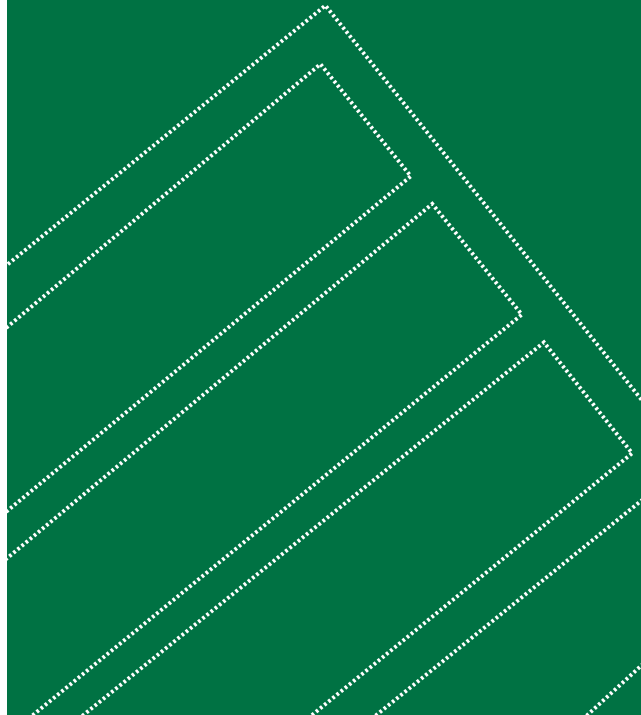


*Effects of*  
Longwall Mining on Hydrogeology,  
Leslie County, Kentucky

Part 3: Post-Mining Conditions



Shelley Minns Hutcheson, James A. Kipp,  
James S. Dinger, Daniel I. Carey,  
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Gregory L. Secrist

**Kentucky Geological Survey**  
James C. Cobb, State Geologist and Director  
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# Effects of Longwall Mining on Hydrogeology, Leslie County, Kentucky

## Part 3: Post-Mining Conditions

Shelley Minns Hutcheson<sup>1</sup>, James A. Kipp<sup>2</sup>,  
James S. Dinger<sup>1</sup>, Daniel I. Carey<sup>1</sup>,  
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### ABSTRACT

The effects of longwall coal mining on hydrology in the Eastern Kentucky Coal Field have been investigated since 1991. The study area is in the Edd Fork watershed in southern Leslie County, over Shamrock Coal Company's Beech Fork Mine. Longwall panels approximately 700 ft wide are separated by three-entry gateways that are approximately 200 ft wide. The mine is operated in the Fire Clay (Hazard No. 4) coal; overburden thickness ranges from 300 to 800 ft. Mining began in panel 1 in September 1991 and concluded with panel 8 in September 1994. Long-term monitoring consisting of a network of piezometers and time-domain reflectometry (TDR) cables previously installed over panel 7, in conjunction with a continuously recording rain gage and flume, began after the completion of mining.

Two new core holes were drilled over panel 7 approximately 1 year after mining ceased in panel 8 to determine depth of collapse and hydraulic conductivity of strata. Water levels were measured in two new monitoring wells installed after mining to complement the 11 piezometers installed prior to mining that were still functioning. Precipitation was measured through July 1996, and streamflow was measured in Edd Fork on a monthly basis using a cross-section gaging method.

Physical failure of piezometers, core drilling, and the movement of air into deeper piezometers after mining indicate that extensive fracturing occurred to a height of 450 ft above the mine, which is approximately 60 times the extracted coal-seam thickness. Hydraulic conductivity values determined from pressure-injection tests were 10 to 100 times greater after mining than before mining; many values were in the range of  $10^{-2}$  to  $10^{-4}$  ft/min for all lithologies. At a minimum, a zone of rock approximately 200 ft above the mined coal was dewatered beneath Edd Fork. Ground-water levels in ridgetop piezometers fluctuated slightly more after mining than they did before, which indicates that the upper part of the ridge is more hydraulically connected to surface recharge from precipitation since mining took place. The existence of ground water in the shallow ridgetop piezometers suggests that an underlying aquitard zone developed during mine collapse, which retards the downward movement of shallow ground water to the mined-out area. Water level declined in a sandstone unit approximately 300 ft above the mine after mining, but recovered within a year. This indicates that the underlying regional aquitard still retards downward ground-water movement, despite the hydraulic conductivity of the unit increasing 100 times after mining. Edd Fork, approximately 375 ft above the mine in panel 7, resumed surface flow 2 months after completion of mining; however, flow diminishes downstream at about the centerline of panel 8. Mining is still active in other areas of the mine, and mechanical dewatering activities will most likely keep water levels in the deep zones artificially depressed in the study area until mining is completed and dewatering activities cease.

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## INTRODUCTION

In longwall underground mining, a working face several hundred feet wide is advanced between parallel headings, producing a series of large, rectangular, mined-out panels. The face is temporarily supported while the coal is being extracted by movable hydraulic jacks. As these supports advance with the face, the unsupported roof fractures into blocks that collapse into the mined-out area. The remaining overburden then subsides onto this rubble.

Subsidence affects the hydrology of the mined area, and can cause loss or interruption of water supplies, which is a concern of both mine operators and adjacent landowners. This report summarizes findings from August 1992 through September 1996 for a long-term investigation of the hydrologic effects of longwall mining in eastern Kentucky. The impetus for the study came from the Hydrology Steering Committee, formed to implement parts of a settlement agreement between the National Wildlife Federation and the U.S. Office of Surface Mining and the Kentucky Department for Surface Mining Reclamation and Enforcement. The agreement directs that the hydrologic regime of Kentucky's coal fields be more fully characterized to assist the regulatory agencies in meeting their hydrologic protection mandates.

The Edd Fork watershed, in southern Leslie County, in the Helton 7.5-minute quadrangle, was chosen for study (Fig. 1). This area is included in the Eastern Kentucky Coal Field, a hilly to mountainous region characterized by narrow, winding ridges, V-shaped valleys, and high topographic relief. The study watershed is drained by Edd Fork, a first-order tributary of Trace Branch. Trace Branch flows into Beech Fork, a major tributary of the Middle Fork of the Kentucky River. The Edd Fork Basin is located approximately midway between Beech Fork and the Middle Fork of the Kentucky River. These are third- and fourth-order streams, respectively, which represent local base level. Elevations in the Edd Fork watershed range from about 2,160 ft on the ridgetops to about 1,550 ft at the mouth of Edd Fork. Terrain in the watershed is steep; slopes average 26°. Surface mining has previously taken place here.

Phase 1 of the study (Minns and others, 1995) characterized the study area before mining took place so that the impact of future mining could be evaluated. Phase 2 evaluated hydrologic responses to undermining of the Edd Fork watershed (Hutcheson and others, 2000b). This third and final phase of the investigation documents hydrologic responses for the 2 years following the completion of undermining in the Edd Fork watershed. It assesses the availability, quality, and quantity of

ground water in the valley bottom and ridgetop after mining; assesses changes in hydraulic properties of rocks as a result of mining; and evaluates the long-term response of Edd Fork to undermining.

## SITE INVESTIGATION

The Edd Fork watershed was undermined by Shamrock Coal Company's Beech Fork Mine, operating in the Fire Clay (Hazard No. 4) coal bed. Overburden thickness in the watershed ranges from about 300 ft in the valley bottom to about 800 ft on the ridgetops. The configuration of the mine is shown in Figure 2. Mining was by longwall-mining methods, and occurred in 700-ft-wide panels. The panels were separated by 200-ft-wide, three-entry gateways developed by conventional room and pillar methods.

The mine began operation with panel 1 in April 1991 and ended with panel 8 in September 1994. Mining directly below the watershed was intermittent, as the active mine face moved in and out of the Edd Fork watershed during mining of panels 5 through 8. Mining under the watershed began with panel 5 in late August 1993 and continued until the mining ceased in September 1994.

Three sites over panel 7, representing the valley side (site A), ridgetop (site B), and valley bottom (site C), were selected for monitoring (Fig. 3). Each site contains a core hole and a closely spaced piezometer nest.

## Previous Work

**Phase 1.** An NX-size core hole was drilled at each site during the winter of 1991-92 to provide stratigraphic control for piezometer locations, evaluate the nature of fracturing, conduct pressure-injection tests, and install time-domain reflectometry instrumentation to evaluate rock strain. Geologic cross section A-A' (Fig. 4) was constructed from these core data. General geology of the area was described by Rice (1975).

Twenty-four piezometers were completed in July 1992 to provide information on discrete stratigraphic zones in the topographic settings represented by the three sites (Fig. 5). Six of the piezometers were located at site A, ranging in depth from 35 to 417 ft. Twelve of the piezometers were installed at site B, ranging in depth from 67 to 684 ft. The remaining six piezometers were installed at site C, ranging in depth from 18 to 262 ft. A rain gage and flume were also installed in the study basin during the summer of 1992 to provide additional data for hydrologic analysis (see Figure 3).

Before mining began, Minns (1993) developed a conceptual model of ground-water flow in the basin. She differentiated three ground-water zones on the basis of fracture occurrence and hydraulic properties

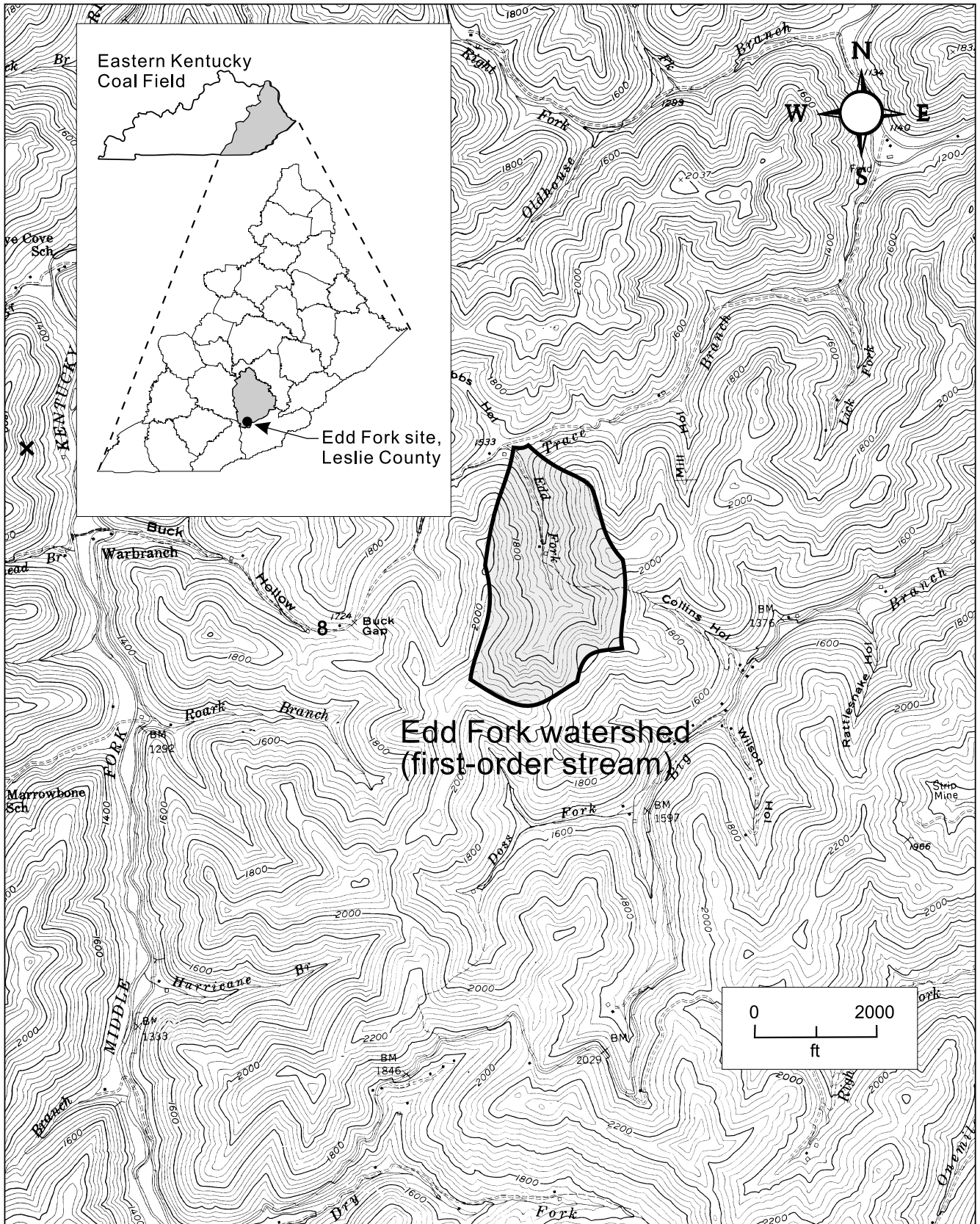


Figure 1. Location of the Edd Fork research area (from Minns and others, 1995, Fig. 2).

