University of Kentucky
UKnowledge

Kentucky Geological Survey Report of Investigations

Kentucky Geological Survey

1995

Effects of Longwall Mining on Hydrogeology, Leslie County, Kentucky Part 1: Pre-Mining Conditions

Shelley A. Minns
University of Kentucky

James A. Kipp
University of Kentucky, jim.kipp@uky.edu

Daniel I. Carey
University of Kentucky, carey@uky.edu

James S. Dinger
University of Kentucky, james.dinger@uky.edu

Lyle V. A. Sendlein
University of Kentucky

Repository Citation

Minns, Shelley A.; Kipp, James A.; Carey, Daniel I.; Dinger, James S.; and Sendlein, Lyle V. A., "Effects of Longwall Mining on Hydrogeology, Leslie County, Kentucky Part 1: Pre-Mining Conditions" (1995). *Kentucky Geological Survey Report of Investigations*. 49.
https://uknowledge.uky.edu/kgs_ri/49

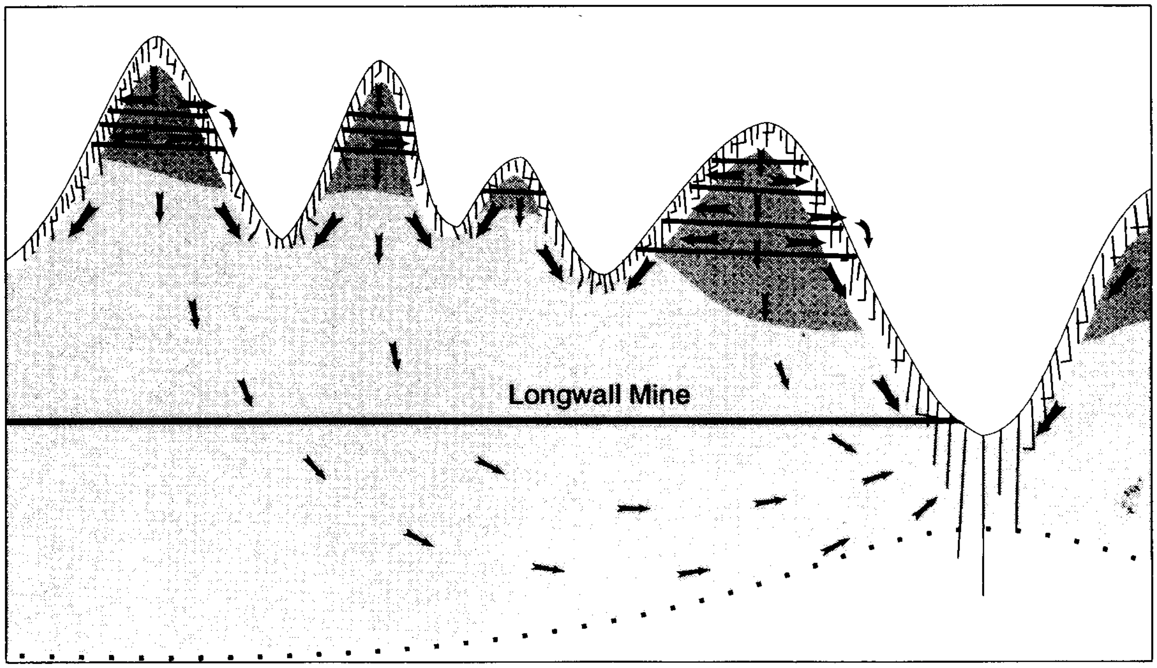
0075-5591

Kentucky Geological Survey
Donald C. Haney, State Geologist and Director
UNIVERSITY OF KENTUCKY, LEXINGTON

Effects of Longwall Mining on Hydrogeology, Leslie County, Kentucky

Part 1: Pre-Mining Conditions

Shelley A. Minns, James A. Kipp, Daniel I. Carey,
James S. Dinger, and Lyle V.A. Sendlein



REPORT OF INVESTIGATIONS 9
Series XI, 1995
https://doi.org/10.13023/kgs.ri09.11

DISCLAIMER

The Kentucky Geological Survey provides online versions of its publications as a public service. Publications are provided as Adobe PDF (portable document format) files. Hard-copy versions are available for purchase by contacting the Survey at:

Kentucky Geological Survey
Publication Sales Office
228 Mining and Mineral Resources Building
University of Kentucky
Lexington, Kentucky 40506-0107

Phone: 606-257-5500
Fax: 606-257-1147

Selected KGS reports published before 1999 have been scanned and converted to PDF format. Scanned documents may not retain the formatting of the original publication. In addition, color may have been added to some documents to clarify illustrations; in these cases, the color does not appear in the original printed copy of the publication. Every effort has been made to ensure the integrity of the text. KGS maps and charts are supplied either whole or in part and some are too large to be printed on most plotters. Open-file reports are reproduced from the best available copy provided by the author, and have not undergone KGS technical or editorial review.

The Kentucky Geological Survey disclaims all warranties, representations, or endorsements, expressed or implied, with regard to the information accessed from, or via, this server or the Internet.

KENTUCKY GEOLOGICAL SURVEY
Donald C. Haney, State Geologist and Director
UNIVERSITY OF KENTUCKY, LEXINGTON

EFFECTS OF LONGWALL MINING ON HYDROGEOLOGY, LESLIE COUNTY, KENTUCKY

Part 1: *Pre-Mining Conditions*

Shelley A. Minns, James A. Kipp, Daniel I. Carey,
James S. Dinger, and Lyle V.A. Sendlein

REPORT OF INVESTIGATIONS 9
https://doi.org/10.13023/kgs.ri09.11

Series XI, 1995

UNIVERSITY OF KENTUCKY

Charles T. Wethington, Jr., President Delwood C. Collins, Acting Vice President for Research and Graduate Studies Jack Supplee, Director, Fiscal Affairs and Sponsored Project Administration

