apparently from the July 28 storm. Although the rainfall was not of exceptional intensity (maximum 1-hour rainfall was 0.82 inches), peak unit discharge on the Unnamed Tributary (38.4 $ft^3/s/mi^2$) exceeded peak unit discharge from Spring Branch and Ballard Fork (26.2 and 23.7 $ft^3/s/mi^2$, respectively).

During all storms with 1-hour rainfall greater than 0.75 inches or 24-hour rainfall greater than 1.75 inches during which all gaging stations recorded a complete record, the Unnamed Tributary yielded the most total unit flow. (During several storms, however, sediment was deposited on one or more gage orifices following the peak, which decreased the reliability of the streamflow record on the recession and prevented a valid comparison of total flow among streams.) Hydrographs are typically separated into base flow and overland flow. This was not done, because the secondary peaks in the hydrographs from the Unnamed Tributary apparently had characteristics of both these hydrograph components. Instead, hydrographs were

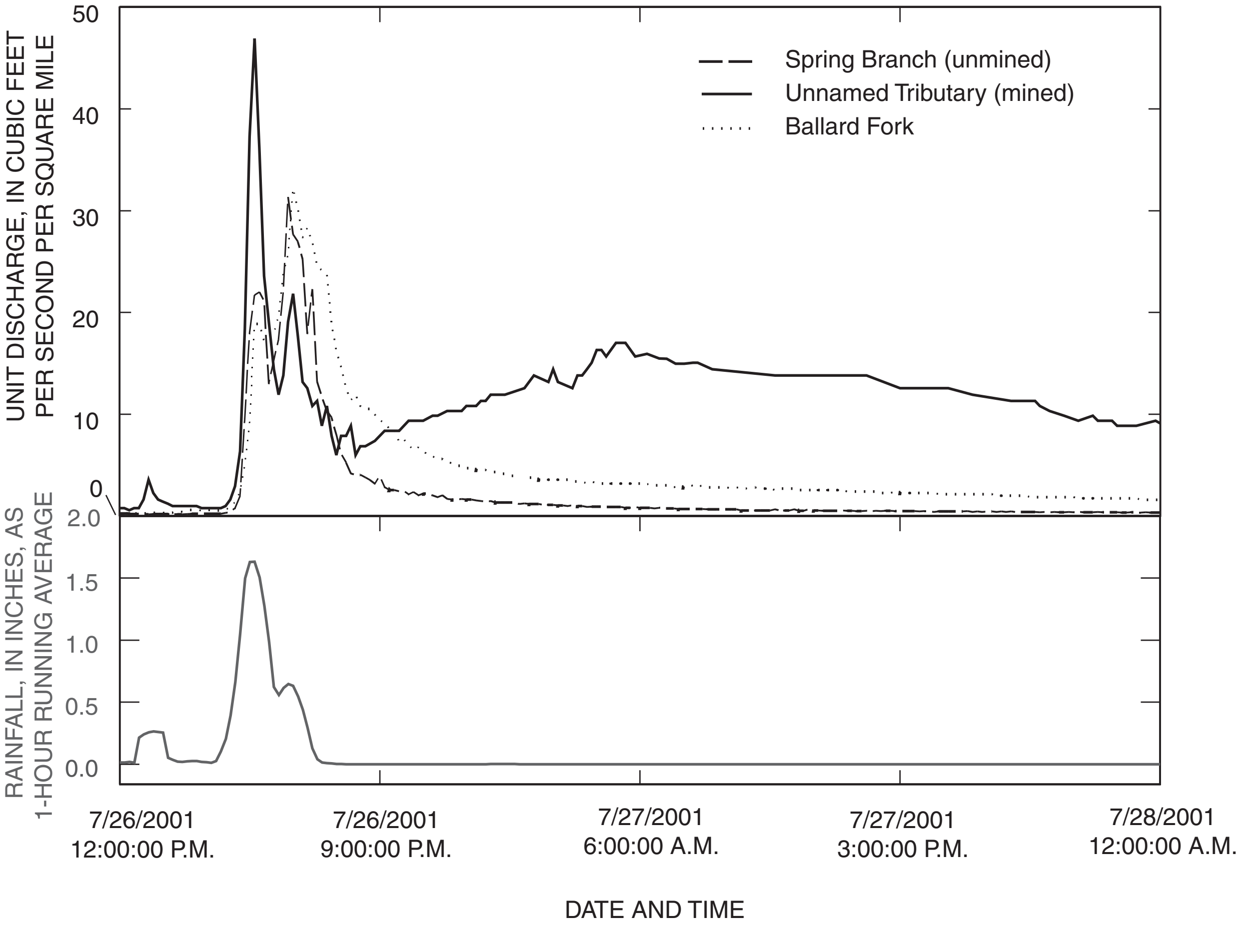


Figure 5. Storm hydrograph for July 26–28, 2001, for three stream-gaging stations, and rainfall as a 1-hour running average for four rain gages in the Ballard Fork Watershed, West Virginia.

divided by time into periods of storm runoff and recession. In three storms, hydrographs from Spring Branch were divided into storm runoff and recession on the basis of inflection points in the hydrograph, and if substantial rain was received before streams began to rise, into an initial rain period (fig. 7, table 5). The timing of peaks and recessions from Spring Branch were compared to the other two streams, and because differences were minor (fig. 7), storm runoff from all three streams was separated from recession at the same times. In all three storms, total unit flow from the Unnamed Tributary was greatest during recessions. Additionally, total unit flow from the Unnamed Tributary was greatest among the streams during all three recessions. Total unit flow during storm runoff was typically less in the Unnamed Tributary than in the other two streams. In the three storms analyzed, however, total unit flow from the Unnamed Tributary was greatest among the three streams during two storm-runoff periods (July 28 and July 29), both of which took place before the storm runoff on the Unnamed Tributary had fully receded. Total unit flow from Ballard Fork was greatest among the three sites during one storm-runoff period (July 26), when the largest 1-hour rainfall of the study period was received, and in the other two storm-runoff periods, total unit flows from Spring Branch and Ballard Fork were about the same.

Water was partitioned differently between hydrograph components among the three sites. During all storms, more water ran off into the Unnamed Tributary during the recession than during storm