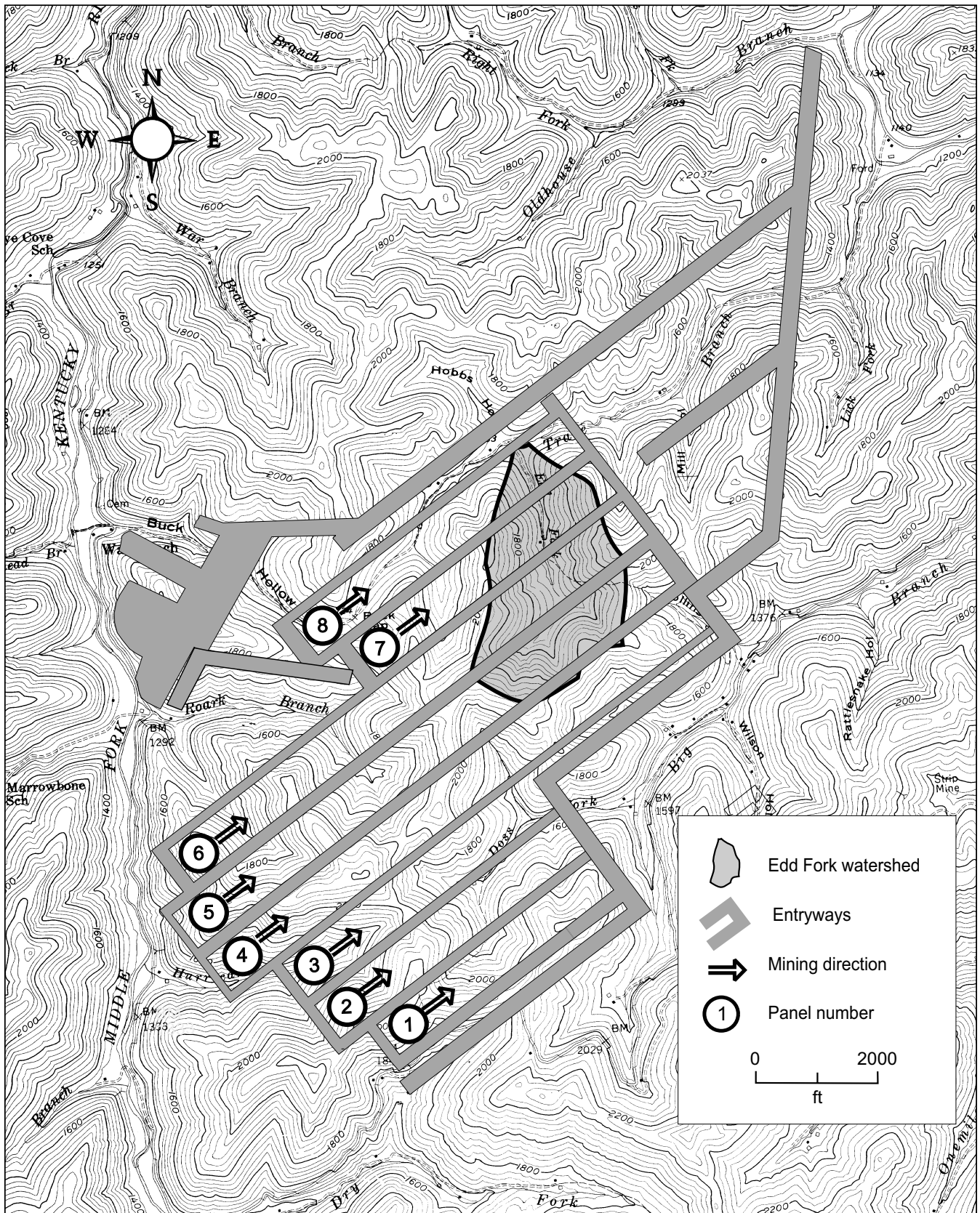


Figure 2. Configuration of the longwall mine in and surrounding the Edd Fork watershed (from Minns and others, 1995, Fig. 5).

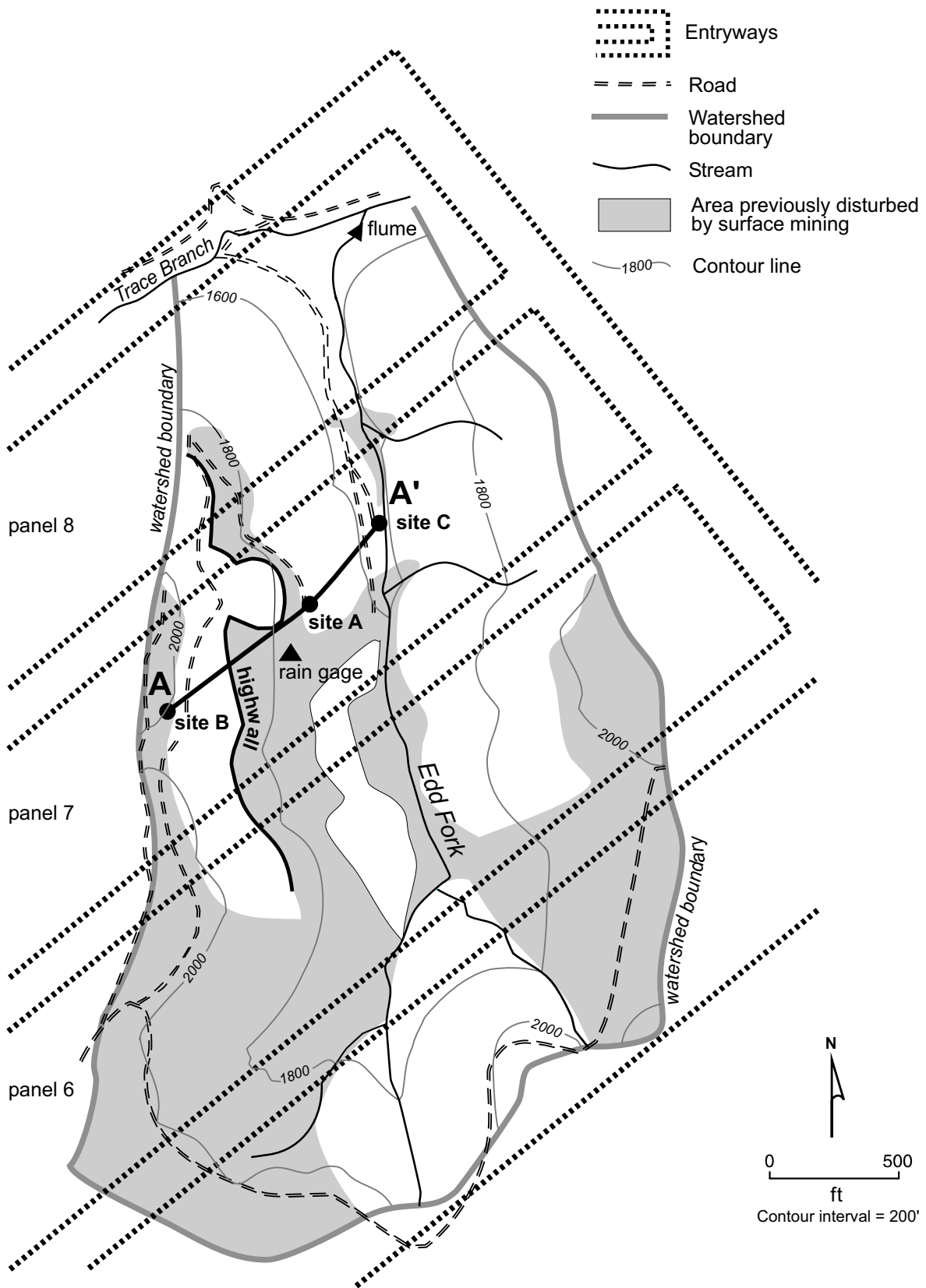


Figure 3. Locations of monitoring sites in the Edd Fork watershed used in the pre- and during-mining project phases. A–A' is the line of cross sections shown in Figures 4–5. (From Minns and others, 1995, Fig. 6.)