KENTUCKY GEOLOGICAL SURVEY ADVISORY BOARD

Hugh B. Gabbard, Chairman, Richmond
Steve Cawood, Pineville
Larry R. Finley, Henderson
Kenneth Gibson, Madisonville
Wallace W. Hagan, Lexington
Phil M. Miles, Lexington
W. A. Mossbarger, Lexington
Henry A. Spalding, Hazard
Jacqueline Swigart, Louisville
Ralph N. Thomas, Owensboro
George H. Warren, Jr., Owensboro
David A. Zegeer, Lexington

KENTUCKY GEOLOGICAL SURVEY

Donald C. Haney, State Geologist and Director
John D. Kiefer, Assistant State Geologist for Administration

ADMINISTRATIVE DIVISION

Personnel and Finance Section:
James L. Hamilton, Administrative Staff Officer 11
Roger S. Banks, Account Clerk V

Clerical Section:
Jody L. Fox, Staff Assistant VII
Joyce Belcher, Staff Assistant VI
Juanita G. Smith, Staff Assistant V, Henderson Office

Publications Section:
Donald W. Hutcheson, Head
Margaret Luther Smath, Geologic Editor III
Terry D. Hounshell, Chief Cartographic Illustrator
Richard A. Smath, Geologist 111, ESIC Coordinator
Michael L. Murphy, Principal Drafting Technician
Gwenda K. Rulo, Drafting Technician
William A. Briscoe, 111, Publication Sales Supervisor
Shirley D. Dawson, Staff Assistant V

Geologic Data Center:
0. Barton Davidson, Geologist 11
Eugenia E. Kelley, Staff Assistant V
Frances A. Benson, Staff Assistant IV
Luanne Davis, Staff Assistant IV
Kimberly B. Stroth, Staff Assistant IV

GEOLOGICAL DIVISION

Coal and Minerals Section:
Donald R. Chesnut, Jr., Acting Head
Garland R. Dever, Jr., Geologist VII
Cortland F. Eble, Geologist V
David A. Williams, Geologist V, Henderson Office
Warren H. Anderson, Geologist IV
Gerald A. Weisenfluh, Geologist IV
Stephen F. Greb, Geologist III
Robert E. Andrews, Geologist I

Petroleum and Stratigraphy Section:
James A. Drahovzal, Head
Ronald L. Street, Associate Professor
Terence Hamilton-Smith, Geologist V
Patrick J. Gooding, Geologist IV
David C. Harris, Geologist IV
Brandon C. Nuttall, Geologist IV
Matthew Humphreys, Geologist 11
Gerald J. Kinsella, Geologist I
Thomas N. Sparks, Geologist I
Anna E. Watson, Geologist I
Robert R. Daniel, Laboratory Technician B
Theola L. Evans, Staff Assistant IV

Water Resources Section:
James S. Dinger, Head
James A. Kipp, Geologist V
Daniel 1. Carey, Hydrologist IV
James C. Currens, Geologist IV
David R. Wunsch, Geologist IV
Alex W. Fogle, Hydrologist III
Philip G. Conrad, Geologist 11
Gary K. Felton, Geologist 11
Dwayne M. Keagy, Geologist 11
Shelley A. Minns, Geologist 11
Wendy S. Romain, Program Coordinator
C. Douglas R. Graham, Geological Technician
Steven Kendrick, Geological Technician
Timothy D. Montowski, Geological Technician
Kevin J. Wente, Geological Technician

Computer and Laboratory Services Section:
Steven J. Cordiviola, Head
Richard E. Sergeant, Geologist V
Joseph B. Dixon, Systems Programmer
James M. McElhone, Sr. Systems Analyst Programmer
Henry E. Francis, Associate Scientist
Karen Cisler, Senior Research Analyst
Steven R. Mock, Research Analyst
Alice T. Schelling, Research Analyst
Mark F. Thompson, Research Analyst
Tammie J. Heazlit, Senior Laboratory Technician

CONTENTS

ILLUSTRATIONS

TABLES

EFFECTS OF LONGWALL MINING ON HYDROGEOLOGY
LESLIE COUNTY, KENTUCKY
PART 1: PRE-MINING CONDITIONS

Shelley A. Minns, James A. Kipp, Daniel I. Carey,
James S. Dinger, and Lyle V.A. Sendlein

ABSTRACT

An investigation of the hydrologic effects of longwall coal mining is in progress in the Eastern Kentucky Coal Field. The study area is located in a first-order watershed in southern Leslie County over Shamrock Coal Company's Beech Fork Mine (Edd Fork Basin on the Helton 7.5-minute quadrangle). Longwall panels approximately 700 feet wide are separated by three-entry gateways 200 feet wide. The mine is operating in the Fire Clay coal (Hazard No. 4); overburden thickness ranges from 300 to 1,000 feet. Mining in the watershed began in late summer 1993. Undermining of the instrumented panel (panel 7) is anticipated for summer 1994. This report documents pre-mining hydrogeologic conditions.

Three sites over panel 7 (ridge-top, valley-side, and valley-bottom settings) were selected for intensive monitoring. An NX core hole was drilled at each site to provide stratigraphic control for well installation, to evaluate fractures, to conduct pressure-injection tests, and to provide a borehole for installation of time domain reflectometry cables. A rain gage and flume were installed in the basin in summer 1992. Twenty-four monitoring wells, completed in July 1992, provide water-level and water-quality data on individual stratigraphic zones represented by the three well locations.

Interpretation of pre-mining conditions was used to develop a conceptual model of ground-water flow in the study basin. Three ground-water zones were identified on the basis of hydraulic properties. The shallow-fracture zone, a highly conductive region parallel to the ground surface, extends to a depth of 60 to 70 feet. The elevation-head zone includes the ridge interior, mostly above drainage, where total head consists of elevation head only. The pressure head zone, largely below drainage, is the region where total head is the sum of elevation head and pressure head. Two fresh-water geochemical facies are also present. Shallow ground water is a calcium-magnesium-bicarbonate-sulfate type, whereas ground water in the deeper regional system is sodium-bicarbonate type.