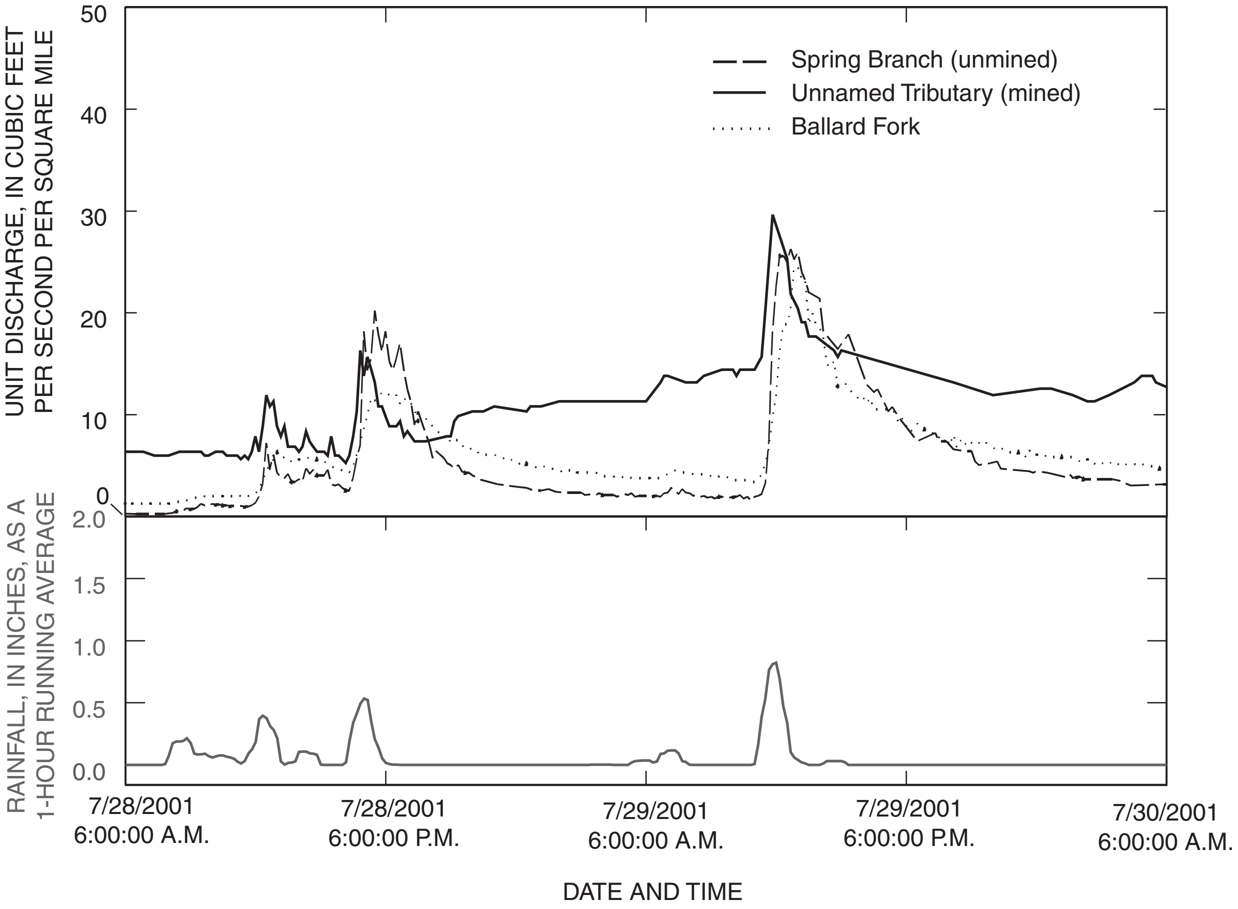


Figure 6. Storm hydrograph for July 28–30, 2001, for three stream-gaging stations, and rainfall as a 1-hour running average for four rain gages in the Ballard Fork Watershed, West Virginia.

runoff. During most storms, more water ran off into Spring Branch during storm runoff than during recessions; one exception was the storm on June 6, 2001, in which most of the rain was received in a short, intense burst. The partitioning of water in Ballard Fork between storm runoff and recessions varied; more water ran off during the recession than during the storm runoff in three of the five storms, with no clear pattern. In all storms, the Unnamed Tributary had the largest proportion of stormflow in the recession among the three streams, and in all but one storm (June 6), the proportion of stormflow in the recession was larger in Ballard Fork than in Spring Branch.

The percentage of runoff varied with rainfall intensity, and in Spring Branch and Ballard Fork, with the season. Of the three analyzed storms, the storm of November 24–26, 1999, a long, soaking storm, produced the smallest percentage (27 percent) of runoff into the Unnamed Tributary. This storm, which took place after leaves had fallen, resulted in 17 percent runoff from both Spring Branch and Ballard Fork. During the storm of June 6, 2001, when average rainfall was 1.36 inches, but 1.02 inches were received in one 10-minute period and another 20-minute period, the largest percentage of rain ran off from all three watersheds among the three analyzed storms, 51 percent from the Unnamed Tributary, 36 percent from Spring Branch, and 34 percent from Ballard Fork. The storms of July 26–29 also yielded high percentages of runoff from the Unnamed Tributary (41 percent) and Ballard Fork (18 percent), but a lower percentage from Spring Branch (13 percent).