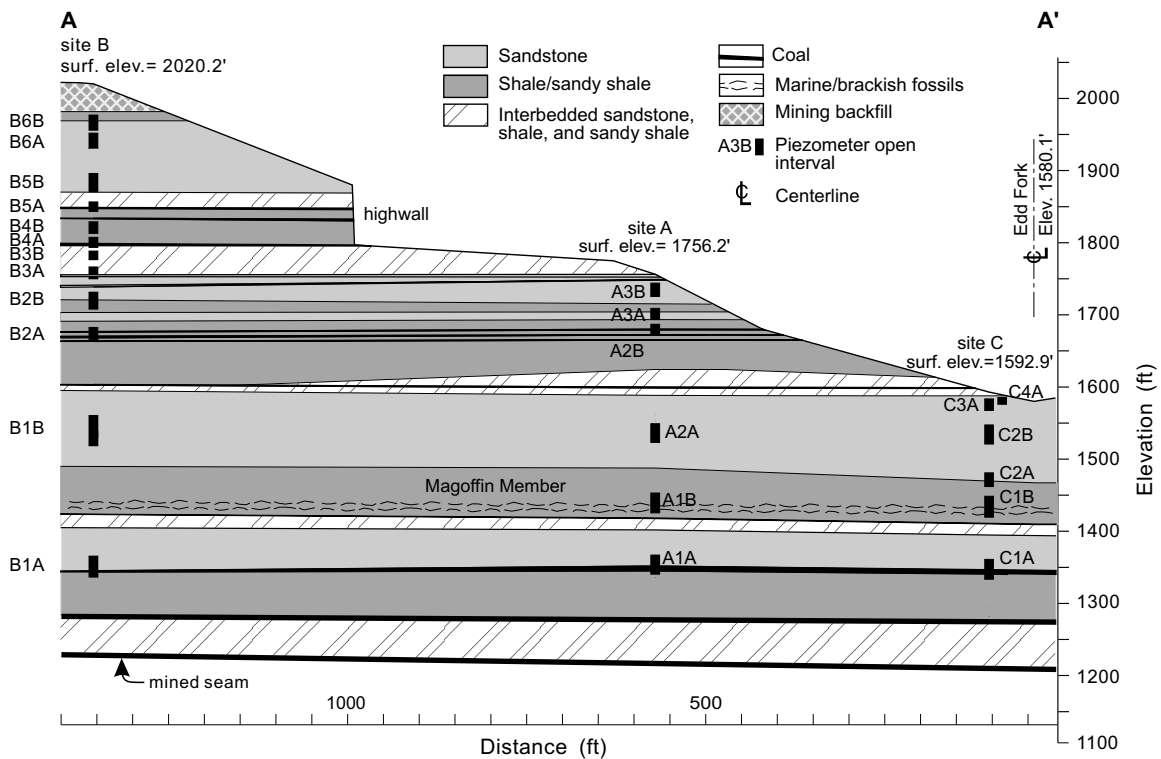
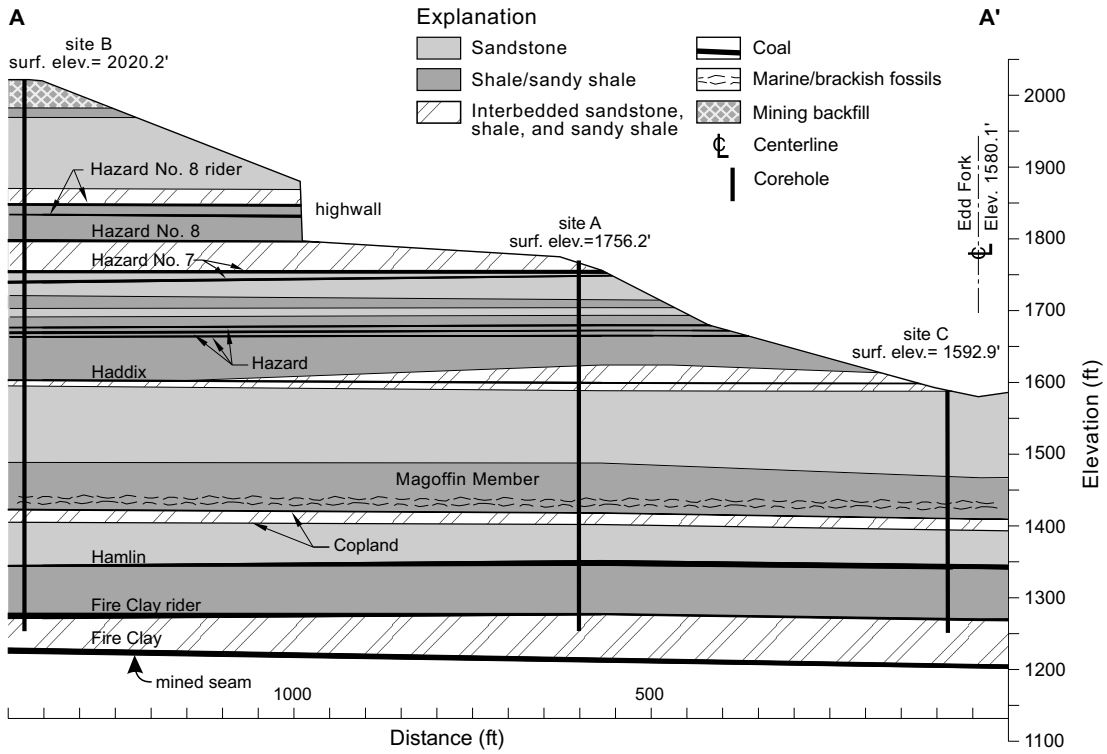


Figure 5. Locations of piezometers installed over panel 7, used in the pre- and during-mining project phases (from Minns and others, 1995, Fig. 12).

(Fig. 6). The shallow-fracture zone is made up of highly fractured strata that parallel the land surface to a depth of 50 or 60 ft. The elevation-head zone, located above drainage, is defined as the region where the head in a piezometer is approximately equal to the elevation of the midpoint of the piezometer's open interval. The pressure-head zone extends downward from the base of the elevation-head zone (or the shallow-fracture zone where the elevation-head zone is absent near valley bottoms). The study area can also be divided into two distinct freshwater geochemical facies. Shallow water is a calcium-magnesium-bicarbonate-sulfate type, and deeper water is a sodium-bicarbonate type (Fig. 6). See Minns and others (1995) for a more thorough description of the geochemical facies.

**A Model of Subsidence Effects.** Fracturing and sagging of strata caused by subsidence over mined panels generally lead to increases in hydraulic conductivity and storativity that can alter ground-water flow patterns. In many cases, wells, springs, and surface streams are affected. Coe and Stowe (1984) developed a hydrologic model of subsidence zones resulting from long-wall mining. The area immediately above the mined panel caves into the void created by the extraction of

the coal. This completely caved rubble zone extends above the mined panel as much as four to six times the extracted thickness.

Above the totally caved zone, a transitional zone of highly fractured rock can reach as much as 30 to 60 times the extracted thickness above the base of the void. This zone is characterized by extensive vertical fracturing and some massive block-type caving. Wells completed in either of the fractured zones normally fail because water can rapidly drain directly to the mine works. Little recovery of water levels can be expected until the mine is allowed to flood after the completion of mining.

If the mine is at sufficient depth, there may be an additional zone above the extensively fractured bedrock in the subsidence trough. Most of the rock movement in this zone is apparently minor horizontal slippage between strata. As a result, the strata in this zone tend to act as a "composite beam," and the integrity of low-permeability layers is generally maintained during subsidence. These intact layers tend to limit the downward movement of ground water to the mine void and cause this zone to serve as an aquitard when it is present. Water levels in wells completed in this zone may temporarily decline slightly because of an increase in por-

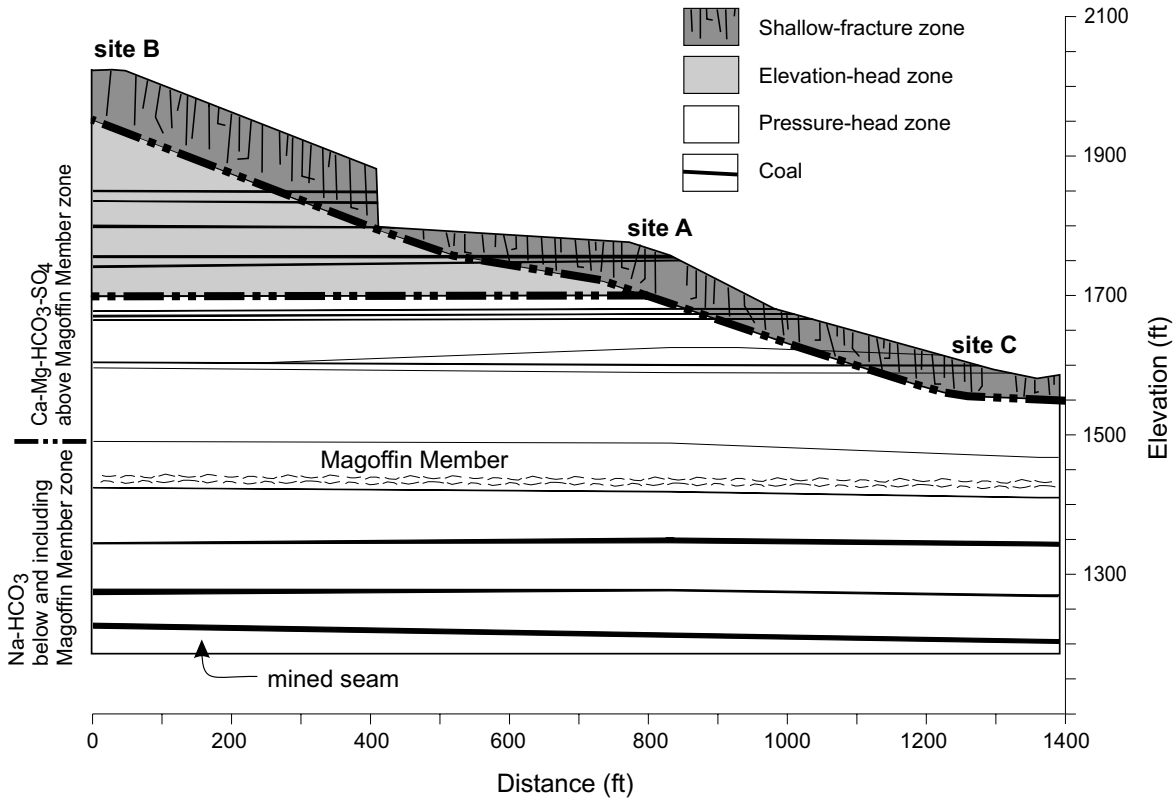


Figure 6. Physical and chemical ground-water zones in the Edd Fork watershed (after Minns, 1993).

rosity, but they often subsequently recover to near pre-mining levels.

Near-surface strata (generally at depths up to about 50 ft) are susceptible to fracturing and movement during subsidence. Although water levels in shallow wells often decline slightly because of increases in porosity and permeability associated with subsidence-induced fracturing, the fracturing may increase availability of ground water in some instances. This is a result of increased recharge of precipitation to the shallow ground-water system enhanced by the fracturing of the land surface during mine subsidence.

**Phase 2.** The during-mining phase (July 1993 through mid-September 1994) commenced approximately when the longwall mine entered the Edd Fork watershed in panel 4 and concluded with the completion of mining in panel 8 (see Figure 2). The existing network was used to monitor hydrologic response to mining, which was varied, as would be expected in a complex flow system. All water-level measurements before and after mining were taken relative to the top of the piezometer casing. Water levels measured in piezometers after the mine face passed beneath them in panel 7 do not represent their true elevation. Approximately 4.5 and 7.5 ft of surface subsidence occurred at the two sites on the mountain (sites A and B) and valley bottom (site C), respectively, as the mine face passed beneath panel 7. Piezometer casings remained attached to the rock into which they were grouted, and many casings sheared and failed at depth when the mine face passed, indicating that the wells reacted with the rock and not as independent entities with regard to rock subsidence. Therefore, for simplicity and in order to relate water levels to pre-mining hydrostratigraphic position, water-level elevations taken after the passage of the mine face in panel 7 and presented in hydrographs and charts do not reflect true elevation, but are relative to pre-mining stratigraphic position.

Responses to mining in adjacent panels 5 and 6 were recorded in 16 different piezometers. Water levels in five piezometers (B6A, B3A, B4A, C2A, and C2B) were higher immediately after mining of panel 6 was completed than they were before mining. Water levels in the remaining 11 piezometers generally were lower after mining of panel 6 was completed.

Undermining of the piezometers, located above panel 7, had the most widespread and dramatic effects; 20 of 24 piezometers responded in some manner. Fifteen piezometers either had lower water levels or went dry, and 13 of the 24 piezometers eventually failed structurally. The only piezometer with a higher water level after mining was piezometer B6A, a piezometer in the shallow-fracture zone, located in the ridge-capping

sandstone. This piezometer was dry until the mine face passed by on the adjacent panel 6. Only one piezometer (B4A) responded to mining in panel 8 (its water level declined as the mine face passed by), but the majority of the piezometers had already failed or experienced a decline in water levels as a result of previous undermining or mining in panel 6.

Piezometers in which water level changed during mining of panel 7 were in conductive coal beds or in fractured intervals. There were no observable water-level changes in piezometers completed in relatively impermeable strata such as shale (the Magoffin Member, for example).