Anticipated effects from longwall mining include a decrease in water levels in the pressure-head zone. Temporary decreases are expected in the shallow-fracture zone as newly created void spaces subsequently fill. The elevation-head zone should not be greatly affected because it is predicted to be in the aquiclude zone.

INTRODUCTION

Loss or interruption of water supplies is a common concern of both mine operators and adjacent land owners. The coal industry, citizens' and environmental groups, State and Federal agencies, policy makers, and individuals need and desire information on the potential effects of mining on springs, surface streams, and water wells. As a public service agency, the Kentucky Geological Survey's mission is to research and provide information on such issues of public interest. Site-specific studies provide the detailed information needed to evaluate complex geologic, topographic, and hydrologic relationships.

This report summarizes pre-mining findings as of June 30, 1993, for an investigation of the hydrologic effect of longwall coal mining in eastern Kentucky. The initial impetus for the study came from the Hydrology Steering Committee formed to implement parts of the National Wildlife Federation settlement agreement with the U.S. Office of Surface Mining Reclamation and Enforcement (OSMRE) and the Kentucky Department for Surface Mining Reclamation and Enforcement (DSMRE). The settlement agreement directs that the hydrologic regime of Kentucky's coal fields be more fully characterized to assist the regulatory agency in meeting its hydrologic protection mandates. To achieve these goals, the Kentucky DSMRE contracted with the Kentucky Geological Survey (KGS) and the University of Kentucky Institute for Mining and Minerals Research (IMMR) to investigate the hydrogeologic impacts of below-drainage underground mining in the Eastern Kentucky Coal Field.

Longwall mining is characterized by rapid subsidence over the mined panel. Subsidence-induced fracturing and downwarping of strata generally increase hydraulic conductivity and storage in the affected rock. In many cases, wells, springs, and streams are affected; however, the horizontal and vertical extent of these impacts, as well as long-term implications, are poorly understood. Evaluation of potential mining impacts in the steep terrain characteristic of eastern Kentucky has been hampered by a general lack of knowledge of the behavior of the ground-water flow system. This study provides sufficient pre-mining characterization of the mined area so that future mining impacts in the study area can be evaluated with some certainty. The information provided should allow industry, regulators, and the public to make informed decisions on potential extent and duration of impacts.

After initial review of prospective study sites, a preliminary work plan was submitted to DSMRE in September 1990. This plan formed the basis for a Memorandum of Agreement between DSMRE and the University of Kentucky (MA 010351), which was signed on October 1, 1990. Additional discussions with the Hydrology Steering Committee in early 1991 led to further refinement of the final work plan that was submitted by KGS and IMMR in April 1991. Time and monetary constraints necessitated that the primary emphasis of the investigation be the collection of baseline data to characterize the pre-mining hydrology and hydrogeology of a study basin scheduled to be mined by longwall underground mining in 1993-94. These efforts provided excellent definition of existing hydrologic and geologic conditions so that future studies can characterize the effects of longwall mining at this site. Researchers currently intend to monitor the area through completion of mining and on a limited basis for several years thereafter. A detailed investigation of post-mining effects could also be undertaken if additional funds are available.

Supporting data for this report is available in Minns and others (1994). In addition, well construction data, water-level and water-quality data, and stream flow data are available from the Kentucky Ground-Water Data Repository at the Kentucky Geological Survey (see Appendix A for record identification numbers).

SITE SELECTION

Preliminary work began on the project in June 1990. MSHA district office managers in Districts 6 and 7 were contacted and requested to provide a listing of total-extraction underground mines. Two lists of potential mines were received in July. Additional mine locations were obtained from the Kentucky Department of Mines and Minerals and the U.S. Office of Surface Mining Reclamation and Enforcement in Lexington. Ninety-four mines were identified as total-extraction mines that would require further investigation. The OSMRE in Lexington provided a cross listing of MSHA numbers and DSMRE mine permit numbers. Permit numbers that were not on this list were obtained through the computer system at the Department of Mines and Minerals. Once permit numbers were compiled, permit files for total-extraction mines were systematically reviewed for the following information:

1. location above or below drainage
2. activity status
3. future reserves for the duration of this study
4. the amount of overburden
5. potential for mining under streams during the time frame of the study.

A list of potential mines was compiled from preliminary permit information. To supplement DSMRE permit information, mine maps from the Department of Mines and Minerals were reviewed to determine the extent of previous mining and projections, if any, for proposed mining. This preliminary review of 94 mines, completed in November 1990, produced a list of 19 candidate mines in which mining would occur beneath streams at depths ranging from 100 to 800 feet.

Shamrock Coal Company, which operates one of the 19 candidate mines, contacted the Lexington office of OSMRE just prior to the completion of the mine-review process to discuss conducting a hydrogeologic investigation at their new longwall mine in Leslie County. The company was contacted by the University of Kentucky research team in early December 1990 to discuss the scope of the project, and a Memorandum of Agreement was finalized in November 1991.

The Edd Fork Basin was selected as the most favorable research location on the basis of core data and mine projections. An initial drawback to this location was that mining would not begin in the basin until approximately 1993, a time frame that was beyond the duration of funding. However, the steering committee agreed that the mining delay would permit collection of useful baseline data prior to mining, resulting in better characterization of eventual mining effects. Four property owners in the affected part of the basin were contacted in May 1991. Final easements for surface access to the landowner's properties were completed and signed in September 1991.

EDD FORK STUDY SITE

Physiography and Climate

The study watershed, containing approximately 175 acres, is located in southern Leslie County, Kentucky, on the Helton 7.5-minute quadrangle (Figs. 1-2). 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 feet on the ridge tops to about 1,550 feet at the mouth of Edd Fork. Terrain in the watershed is steep; slopes average 26'.