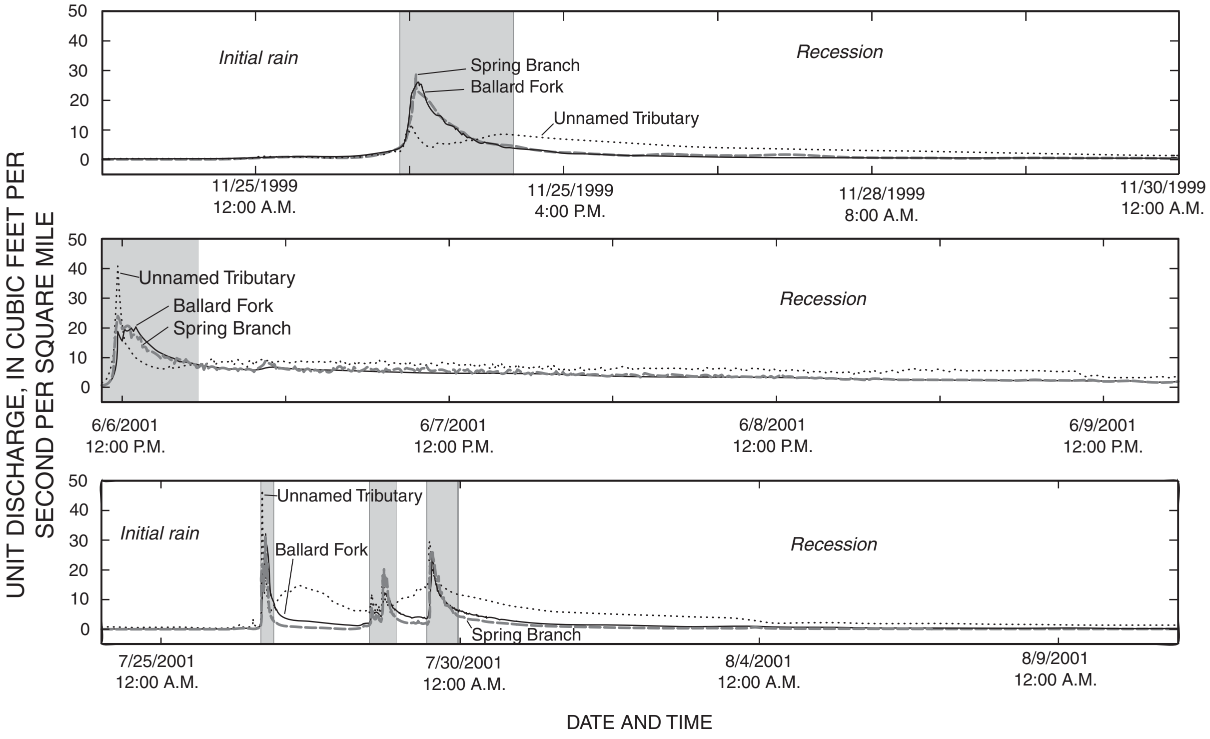


Figure 7. Storm runoff and recession during three selected storms for three stream-gaging stations in the Ballard Fork Watershed, West Virginia.

Table 5. Volume of water running off during specific hydrologic periods during three selected storms in the Ballard Fork Watershed, West Virginia

[ft^3/mi^2, cubic feet per square mile]