All but one of the 13 piezometers that failed were completed in holes that apparently extended down into the zone of deep fracturing present over the mine void. Piezometer B6B, the exception, was completed near the surface in sandstone. Indications are that the zone of deep fracturing resulting from mine collapse extends approximately 450 ft upward (60 times the extracted coal thickness), which is near the upper end of the range for documented deep fracturing reported by Coe and Stowe (1984). One stratigraphic interval in which piezometers consistently broke was the Hazard coal zone, which, at an elevation of approximately 1,675 ft, is about 450 ft above the mined-out seam (see Figure 4). Four of the 13 piezometers that failed (B1A, B1B, A1A, and A1B) were most likely connected through rock fractured by collapse during the active mining in the Fire Clay seam (Hazard No. 4), as evidenced by vacuums forming at piezometer heads after mining (Hutcheson and others, 2000b) (see Figure 5).

The Hazard coal zone, a 10-ft-thick zone of multiple coal beds, is apparently susceptible to mining-induced strain. Partial breaks in the time-domain reflectometry (TDR) cables at sites A and B were documented in the Hazard coal zone as the mine face passed underneath on panel 6. Water levels in the two piezometers completed in the same zone (A2B and B2A) also declined significantly during the period. Panel 7 mining resulted in cable breaks in front of the advancing face in the Hazard coal zone at sites A and B when the face was about 1,000 ft away from site A and more than 1,100 ft from site B. Piezometer casing broke at the depth corresponding to the Hazard coal in four piezometers (A2A, A2B, B1A, and B2A) as the mining passed under each site.

TDR cables broke in two intervals. Breakage in the Hazard coal zone, the only zone where complete breakage was recorded at depths greater than 50 ft, occurred well in advance of the active face at corresponding angles from 60 to 70° of vertical. All three TDR cables also broke within 50 ft of the surface as the mining passed under each site. The shallowest piezometer at

site B (B6B) also broke at a depth of about 50 ft as the mine face passed underneath the piezometer. Shallow rock breakage (less than 50 ft, which corresponds to the zone of surface fracturing) was associated with undermining, whereas breakage in the weak coal zone occurred well in advance of the mine face. Breaks in lower zones most likely occurred during undermining, but could not be detected because the TDR cables had already been severed near the surface.

The surface-water monitoring station on Edd Fork overlies panel 8. No distinct response was detected during mining in panels 5 through 7. Edd Fork went dry for the first time as the active face undermined the stream. Because of a lack of rainfall during that period, the immediate effects of mining on the surface water in the watershed are unclear.

Surface cracks were observed along roads and on bare areas of spoil in the watershed. These fractures appeared abruptly as the mine face passed. Measured fractures ranged from a few feet in length to nearly 100 ft. Some fracture traces that passed from bare areas into heavy vegetation and were no longer visible may be longer. Fracture widths varied from hairline cracks to spoil collapses that were 20 ft wide. Fractures were gen-

erally subparallel to panel direction or parallel to ground slope.

## METHODOLOGY

### Core Drilling and Pressure-Injection Testing

Approximately 1 year after mining began in panel 7, and 9 months after mining was completed, two new core holes were drilled in panel 7, and zones were pressure tested to determine hydraulic conductivity. Core logs are presented in Hutcheson and others (2000a). Core hole B-PM is located at the ridgetop site (site B), 30 ft southwest of the original core hole (CH-B). It was drilled through the Magoffin Member and Copland coal bed into the top of the underlying sandstone (Fig. 7). Core hole B-PM is 628 ft deep, terminating approximately 150 ft above the mined-out panel; poor drilling conditions, most likely induced by fracturing of rock during mining, prevented drilling any deeper. Core hole C-PM is located at the valley-bottom site (site C), about 100 ft closer to panel 8 than the original core hole (CH-C). It was drilled approximately 30 ft into the sandstone underlying the Magoffin Member (Fig. 7). Core hole C-PM is 232 ft deep, terminating about 160 ft above the mine, approximately 20 ft short of the target depth.

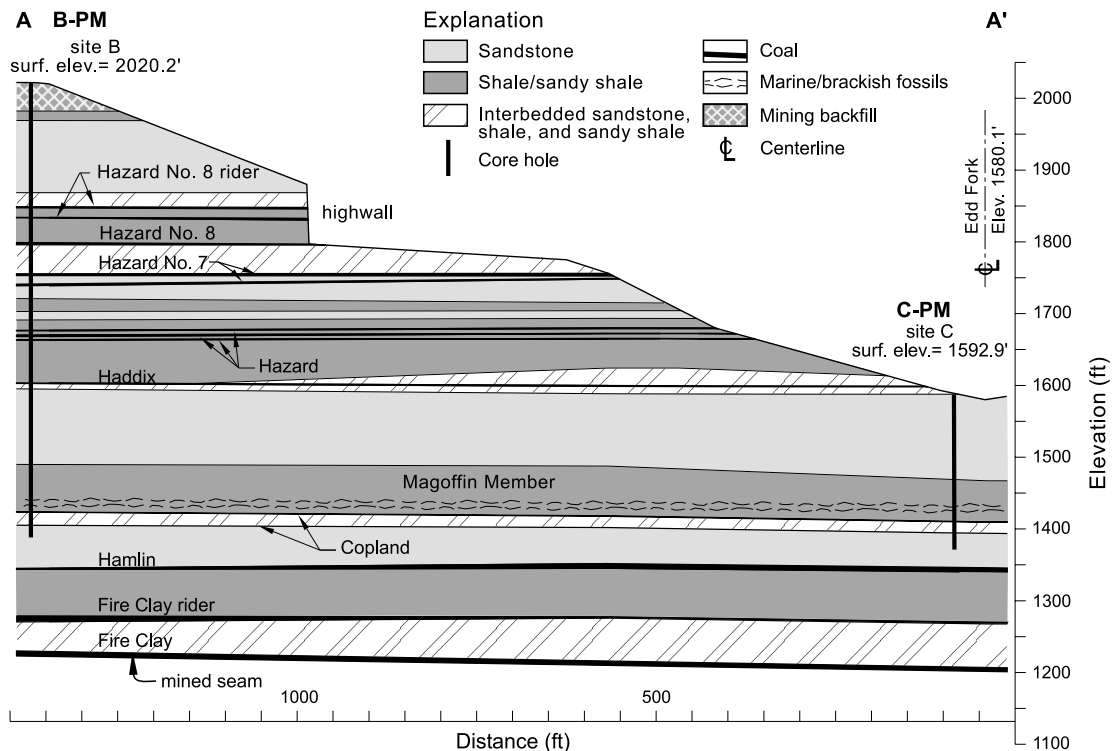


Figure 7. Locations of core holes B-PM and C-PM, shown in cross section through panel 7.

Voids estimated by drillers to be up to 8 in. wide, encountered in the target sandstone, prevented the core hole from being advanced farther.

Pressure-injection tests were conducted on core holes B-PM and C-PM immediately after completion of drilling. Ten-foot-long intervals along the entire length of the core holes were tested for hydraulic conductivity; these results are found in Hutcheson and others (2000a). The procedures used are the same as those used during phase 1 (Minns and others, 1995).

### Piezometers

Thirteen of the original 24 piezometers installed during phase 1 were destroyed by undermining. The piezometers that remained intact were A3A, A3B, B3A, B3B, B4A, B4B, B5A, B5B, B6A, C3A, and C4A. The riser pipes of the failed piezometers, except for the one for B6B, were sealed and abandoned in the summer of 1995.

Two new monitoring wells were installed in the summer of 1995 at site C in the valley bottom (wells C5 and C6 in Figure 8). They were designed to replace piezometers in two below-drainage horizons that were destroyed by undermining. Well C6 was completed in sandstone above the Magoffin Member, and well C5 was completed in the sandstone and coal seam below the

Magoffin Member; see Hutcheson and others (2000a) for well-construction details. Water levels were measured at monthly intervals in the new wells and the intact piezometers from phase 1. Figure 8 shows the locations of wells and piezometers used during this phase of the study. Water-level data collected from the time of installation through the post-mining period for sites with measurable water levels are presented in Hutcheson and others (2000a).

### Precipitation Measurement

A tipping-bucket rain gage connected to a digital data logger recorded precipitation in the Edd Fork watershed from July 1992 to July 1996. Daily totals are presented in Hutcheson and others (2000a).

### Streamflow Monitoring

Streamflow for Edd Fork was monitored at the flume installed at the mouth of Edd Fork throughout all phases, but after mining, storm runoff frequently deposited sediment in the flume, and the stream bed was often dry, so that base-flow data could not be collected most of the time after mining. Only storm-flow data were collected using the data logger. To augment the flume, an in-stream cross section was established in Edd Fork adjacent to site C in January 1996. Flow was mea-

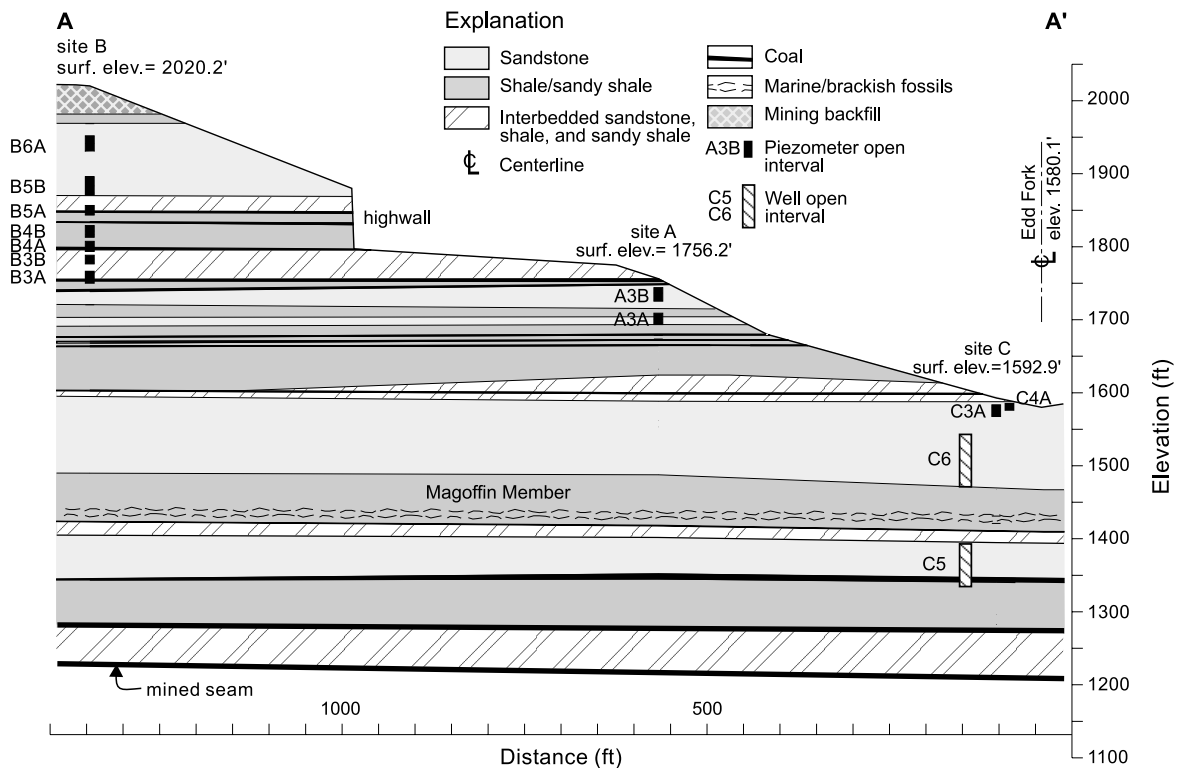


Figure 8. Locations of piezometers remaining intact after the completion of mining, and newly installed wells C5 and C6.

sured at monthly intervals using a water-velocity meter in cross section of the stream below site C.