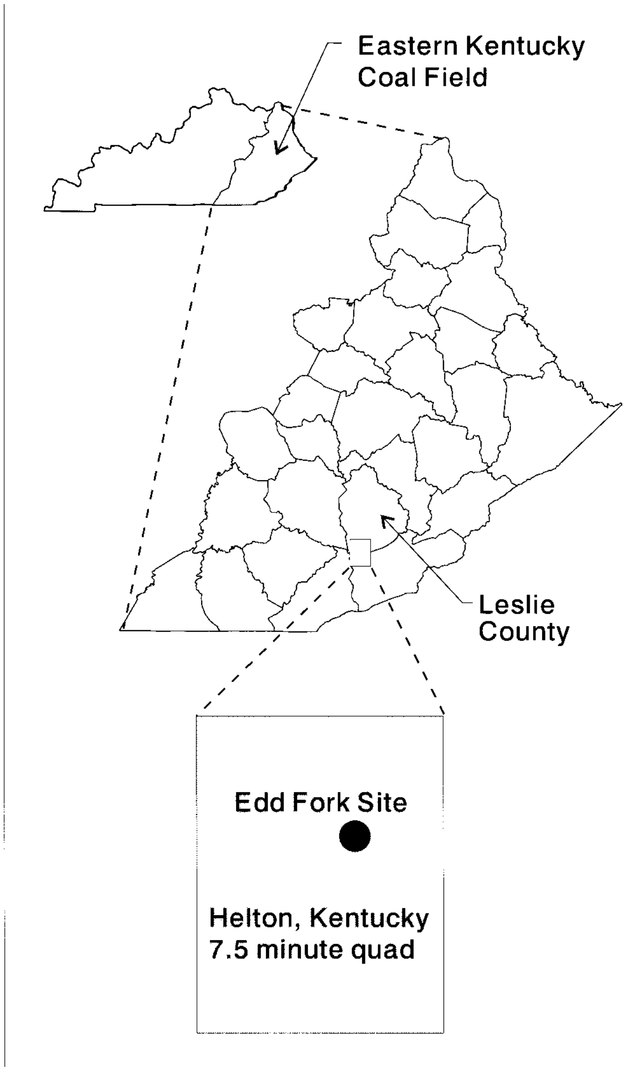


Figure 1. Location of Edd Fork watershed.

Eastern Kentucky has a humid temperate climate. The average annual temperature is 57'F. Temperatures range from below O'F in the winter to more than 100'F in the summer. Rainfall in Leslie County averages 48 to 50 inches per year (Kentucky Water Resources Study Commission, 1959). Most of the precipitation in eastern Kentucky occurs from January through March, and the least occurs from August through October (Quinones and others, 1981). Intense precipitation events average 4.3 to 4.5 inches in 24 hours for a 10-year occurrence interval (Quinones and others, 1981; Leist and others, 1982). Winters are cold and wet; snow is generally negligible except in severe winters. Water tables generally rise during winter and early spring, when infiltration exceeds evapotranspiration. Ground-water levels generally decrease in the summer and fall, when rainfall decreases and evapotranspiration reaches maximum levels.

Site Features

Figure 3 shows surface disturbances relative to past surface-mining activity. Most of the site is forested except in mined areas where vegetation is predominantly lespedeza and locust. The Hindman coal, at an elevation of 2,000 feet, was extensively mountaintop-mined in the 1980's. Ridges higher than 2,000 feet consist primarily of replaced overburden. Survey data, however, indicate that post-mining elevations are similar to pre-mining elevations shown on topographic maps. A contour surface-mine cut in the Hazard No. 8 coal is located along the western slope of the Edd Fork Basin. This disturbance has been partially reclaimed, but a prominent highwall is present. Other mine-related features include a small hollow fill, breached sediment-pond embankments, and downslope overburden material. Although this watershed has been disturbed by previous surface mining, this type of disturbance is typical of small watersheds in eastern Kentucky. Edd Fork has not been previously mined by underground methods. There are no human inhabitants in the Edd Fork Basin.

Geology

Strata in the study area belong to the Breathitt Formation of Middle Pennsylvanian age (Rice, 1975). Above-drainage strata in the watershed range from the Hindman coal down to just below the Haddix coal. Stratigraphy in the vicinity of the site is illustrated in Figure 4.