Storm	Flow (ft^3/mi^2)			Rainfall (ft^3/mi^2)
	Unnamed Tributary	Spring Branch	Ballard Fork	
November 24, 1999–November 30, 1999				
Initial rain (November 24, 10:00 p.m.–November 25, 10:30 p.m.)	95,400	113,000	90,600	4,320,000
Storm runoff (November 25, 10:40 p.m.–November 26, 4:00 p.m.)	431,400	690,000	690,000	2,740,000
Recession (November 26, 4:10 p.m.–November 30, 11:50 p.m.)	1,360,000	364,000	429,000	0
Total	1,890,000	1,170,000	1,210,000	7,060,000
June 6, 2001–June 9, 2001				
Storm runoff (June 6, 10:30 a.m.–June 6, 5:30 p.m.)	238,000	287,000	285,000	3,160,000
Recession (June 6, 5:40 p.m.–June 9, 5:30 p.m.)	1,660,000	1,060,000	990,000	581,000
Total	1,900,000	1,350,000	1,270,000	3,740,000
July 26, 2001–August 2, 2001				
Initial rain (July 26, 5:20 a.m.–July 26, 4:20 p.m.)	38,300	9,030	13,300	2,880,000
First storm runoff (July 26, 4:30 p.m.–July 26, 8:50 p.m.)	249,000	240,000	312,000	4,460,000
First recession (July 26, 9:00 p.m.–July 28, 11:50 a.m.)	1,450,000	103,000	371,000	1,120,000
Second storm runoff (July 28, 12:00 p.m., July 28, 10:00 p.m.)	311,000	267,000	271,000	2,180,000
Second recession (July 28, 10:10 p.m.–July 29, 10:50 a.m.)	540,000	110,000	205,000	348,000
Third storm runoff (July 29, 11:00 a.m.–July 29, 10:20 p.m.)	660,000	507,000	464,000	2,090,000
Third recession (July 29, 11:00 p.m.–August 2, 3:20 p.m.)	2,120,000	423,000	728,000	0
Total	5,370,000	1,660,000	2,380,000	13,100,000

EFFECTS OF SURFACE MINING USING VALLEY FILLS AND MECHANISMS OF WATER FLOW

Much of the impetus for this study came from anecdotal evidence that peak flows were diminished and attenuated, and low flows were relatively greater, in streams draining valley fills than in streams draining unmined watersheds. Stream measurements made in small streams in the mountaintop-removal mining region in West Virginia in October 1999, during a drought, documented significantly higher unit discharge from valley fills than from adjacent unmined watersheds (Wiley and others, 2001). The working explanation for these observations was based on the idea that valley fills are piles of large, poorly sorted rocks that contain a large amount of void space. Because of this void space, a valley fill would act like a sponge. Water running across the surface would infiltrate the fill instead of running into the stream. This water would be temporarily stored in the fill, and then gradually drain into the receiving stream over a period of days instead of hours (as would direct surface runoff), thereby decreasing peak flow and increasing base flow. According to this explanation, valley fills increase ground-water storage in small watersheds. This explanation of flows downstream from valley fills failed to take into account the importance of surface conditions on mines and water storage in vegetation and soils, and thus did not predict the sharp initial peak from the Unnamed Tributary Watershed observed in response to intense rain.

Hortonian (excess overland) flow appears to be important in the Unnamed Tributary Watershed following intense storms, and may cause the initial spike on the rising arm of storm hydrographs. Reconnaissance of the Unnamed Tributary Watershed shows that on some steeply sloped areas, surface rills and gullies are prominent (fig. 8). Rills and gullies are usually formed by excess overland flow. Intense storms did not seem to exceed the infiltration capacity of unmined parts of the watershed, except on roads. If storms exceeded the infiltration capacity of the mined watershed, it was probably a consequence of soil compaction. Soil measurements were not made as part of this study, but studies of soils on reclaimed mines have consistently found soils to be highly compacted on reclaimed mine sites. Much of the land reclaimed since enactment of the 1977 Surface Mining Control and Reclamation Act is over-compacted during reclamation activities (Conrad and others, 2002). Soils at many mine sites in southwestern Virginia were found to be highly compacted (bulk density was greater than 1.6 g/cm^3, compared to 1.1 to 1.5 g/cm^3 for undisturbed soils) within several feet of the surface due to heavy machinery traffic (Daniels and Zipper, 1997). On a large surface mine in Kentucky, infiltration rates on the bench and into the spoil pile were found to be very low, and at many points, soil on the reclaimed mine was found to be dry a few inches under the surface shortly after a heavy rain (Wunsch and others, 1996). Mining in Ballard Fork followed accepted industry practice, so soils on these mines are probably heavily compacted. Drainage structures on the mine are designed to convey excess runoff of the sort that would be generated from intense storms on compacted soils.