## POST-MINING EFFECTS

### Core Drilling and Pressure-Injection Testing

Hydraulic conductivity in core hole CH-B (Fig. 9), determined by pressure-injection testing before mining, was compared with hydraulic conductivity in core hole B-PM (Fig. 10), determined by pressure-injection testing after mining, at site B. Similarly, hydraulic conductivity in core hole CH-C (Fig. 11), determined by pressure-injection testing before mining, was compared with hydraulic conductivity in core hole C-PM (Fig. 12), determined by pressure-injection testing after mining, at site C. Before mining, conductivity values varied depending on lithology. Before site B (ridgetop) was undermined, hydraulic conductivity values were generally  $1 \times 10^{-5}$  ft/min or less. Only above-drainage coal beds and fractured rocks had values greater than  $1 \times 10^{-5}$  ft/min. After undermining, hydraulic conductivity values ranged between  $1 \times 10^{-3}$  and  $1 \times 10^{-5}$  ft/min. After mining, there were no major differences between specific lithologies. The Magoffin Member, which consistently had low conductivity prior to undermining (approximately  $2 \times 10^{-7}$  ft/min), had post-mining conductivity values ranging between  $1 \times 10^{-6}$  and  $5 \times 10^{-4}$  ft/min.

Hydraulic conductivity values measured at site C prior to mining were generally less than  $1 \times 10^{-6}$  ft/min for unfractured strata. After undermining, hydraulic conductivity ranged from  $5 \times 10^{-3}$  to  $1 \times 10^{-4}$  ft/min. Post-mining conductivity measurements for the Magoffin Member were lower than for other strata in the core hole. The Magoffin Member was nevertheless two to three orders of magnitude more conductive after undermining than prior to mining (approximately  $1 \times 10^{-4}$  ft/min after mining compared to  $4 \times 10^{-6}$  before mining). The lower part of core hole C-PM, represented by highly fractured and void-filled sandstone, was 1,000 times more conductive after undermining than prior to undermining (about  $1 \times 10^{-3}$  ft/min after mining compared to  $6 \times 10^{-6}$  ft/min before mining).

Table 1 gives maximum, minimum, and average hydraulic-conductivity values, measured before and after mining. Fractured rocks have similar mean values both before and after mining ( $4 \times 10^{-4}$  before mining and  $3 \times 10^{-4}$  after mining). Fractures shallower than 100 ft that were found before mining most likely represent the shallow-fracture zone found throughout the Eastern Kentucky Coal Field (Kipp and Dinger, 1991; Minns, 1993). For all lithologies, average hydraulic-conductivity values were 10 to 100 times greater after mining than before mining.

### Fractures Observed in Core

Core samples obtained after mining showed evidence of mining-induced fracturing, whereas cores obtained before mining did not. Fracture counts were made by visually observing core immediately after it was removed from the core barrel. High-angle fractures, nearly absent in cores obtained prior to mining (one in core hole CH-B and one calcite-filled fracture in core hole CH-C), were common in cores obtained after mining. Approximately 58 fractures were observed in the ridgetop core hole B-PM, drilled after mining. Twenty-seven fractures were counted in core hole C-PM to a depth of 193 ft. Beyond this depth, open voids and numerous fractures were encountered, and core loss was common. Drilling was terminated at 232 ft when the bit would not advance farther. In both holes, the Magoffin Member appeared to be more fractured than surrounding strata.

### Water Levels

Eleven of the original 24 piezometers, as well as the two new monitoring wells, were monitored through June 1996. Piezometers A3A, A3B, B3B, B5B, and C3A, as well as newly installed well C5, were dry for 1½ years following undermining.

Six sites (piezometers B3A, B4A, B4B, B5A, B6A, and newly constructed well C6) contained measurable amounts of water. Depth of installation ranged from 92 ft for B6A to 270 ft for B3A. Piezometers B3A, B4A, and B5A are located in coal beds in the upper ridge area (site B). Piezometer B6A is located in the ridge-capping

**Table 1.** Summary of combined pre- and post-mining hydraulic conductivity data.

	Pre-Mining Samples	Post-Mining Samples	Pre-Mining Maximum Value	Post-Mining Maximum Value	Pre-Mining Minimum Value	Post-Mining Minimum Value	Pre-Mining Average Value	Post-Mining Average Value
Natural fracture	10	NC	$4.0 \times 10^{-3}$	NC	$2.0 \times 10^{-5}$	NC	$4.0 \times 10^{-4}$	NC
Mining fracture	NA	41	NA	$3.0 \times 10^{-3}$	NA	$8.0 \times 10^{-7}$	NA	$3.0 \times 10^{-4}$
Coal (below drainage)	13	5	$8.0 \times 10^{-6}$	$3.0 \times 10^{-3}$	$2.0 \times 10^{-7}$	$1.0 \times 10^{-7}$	$8.0 \times 10^{-7}$	$6.0 \times 10^{-5}$
Coal (above drainage)	11	7	$2.0 \times 10^{-4}$	$1.0 \times 10^{-3}$	$1.0 \times 10^{-6}$	$1.0 \times 10^{-7}$	$9.0 \times 10^{-5}$	$1.0 \times 10^{-4}$
Sandstone	45	31	$3.0 \times 10^{-5}$	$3.0 \times 10^{-3}$	$2.0 \times 10^{-7}$	$6.0 \times 10^{-7}$	$1.0 \times 10^{-6}$	$2.0 \times 10^{-4}$
Shale/sandy shale	43	22	$6.0 \times 10^{-4}$	$8.0 \times 10^{-4}$	$3.0 \times 10^{-7}$	$8.0 \times 10^{-4}$	$4.0 \times 10^{-7}$	$8.0 \times 10^{-5}$
Interbedded	18	11	$6.0 \times 10^{-4}$	$3.0 \times 10^{-3}$	$3.0 \times 10^{-7}$	$1.0 \times 10^{-7}$	$2.0 \times 10^{-6}$	$5.0 \times 10^{-5}$

NC=not calculated  
NA=not available

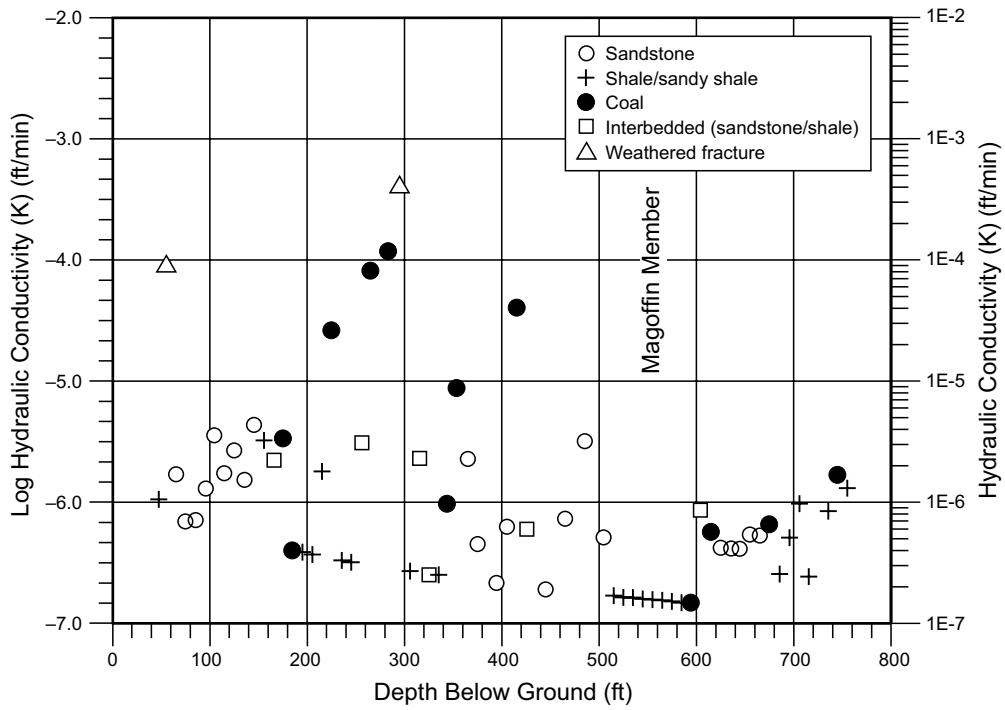


Figure 9. Hydraulic conductivity values for core hole CH-B, before mining.

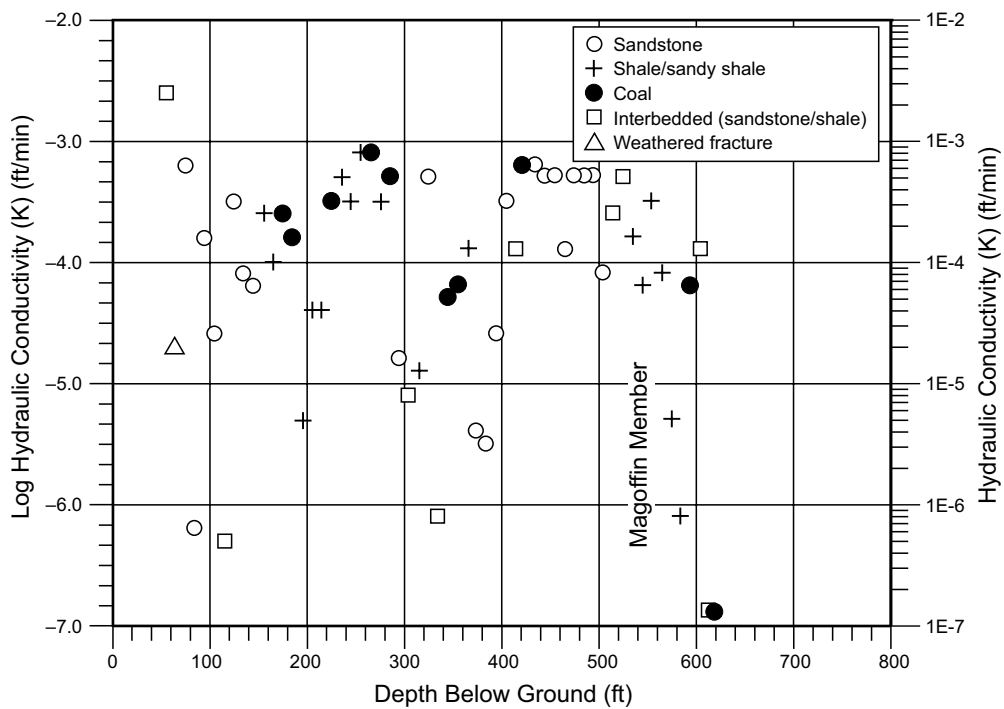


Figure 10. Hydraulic conductivity values for core hole B-PM, after mining.