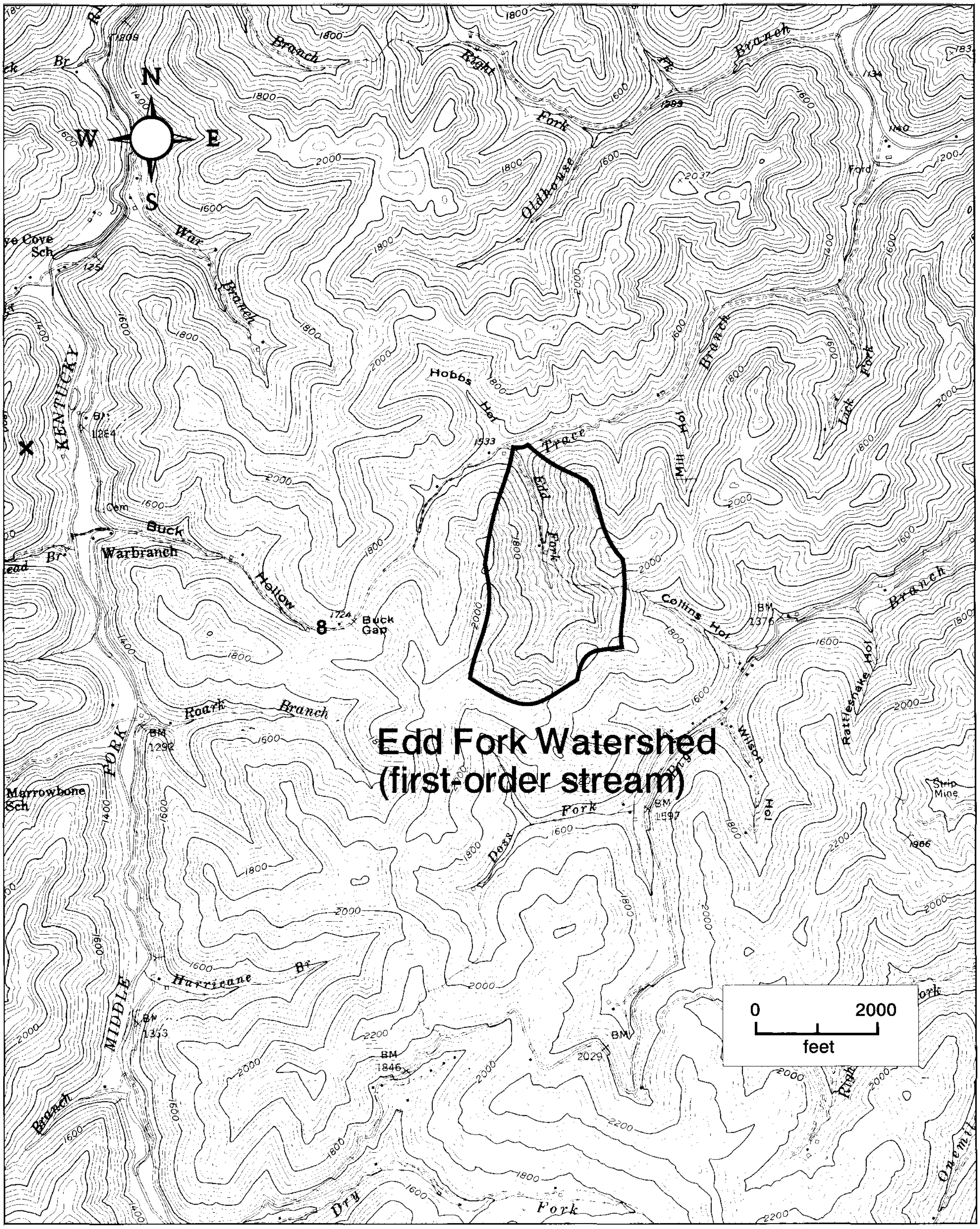


Figure 2. Topography of Edd Fork and vicinity.

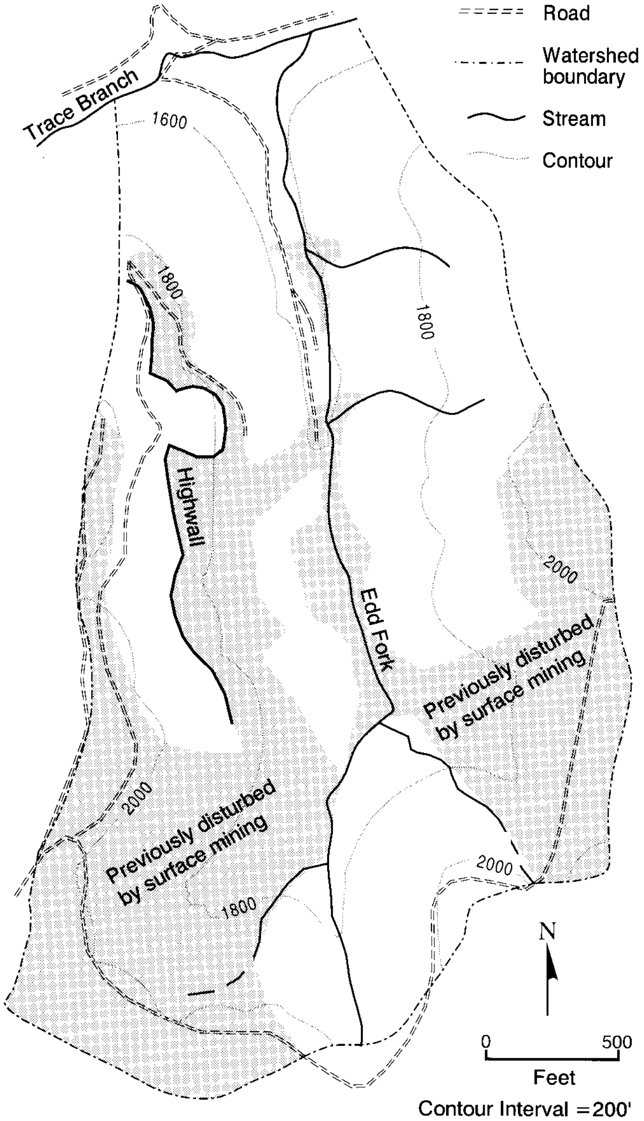


Figure 3. Surface disturbances in the Edd Fork watershed.

The Eastern Kentucky Coal Field's layered stratigraphy resulted from the deposition of Pennsylvanian clastic sediments into a structural trough known as the Appalachian Basin. By the close of the Pennsylvanian, up to several thousand feet of sediment had been deposited, resulting in the significant lateral heterogeneity characteristic of a deltaic depositional environment (Rice and others, 1980).

The Breathitt consists of alternating subgraywacke, siltstone, shale, coal, underclay, and thin limestone. Siltstone and shale are generally carbonaceous and contain plant fragments and ironstone nodules. Massive sandstones are rare as widespread, mappable units; they consist primarily of subgraywackes that are fine grained, micaceous, and contain 55 to 75 percent quartz. Basal contacts are commonly erosional, and contain channel-lag deposits. Many sandstone units grade laterally into siltstones. As a result of lateral heterogeneity, the Breathitt is difficult to divide into mapable units. It contains 30 major coal zones (Rice and others, 1980), making it the primary coal-producing formation in eastern Kentucky.

Subdivision of the Breathitt Formation is based on the identification of key beds. The most useful markers are widespread coal beds and marine zones. The Fire Clay coal (Hazard No. 4) has been used extensively as a marker bed. It contains a characteristic flint-clay parting derived from a volcanic ash fall (Rice and others, 1980). Marine zones, which range from a few inches to more than 100 feet thick, are the primary stratigraphic zones used for widespread correlation. The Lost Creek Limestone of Morse (1931), the Kendrick Shale, and the Magoffin Member are the most widely recognized marine zones in the Breathitt. They are coarsening-upward bayfill sequences of clay, siltstone, and sandy shale (Chesnut, 1981) and represent rapid marine transgressions over extensive flats. The lower section of these deposits is a dark-gray shale that is fossiliferous and commonly contains nodular limestone beds. A coal bed generally is present at the base. The shale grades upward into a siltstone containing siderite lenses. In places, the top of the sequence is overlain by channel sandstones. The Breathitt also contains discontinuous, sparsely fossiliferous marine zones that probably represent salinity changes in small, isolated bays or tidal channels (Rice and others, 1980). The Helton geologic quadrangle map (Rice, 1975) indicates that surface rocks are slightly undulatory in the vicinity of Edd Fork. In general, the rocks dip gently toward the northeast.