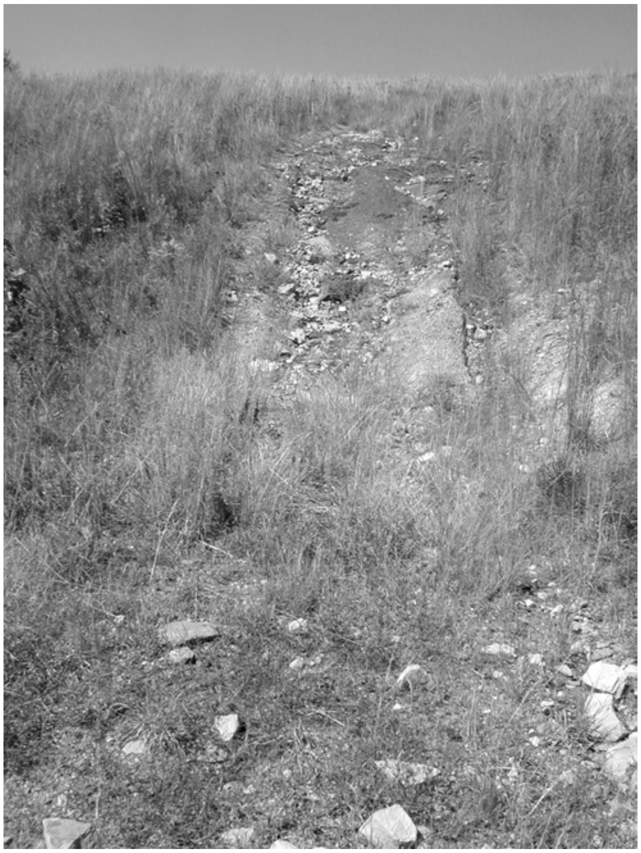


Figure 8. Gullies on a steeply sloped area in the Unnamed Tributary to Ballard Fork Watershed, West Virginia.

Mountaintop-removal mines and other types of surface mines have been permitted on the basis of the assumption that surface mining generally results in a decrease in peak flows (Office of Surface Mining, 2001). Some older studies reported a decrease in peak flows caused by surface mining in which overburden was removed around the contour of a mountain, particularly in combination with underground mining. Total storm runoff was reported to be decreased downstream from surface mines in southern West Virginia on the basis of a study of five small watersheds (Borchers and others, 1991). All three of the mined basins in that study contained extensive deep mines, however, and percolation into deep mines through subsidence cracks was considered one of the major mechanisms that decreased peak flows. Storage of water in ponds on the strip bench was also considered important in reducing peak flows. On the other hand, average peak flows from six small surface-mined watersheds in eastern Kentucky were 36 percent greater than in adjacent unmined watersheds (Bryan and Hewlett, 1981). Peak flow increased only in the summer, however, and maximum annual stormflows, usually in winter or spring, were reduced slightly.

More recent studies of large surface mines have found that mining increases peak flows, particularly flows resulting from infrequent, large storms. Modeling studies of mountaintop-removal watersheds predicted that peak unit runoff would be greater from actively mined and recently reclaimed watersheds than from unmined watersheds, consistent with results found in the present study. Models by the U.S. Army Corps of Engineers (2001) showed that the effects of mining on flow were site-specific. Ten-year and 100-year flows (flows with a probability of taking place once every 10 or 100 years, respectively) on three streams draining large-scale surface mines were modeled as increasing by 42 percent, 13 percent, and 1 percent, respectively, from premining to postmining. The models predicted that peak flows would increase during active mining, decrease somewhat following reclamation (although not to premining flows), and decrease to less than premining flows when "future forested" conditions were attained. These models were based on Natural Resources Conservation Service runoff-curve numbers, which were assumed to change dramatically during a period of 40 years, an interval assumed to be sufficient for reclaimed mines to become fully forested. The reports did not specify how runoff-curve numbers were determined for mountaintop-removal sites that have been reclaimed for 40 years and are "fully forested," a condition that does not currently exist. Reestablishing forests on surface mines reclaimed since the passage of the Surface Mining Control and Reclamation Act of 1977 has commonly been difficult, largely because of soil compaction (Conrad and others, 2002). In 19- to 23-year old mine sites in southern West Virginia, trees were established on mined mountaintops, but canopy cover was much less on mountaintops (14–24 percent) than on mine outslopes (28–70 percent), which in turn was much less than on nearby undisturbed areas (84–88 percent) (Skousen and others, 1998).