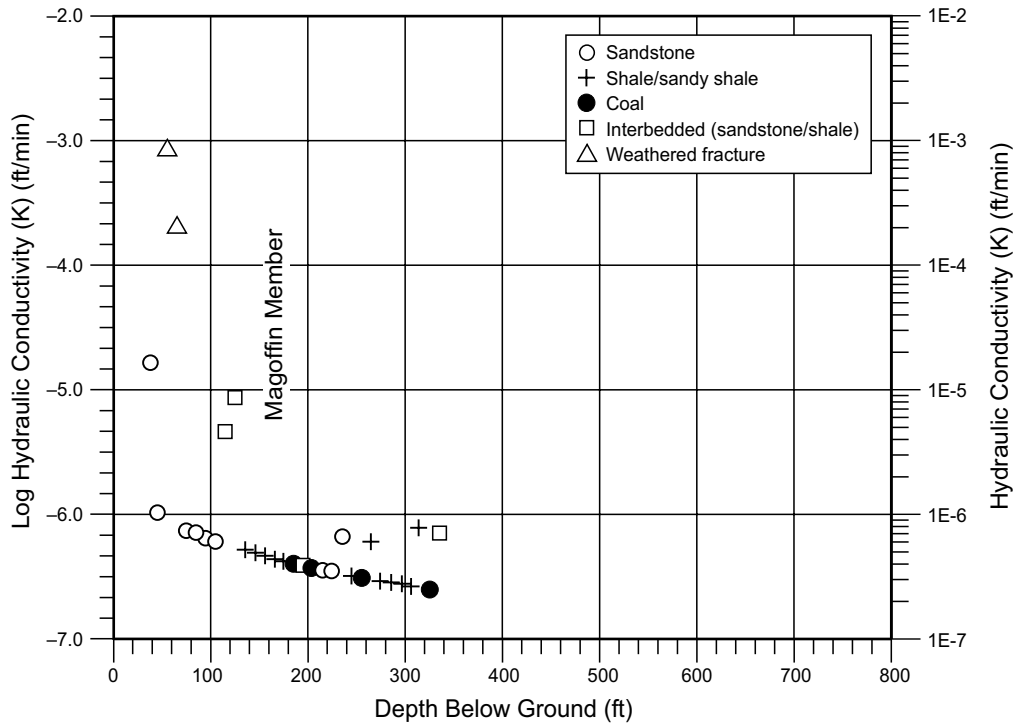


Figure 11. Hydraulic conductivity values for core hole CH-C, before mining.

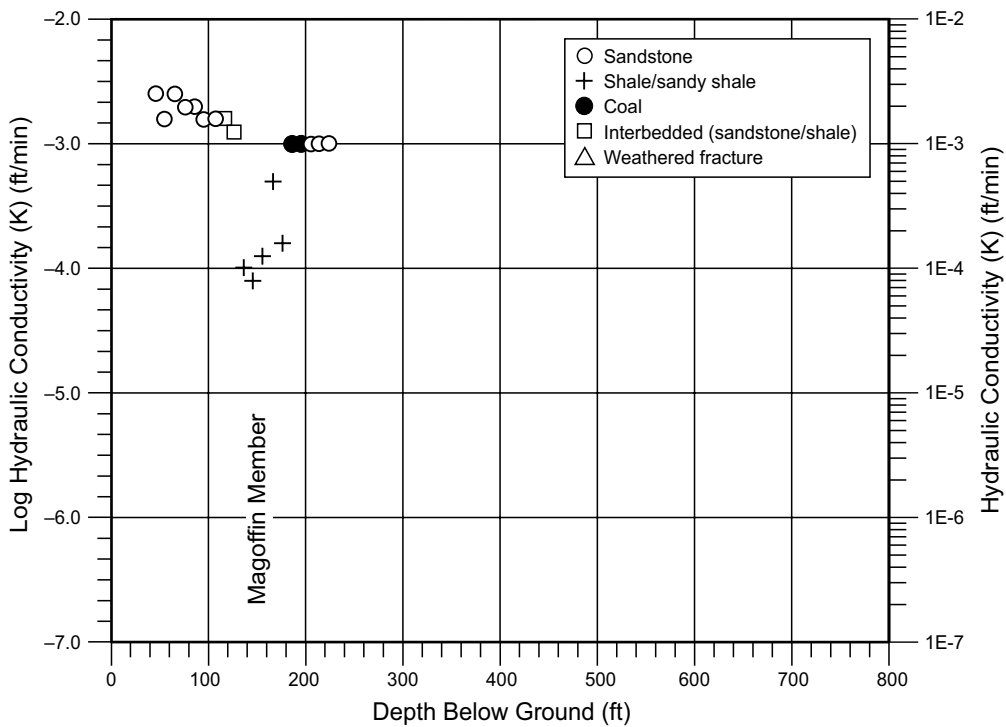


Figure 12. Hydraulic conductivity values for core hole C-PM, after mining.

sandstone at site B. Piezometer B4B was completed in a shale/sandy shale unit between wet coal seams (Fig. 8).

Water level in piezometer B5A, the shallowest coal-bed piezometer, gradually increased during the period following undermining, and appears to be recovering to near the pre-mining level (Fig. 13). This piezometer is located in the uppermost coal that crops out in the exposed highwall below site B (Hazard No. 8 rider). The spike in water level in February 1994, indicated in Figure 13, may be an erroneous measurement.

The next deepest coal-bed piezometer, B4A in the Hazard No. 8 coal, fluctuates with precipitation within the open interval over a 10-ft range (Fig. 14). This coal bed is approximately 3.5 ft thick and crops out at the base of the highwall.

Water levels in piezometer B3A have stabilized and are perched within the Hazard No. 7 coal bed at a level generally 2 or 3 ft lower than pre-mining levels (Fig. 15).

Piezometer B6A, completed in the ridge-capping sandstone, was historically dry at an elevation of 1,931 ft prior to undermining in the watershed. This piezometer stabilized with a water level 4 ft above the bottom of the piezometer after mining (Fig. 16). Monthly measurements indicate that this piezometer goes dry in response to lack of rainfall.

Water level in piezometer B4B, located in a sandstone between two coal beds, was up to 29 ft higher after mining than before (Fig. 17). Prior to mining, water levels were within the screened interval, but after mining the water level has risen as much as 17 ft above the open interval. Water levels in this piezometer drop during dry periods.

A spring, located in a near-vertical crack in the Hazard No. 8 coal, in the highwall between sites A and B (Fig. 18), was first observed after mining in March 1995. This spring flowed consistently (estimated at 5 gal/min) during the remainder of the monitoring period.

The water-level recovery and increases in water levels for the site B piezometers, in conjunction with the flow from the newly created spring, indicate that water is moving through the upper ridge more rapidly after mining than prior to mining. Whether or not there is more water available is uncertain, but undermining has undoubtedly created additional pathways for groundwater recharge and movement in the upper 200 ft of the ridge-capping lithologies. The creation of a lower aquiclude zone, most likely characterized by horizontal slippage between beds during mining (Coe and Stowe, 1984) is supported by the fact that piezometers in the upper zone did not fail and that water levels were either maintained during undermining or recovered

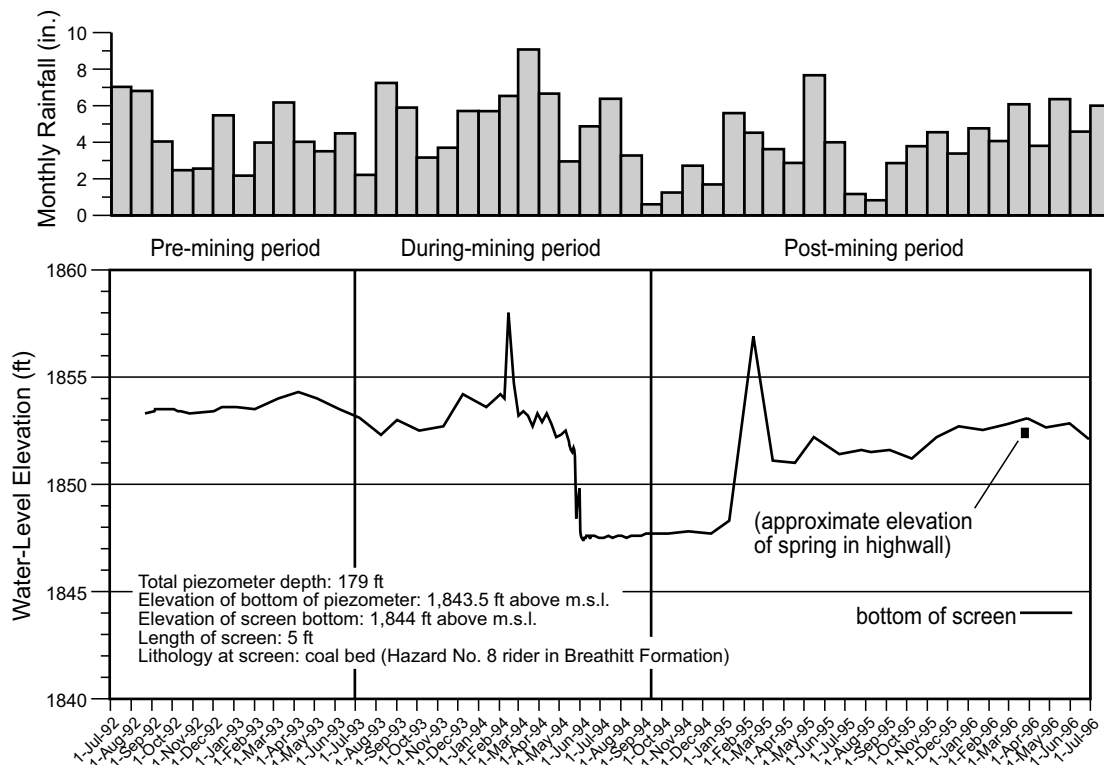


Figure 13. Hydrograph for piezometer B5A, in the Hazard No. 8 rider coal.

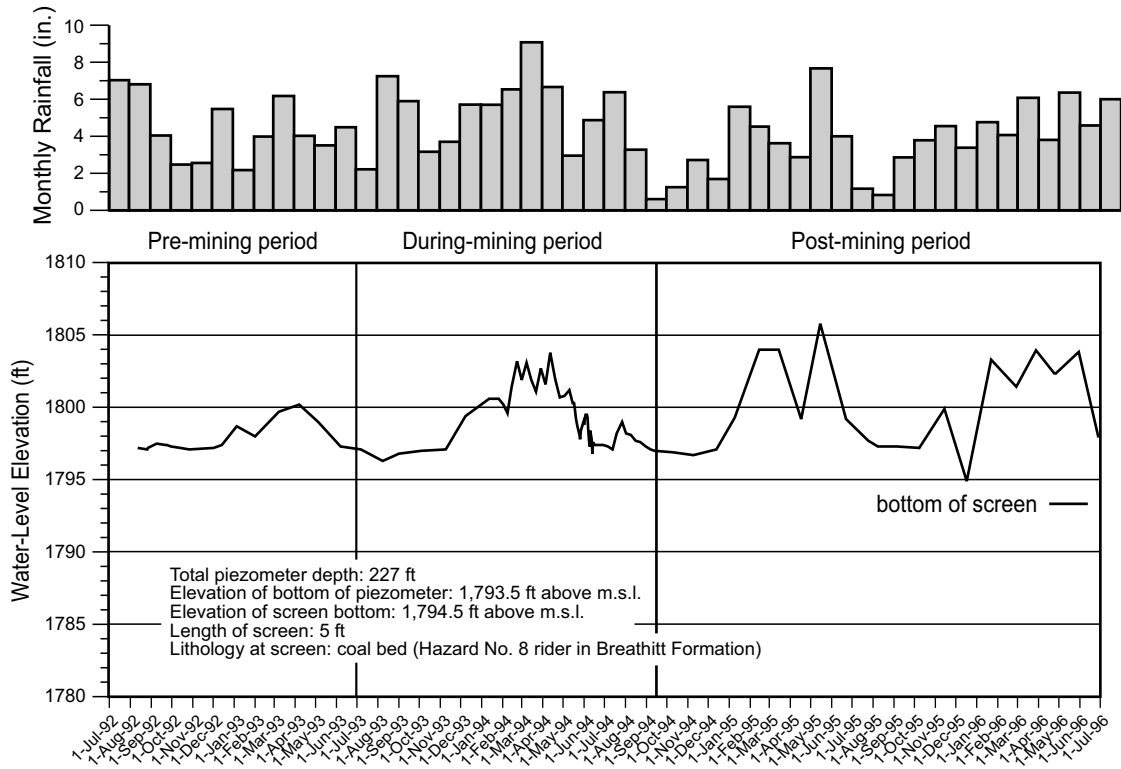


Figure 14. Hydrograph for piezometer B4A, in the Hazard No. 8 coal.