BEECH FORK LONGWALL MINE

Shamrock Coal Company's Beech Fork longwall mine is operating in the Fire Clay (Hazard No. 4) coal. Overburden thickness generally ranges from 300 to 1,000 feet. Configuration of the longwall mine relative to the Edd Fork watershed is shown in Figure 5. Access to the mine is near the mouth of Oldhouse Branch. Mining panels are approximately 700 feet wide and are separated by three-entry gateways that are approximately 200 feet wide. Longwall mining began in panel I in April 1991. Mining direction of each panel and the position of the active face as of June 30, 1993, is shown on Figure 5.

Undermining in the head of Edd Fork began in the late summer of 1993 with panel 5. Mining in Edd Fork will continue through panel 8. Undermining of the instrumented section of panel 7 is anticipated in the summer of 1994. Mining in Edd Fork should be completed by fall 1994. Overburden thickness in the

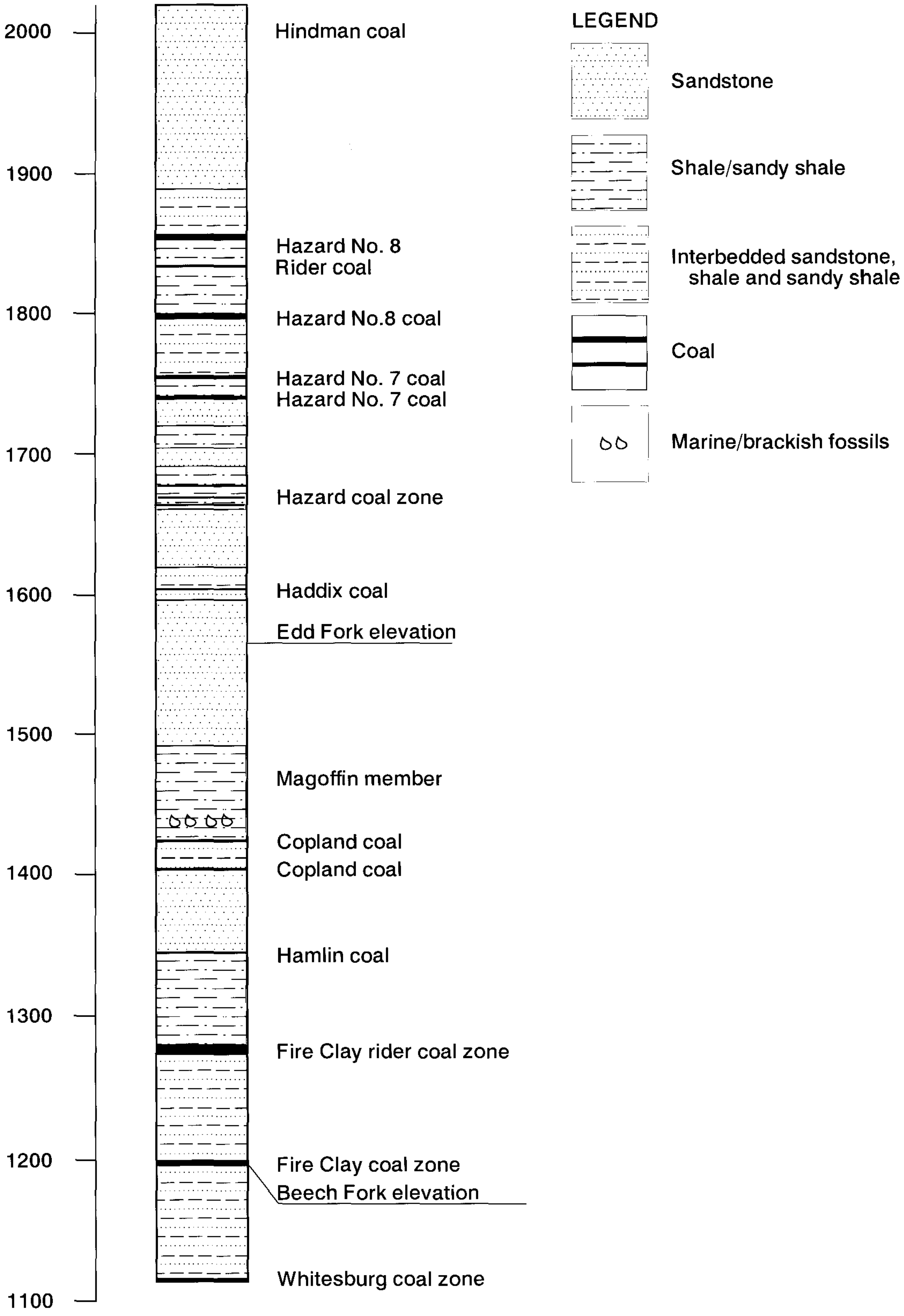


Figure 4. Stratigraphic section of the Edd Fork site.