Another modeling study (West Virginia Department of Environmental Protection, 2002b) also showed that mountaintop-removal and other large-scale surface mining, along with timbering, increased peak flows in the July 8, 2001, flood by between 3 and 21 percent in the three watersheds that were modeled. The WVDEP report recommended that (1) regulations be changed to prohibit any increase in surface-water discharge as a result of mining, (2) consider whole-watershed conditions when issuing permits, and (3) require that any valley fills be built from the bottom up instead of by dumping rock from the mine bench.

The attenuation of peak flows by sediment ponds probably accounts for many of the differences observed between the flows in the Unnamed Tributary, where flows were measured upstream from sediment ponds, and in Ballard Fork, where flows were measured downstream from sediment ponds. Hydrographs for Ballard Fork resembled those from Spring Branch much more closely than they did those for the Unnamed Tributary. The initial peak on hydrographs for the Unnamed Tributary always receded quickly, so the pond downstream from the gaging station, and other ponds downstream from the other valley fills in the watershed, should have had enough capacity to store the water from these initial peaks so that they were not observed downstream. High recession flows from the Unnamed Tributary Watershed and from other mined areas appear to have influenced the Ballard Fork hydrograph, however; in four of the five peaks and recessions analyzed, total unit flow from Ballard Fork during the recession was intermediate between those on the Unnamed Tributary and on Spring Branch.

In addition to mining history, natural factors including watershed size probably influenced relative peak unit flow and hydrograph shape in the three streams. Peak unit runoff in adjacent watersheds with similar vegetation and land use typically decreases with increasing drainage area (Black, 1996). If land use were the same in both watersheds, peak unit flows from Spring Branch would be expected to be smaller than those from the Unnamed Tributary, and peak unit flows from Ballard Fork would be expected to be smaller than those from Spring Branch. Also, Spring Branch is longer relative to its drainage area than the other two streams, which probably attenuates storm peaks and decreases peak unit flow. Peaks in smaller watersheds usually recede more quickly than those in larger watersheds, which could explain part of the relation between recession flows from Spring Branch and Ballard Fork, although not between the Unnamed Tributary and the other two streams.

Most of the peak flows measured during this study were produced by summer thunderstorms. Floods on small streams in West Virginia are usually the result of summer thunderstorms, but floods on large streams are usually the result of other types of storms, either long, soaking winter and spring rains from frontal systems, or rainfall on heavy snow (Runner and Michaels, 1991). The present study does not include records for any streamflows exceeding about the 1.5-year return period, or peaks resulting from winter frontal storms or rain-on-snow events. The question of how streams in the Ballard Fork Watershed might respond to intense rains in the winter remains open. The intense storms (1-hour rainfall greater than 1 inch) that the Ballard Fork Watershed received during the study period were all in the spring and summer. The mined watershed showed a capacity to delay runoff from slow rains as water apparently infiltrated and flowed through the valley fill, but to increase flows 8 to 48 or more hours after the rain fell. In a several-day rain, direct runoff from the mine mixes with water from the delayed peaks, and details of the specific storm would determine whether unit runoff from the mined watershed would be increased or decreased. The effects of leaf interception are important in reducing peak flows from the forested watershed in the summer but less so in the winter, although litter interception is important year-round. The threshold for the intensity of storms when peak unit discharge is greater from the mined watershed than from the unmined watershed may also be different for winter storms, and probably varies within the Central Appalachian coal field and among mines.