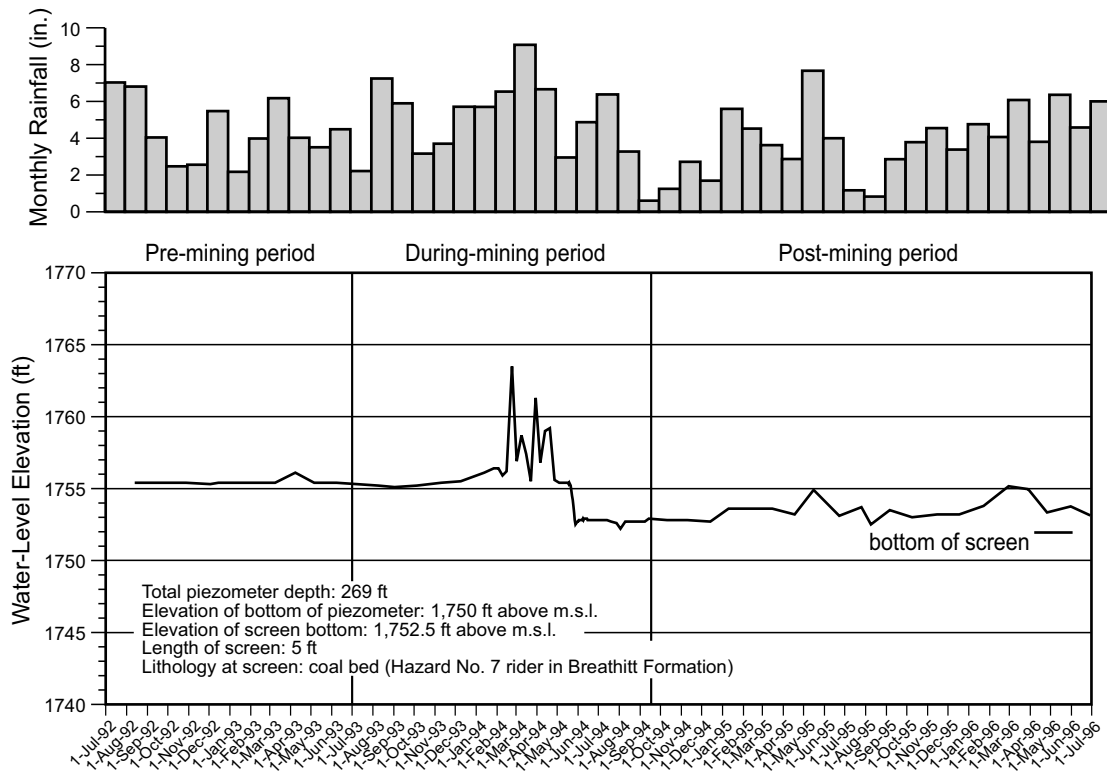


Figure 15. Hydrograph for piezometer B3A, in the Hazard No. 7 coal.

Post-Mining Effects

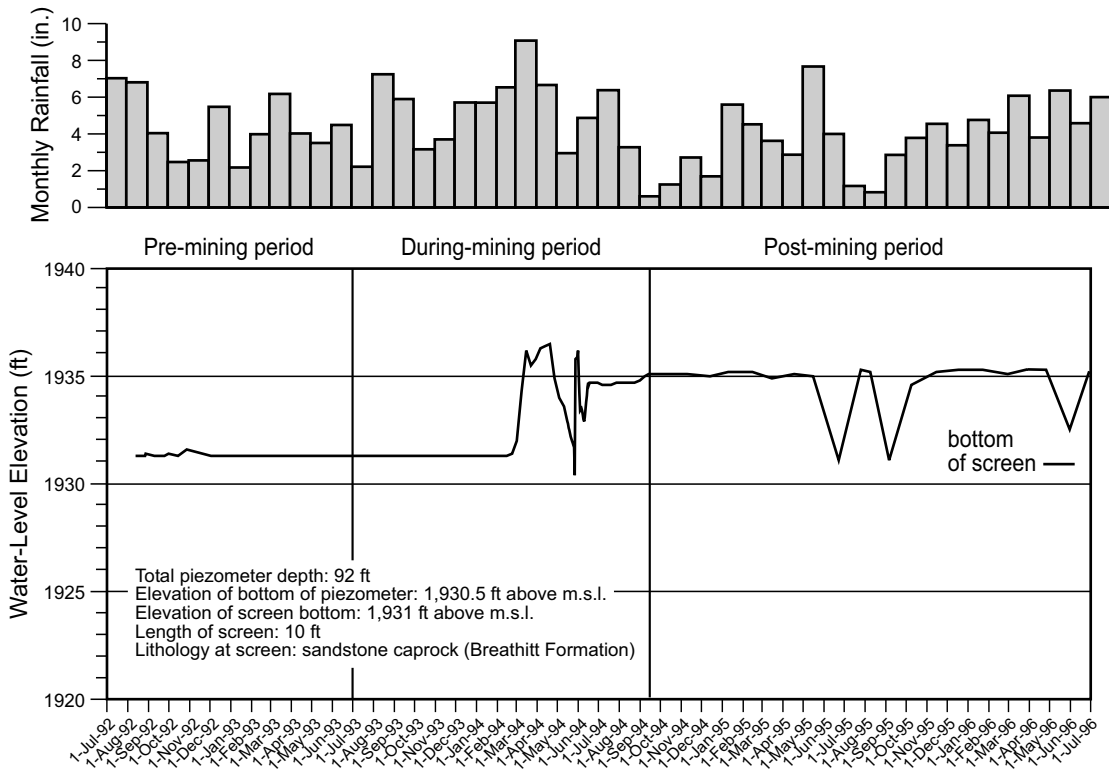


Figure 16. Hydrograph for piezometer B6A, in the ridge-capping sandstone.

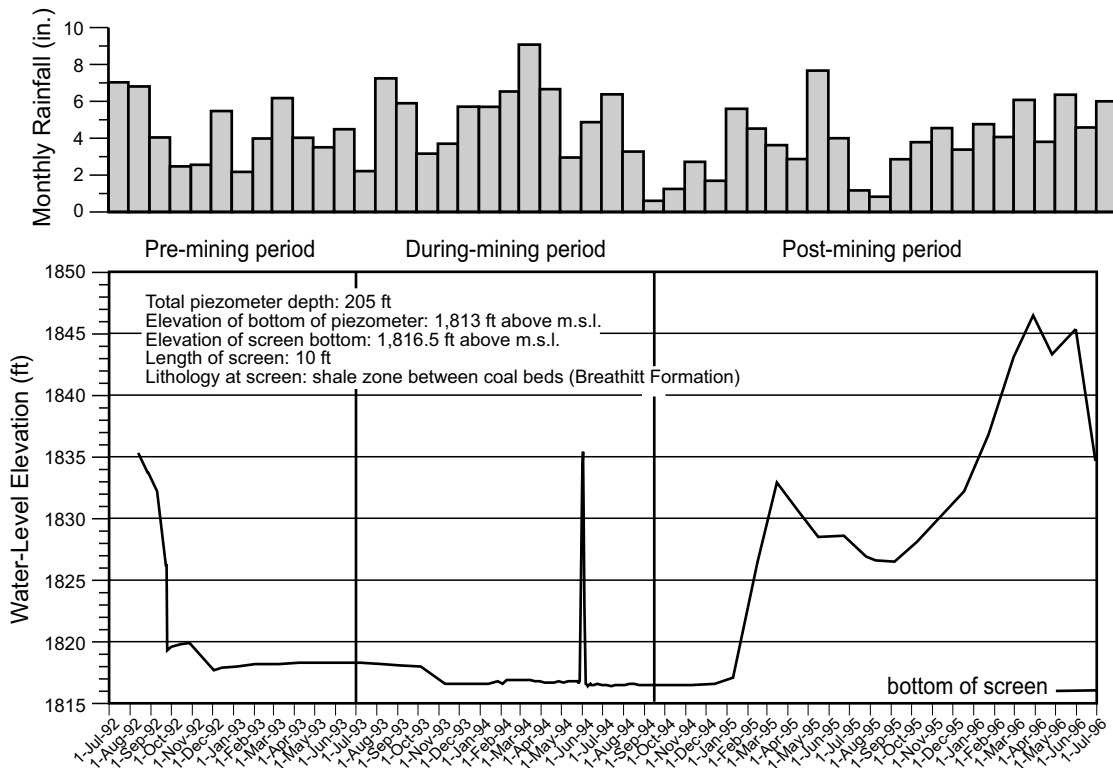


Figure 17. Hydrograph for piezometer B4B, in a sandstone between two coal beds.

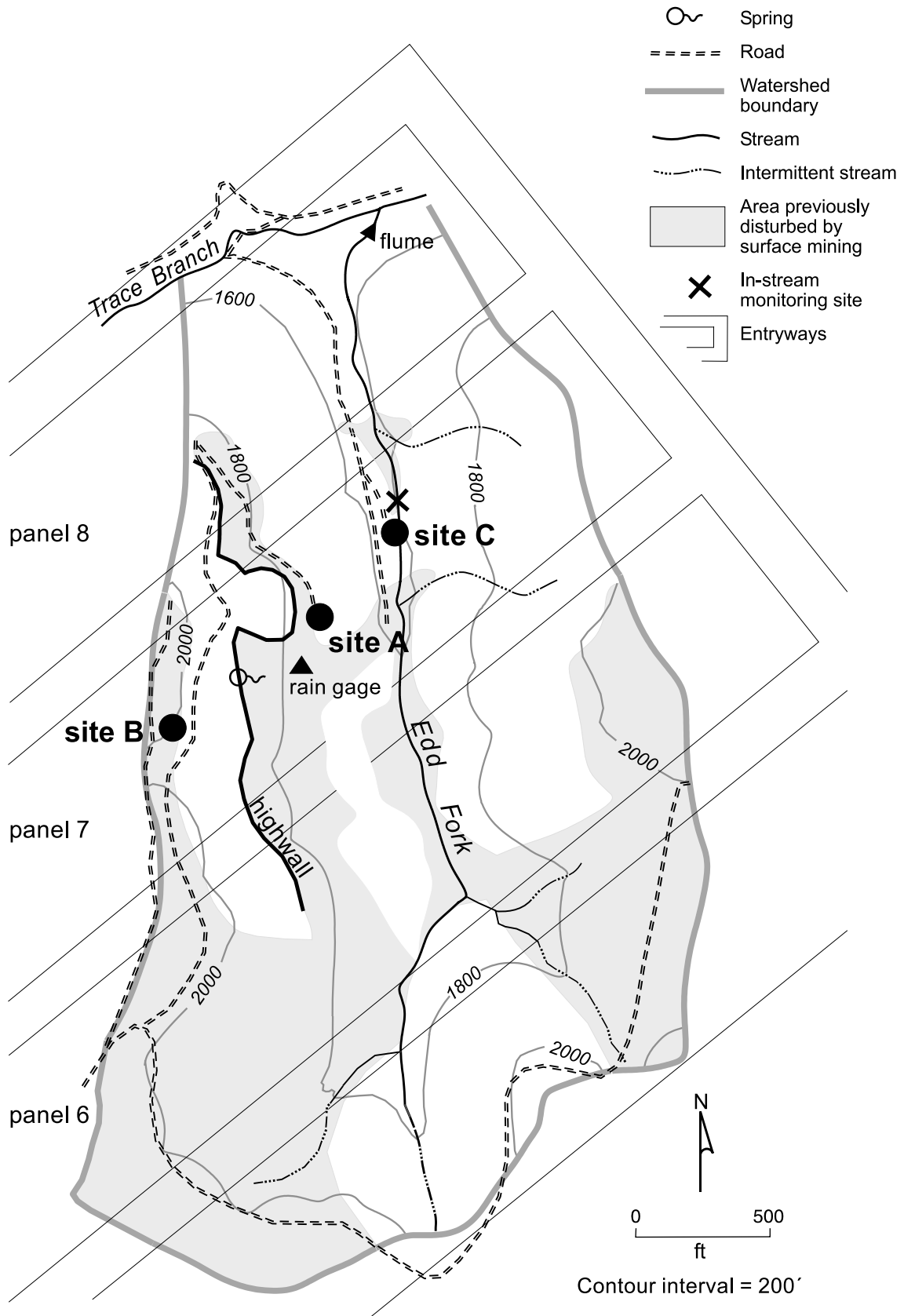


Figure 18. Locations of post-mining monitoring sites in the Edd Fork watershed.

shortly afterward. Deeper piezometers in the zone of deep fracturing did fail (Coe and Stowe, 1984).