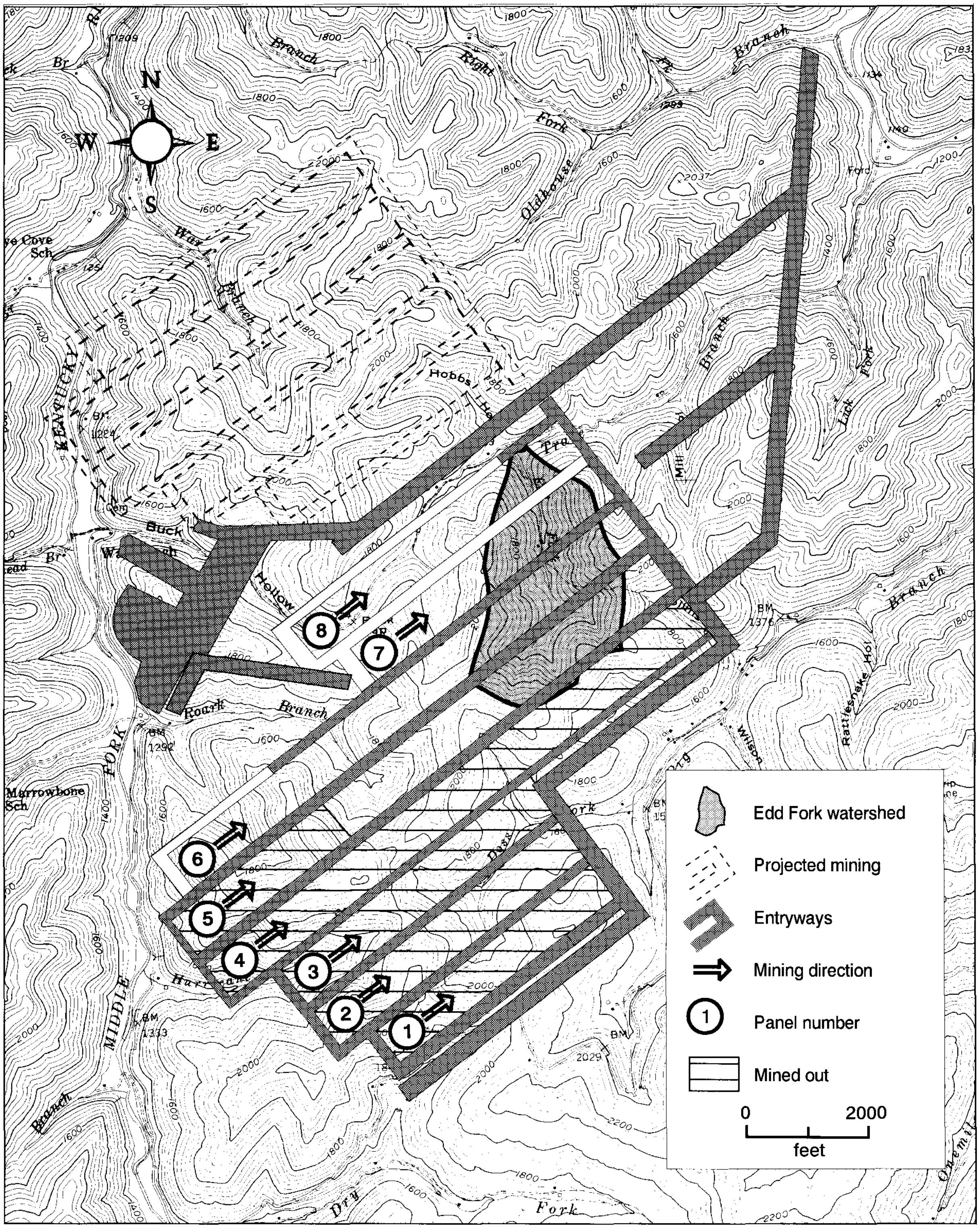


Figure 5. Extent of mining in the Beech Fork longwall mine as of June 30, 1993.

monitored interval ranges from 800 feet on the ridge to 350 feet along Edd Fork. Mining beneath the watershed will be intermittent as the active face moves in and out of the basin on subsequent panels.

SITE INVESTIGATION

Instrumented Panel

Three sites representing ridge top, valley side, and valley bottom were selected in panel 7 for intensive ground-water monitoring. These sites are designated site A (valley side), site B (ridge top), and site C (valley bottom), as shown on Figure 6. Each site contains one core hole and a closely spaced piezometer nest.

Site A is located below a contour strip bench at a surface elevation of about 1,756 feet. This site was selected because it represents the valley-side position and is located in the middle of panel 7. Site B, at an elevation of 2,020 feet, is located on a surface-mined ridge, also in the mid-panel area. Site C, located in an undisturbed area about 65 feet from Edd Fork, is in the quarter-panel adjacent to panel 8 at an elevation of 1,593 feet.

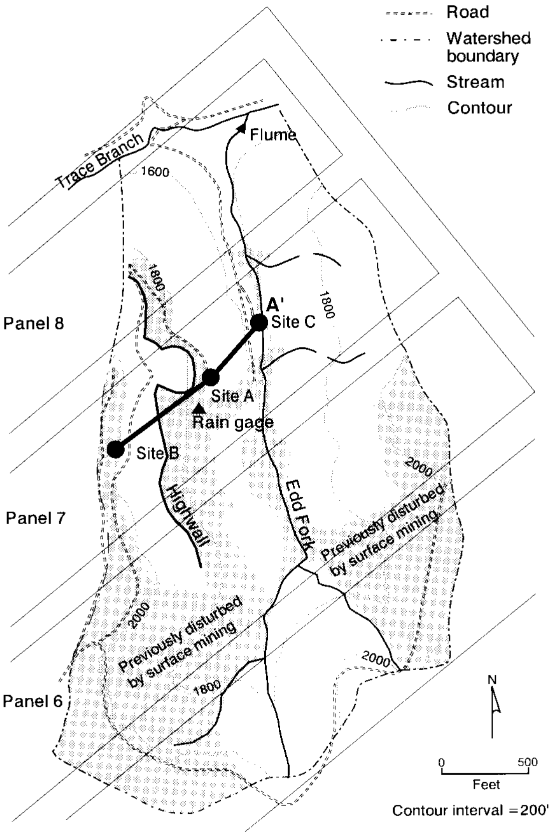


Figure 6. Monitoring-point locations in the Edd Fork watershed.

Core Drilling

One NX (3 inch) core hole was drilled at each site to provide stratigraphic control for well installation, to delineate the nature of fracturing, to conduct pressureinjection tests, and to provide a borehole for installation of time domain reflectometry (TDR) instrumentation. Core-hole depths are 763.4 feet, 500.5 feet, and 344.0 feet for the ridge-top (core hole B), valley-side (core-hole A), and valley-bottom (core hole Q settings, respectively. Generalized geologic cross section A-A' (Fig. 7) was constructed using data from these core holes.