SUMMARY

Large-scale surface coal mining in the Ballard Fork Watershed in southern West Virginia changed the response of streams to storms. During summer storms when rainfall intensity exceeded about 1 inch per hour, peak unit (area-normalized) runoff from the Unnamed Tributary (surface mined and valley-filled) Watershed exceeded peak unit runoff from the Spring Branch (unmined) Watershed. During most storms, those with intensity less than about 1 inch per hour, peak unit flows were greater from the Spring Branch Watershed than the Unnamed Tributary Watershed. One storm that produced less than an inch of rain before the secondary peak from the previous storm had receded caused peak unit flow from the valley-filled watershed to exceed peak unit discharge from the unmined watershed. This suggests that large-scale surface mining is especially likely to increase the severity of flooding during a summer storm when a period of intense rainfall follows several days of continuous rainfall. Typical canopy interception rates in eastern hardwood forests are about 10 percent of gross rainfall, and dry leaf litter may intercept several tenths of an inch of throughfall; water that would have been retained by these processes in forested watersheds was available to run off the mined and reclaimed Unnamed Tributary Watershed.

Following all storms with sufficient rainfall intensity, about 0.25 inch per hour, the storm hydrograph from the valley-filled watershed showed a double peak, as a sharp initial rise was followed by a decrease in flow and then a delayed secondary peak of water that had apparently flowed through the valley fill. Storm response of streams from the mined watershed is influenced by the compaction of soils on the mine, the apparent low maximum infiltration rate into the valley fill compared to that in the forested watershed, storage of water in the valley fill, and the absence of interception from trees and leaf litter. Hortonian (excess overland) flow may be important in the Unnamed Tributary Watershed during intense storms, and may cause the initial spike on the rising arm of storm hydrographs; the water composing the initial peaks may be conveyed by drainage structures on the mine.

During all storms with 1-hour rainfall greater than 0.75 inches or 24-hour rainfall greater than 1.75 inches for which a complete record of flow was obtained at all gaging stations, the Unnamed Tributary yielded the most total unit flow. In three selected major storms, total unit flow from the Unnamed Tributary was greatest during recessions, and its total unit flow was greatest among the streams during all three recessions. Total unit flow during peaks, however, was typically less in the Unnamed Tributary than in the other two streams. During all storms, more water ran off the Unnamed Tributary during the recession than as storm runoff. During most storms, more water ran off the Spring Branch Watershed as storm runoff than as recession flow; one exception was the storm on June 6, 2001, in which most of the rain (1.02 of 1.36 inches) was received in 10- and 20-minute bursts.

The greatest 1-hour total precipitation during the study period was received on July 26 between 3:30 p.m. and 4:30 p.m., when the four rain gages in the watershed recorded an average of 1.63 inches; the 1-hour 5-hour precipitation for the study area is about 1.7 inches. Maximum instantaneous flow during the study period was 8.9 ft^3/s for the Unnamed Tributary (July 26, 2001), 87 ft^3/s for Ballard Fork (May 18, 2001), and 34 ft^3/s for Spring Branch (February 19, 2000). The only instantaneous flow recorded during the study period that exceeded the 1.1-year return magnitude was for Spring Branch on February 19, 2000. Relative peak unit flow among the three streams in this study could be different in larger storms. Most of the intense rainfall recorded in the Ballard Fork Watershed fell during summer thunderstorms, and storm response to winter frontal systems or major rain-on-snow events remains unknown. Rainfall-runoff relations on altered landscapes are site-specific and aspects of mining and reclamation practice that affect storm response of streams may vary among mines.

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Ballard Fork near Mud, West Virginia.