The other water-level monitoring points are the newly constructed wells C5 and C6 and the previously installed piezometer C4A. Wells C5 and C6 are located in the valley-bottom sandstone that crops out at the surface (Fig. 8). This sandstone is underlain by the Magoffin Member, which functioned as a leaky confining unit prior to mining. Cores recovered after mining indicate that the sandstone unit in which these two wells were completed contains fractures, which probably control water levels in the sandstone. Water levels in piezometer C4A and well C6 and observed flow in Edd Fork indicate that water levels in the sandstone overlying the Magoffin Member recovered within a few months after undermining. Shallow piezometer C4A exhibited low water levels during the 3 months following completion of mining on panel 7 (September, October, and November 1994) (Fig. 19). Surface flow in Edd Fork adjacent to site C was nonexistent during the same period. Surface flow had resumed and water level in C4A had rebounded by the December 1994 sampling date. Periods of low water levels in piezometer C4A and Edd Fork coincided with low rainfall.

Well C6, constructed 10 months after the completion of undermining in the watershed, began to accumulate water during the fall of 1995, approximately 2

months after installation (Fig. 20). The highest water level reached during the post-mining monitoring period was in March 1996, when the well contained about 20 ft of water. Water levels began to decline in April 1996. Although pressure-injection tests indicate that the Magoffin Member is fractured as a result of mining, they also indicate that the hydraulic conductivity of the Magoffin Member is still lower than for the overlying sandstone, and the Magoffin may still retard downward leakage into the highly fractured and dewatered strata below it.

Well C5, drilled after mining into the strata below the Magoffin Member, stayed dry for the year following installation.

### Streamflow in Edd Fork

Edd Fork, at both the flume and the in-stream observation point at site C (Fig. 18), stayed dry until approximately 2 months after completion of active mining in panel 8. By mid-December 1994, flow had resumed at the in-stream station at site C. Flow was noted at the flume only during rainfall. Surface base flow appeared to diminish about 200 ft upstream from the flume near the center of panel 8.

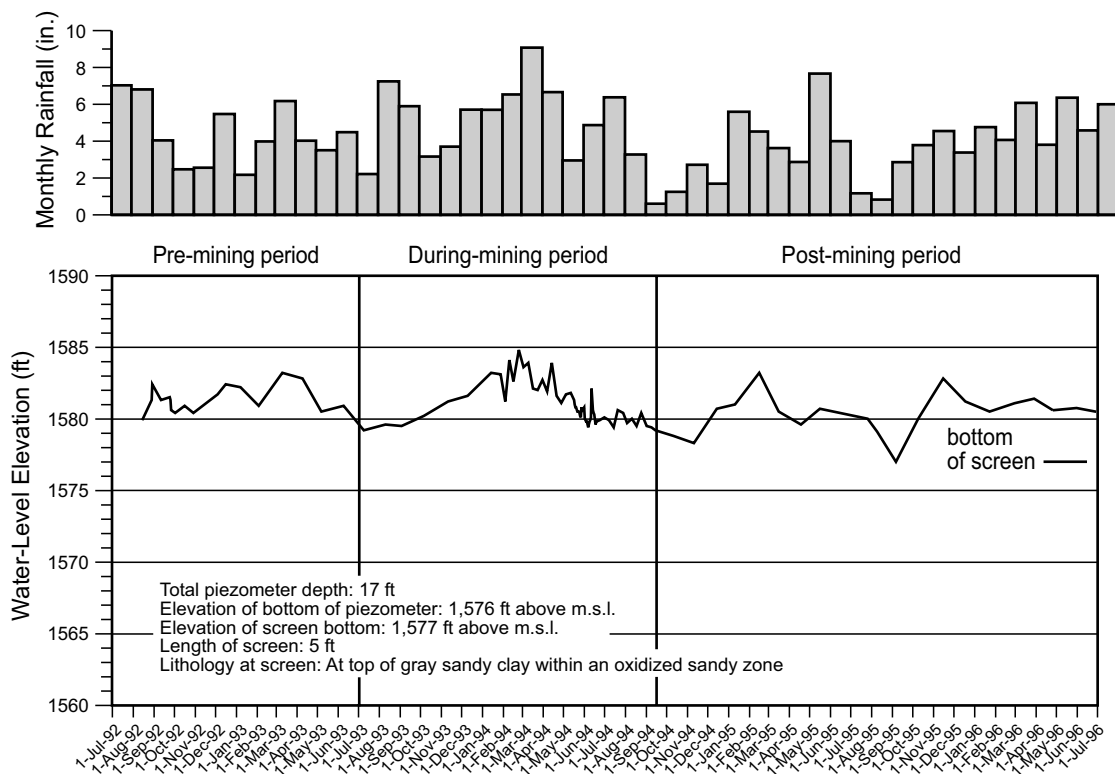


Figure 19. Hydrograph for shallow piezometer C4A.

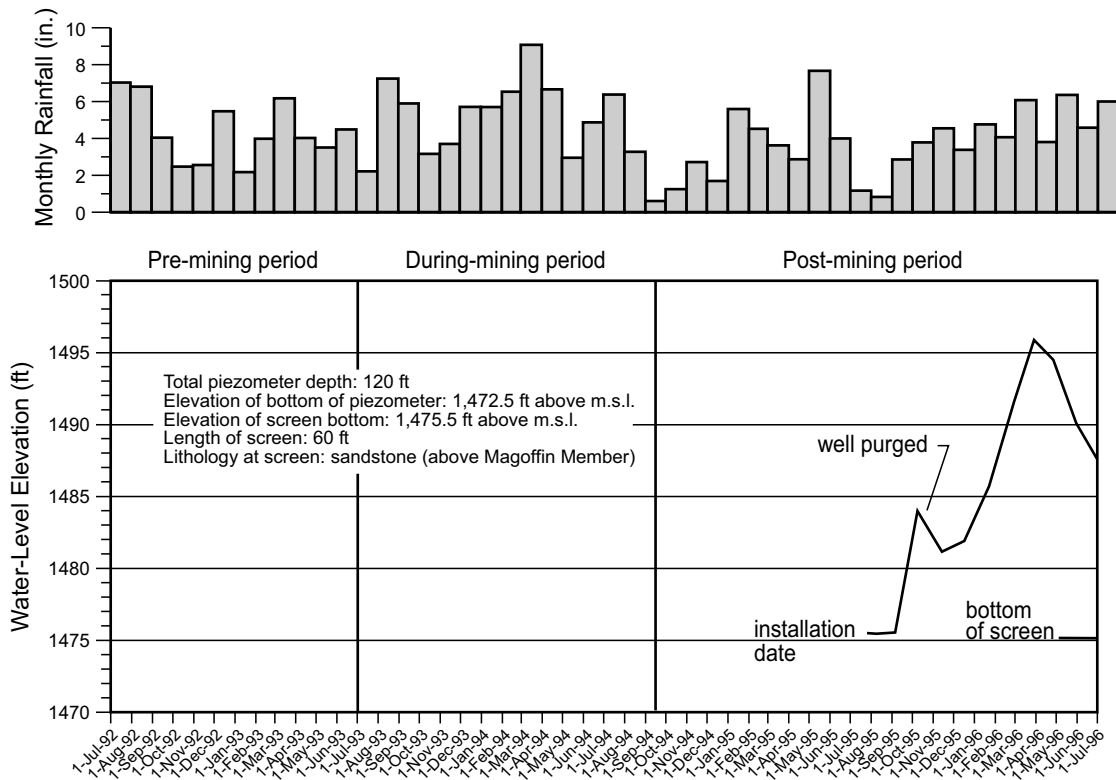


Figure 20. Hydrograph for sandstone well C6.

## CONCLUSIONS

- Physical failure of piezometers during the mining phase, core drilling after mining, and the movement of air into deeper piezometers at sites A and B after mining indicate that extensive fracturing occurred to a height of 450 ft above the mine (elevation 1,650 ft), approximately 60 times the extracted coal-seam thickness. This is equivalent to the maximum limit of the zone of increased secondary permeability reported by Coe and Stowe (1984).
- Core drilling and pressure-injection tests indicate that the strata are more fractured after undermining. Hydraulic conductivity values measured after mining were 10 to 100 times greater on average than measurements made before mining.
- After mining, no major differences in hydraulic conductivity were observed between specific lithologies (major differences had been measured prior to mining).
- A zone of rock at least 200 ft above the mined coal was dewatered beneath Edd Fork valley, as indicated by the lack of water in well C5 in the valley bottom. The extent of this dewatering beneath the valley side (site A) and ridgetop (site B) cannot be accurately determined from the available data.
- Water levels in ridgetop piezometers (site B) fluctuated slightly more after mining than they did before mining, which indicates that the upper part of the ridge is more hydraulically connected to surface recharge since mining took place. This connection is most likely the result of fracturing in the near-surface caused by the collapse of the mine.
- The presence of ground water in the shallower ridgetop piezometers (B6A, B5A, B4B, and B4A) suggests that an underlying aquitard zone developed during the mine-collapse process. This zone must somewhat retard the downward movement of ground water, which results in higher water levels in the post-mining phase.
- Along the valley-side slope (site A), natural, near-surface fracturing (Kipp and Dinger, 1991; Minns, 1993) prior to mining precluded the development of extensive water tables (Table 1 and Fig. 10 of Hutcheson and others, 2000b). The mine-collapse zone most likely intersects this near-surface fracture zone in the valley bottom and along the lower valley sides, and may divert ground water downward into the mined-out area.
- The shallow sandstone unit above the Magoffin Member in the valley bottom (site C) has been fracture-enhanced by mining. Water levels declined

after mining, but were reestablished within the following year at well C6 and piezometer C3A.

- The Magoffin Member, although more conductive after mining than prior to it, still retards downward ground-water movement at site C, based on water levels in well C6.
- Observed fractures and the fact that well C5 is dry indicate that the strata below the Magoffin Member are most likely draining directly to the mine. This zone would not be expected to recover as long

as the mine is draining or being pumped dry, as is the situation at present.

- Edd Fork resumed surface flow at site C, 2 months after completion of undermining in panel 8, about the same time that the water level recovered in shallow piezometer C4A. The stream had a tendency to dry up in the fall of 1995. Edd Fork did not sustain base flow at the flume, and flow seemed to diminish about 200 ft upstream of the flume, near the centerline of panel 8.

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