Coring began in November 1991 and was completed in early January 1992. All core samples were examined in the field immediately upon removal from the core barrel. Core descriptions were completed using the classification developed by Ferm and Melton (1977). Additional features such as fractures and weathered zones were also described. All cores were boxed and placed in storage at the Kentucky Geological Survey.

Pressure-injection Testing

Testing Methods

Pressure-injection tests were performed on core holes A, B, and C immediately after completion of drilling. The packer assembly used for testing was a 10-footlong section of perforated steel pipe connected to sliding-end inflatable packers from Tigre Tierra. The packer assembly was lowered to the bottom of the borehole on drill rods. Packers were inflated through 1/4-inch high-pressure tubing using bottled nitrogen. Water was injected into the test interval using a dieselpowered water pump capable of pumping 50 gallons per minute (gpm). Flow to the test interval was controlled by valves that permitted excess water to bypass the packer system. Water pressure was measured with a damped gage calibrated in 2-psi increments. Water flow to the test interval was measured using a Sensus water meter calibrated in 0. 1 -gallon increments. flow rates less than 0.1 gpm were interpolated to hundredths of a gallon. The injection rate for intervals that did not take water was recorded as 0.01 gpm. Upon completion of testing in an interval, the packer assembly was raised to the next test interval by removing the 10-foot-long drill rod.

Hydraulic Conductivity

Pressure-injection tests require that a fluid, usually water, be injected into a borehole interval isolated between two inflatable packers until injection pressure and injection rate stabilize. These tests provide an equivalent-porous-media estimate of horizontal hydraulic conductivity of discrete intervals in the strata

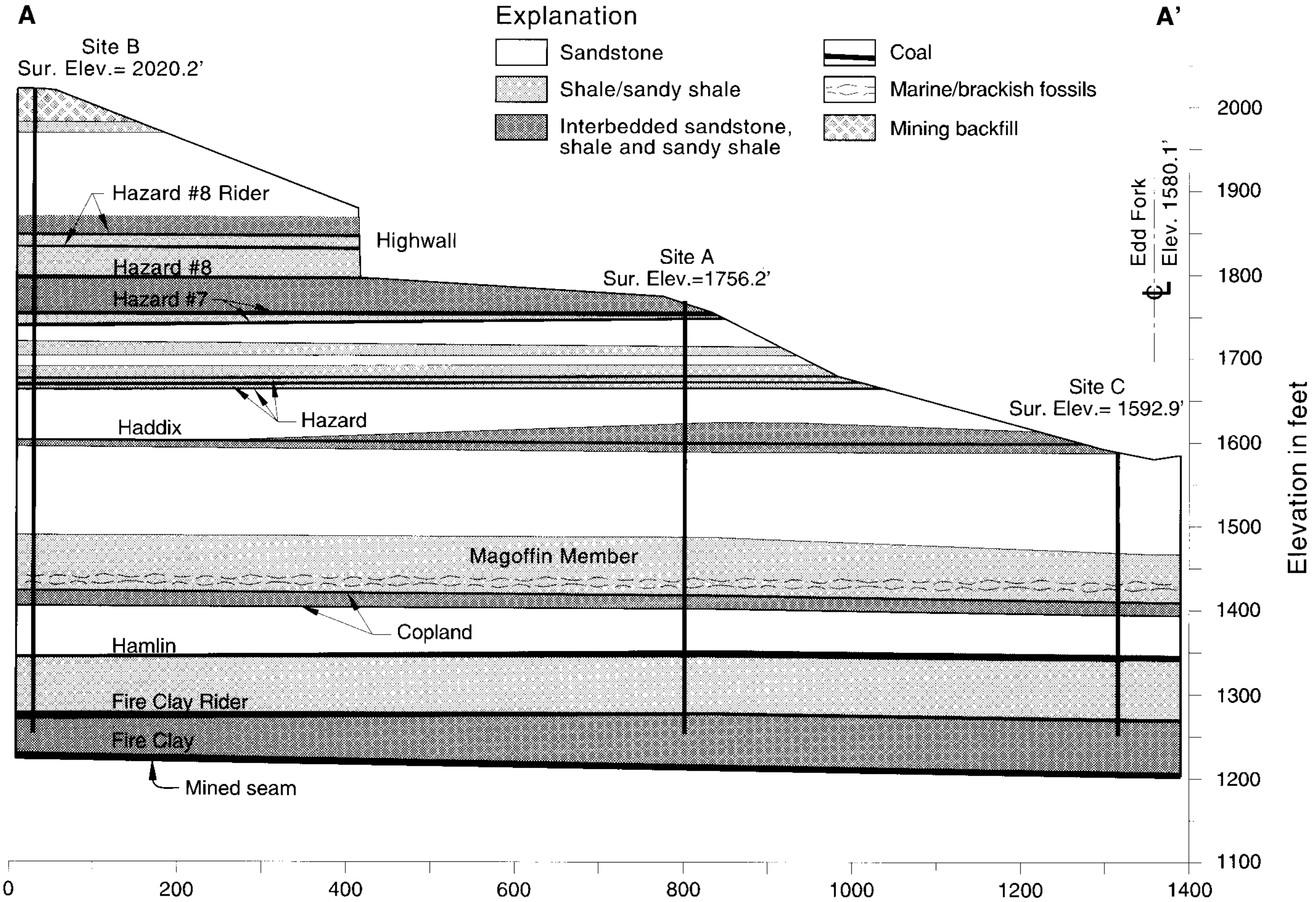


Figure 7. Geologic cross section A–A' (see Figure 6 for location).

adjacent to the borehole. Conductivity estimates from pressure-injection data are calculated assuming that water is injected into the formation over the entire area of the test interval. In layered and fractured strata, the interval accepting water may be a discrete non-horizontal fracture or a particular lithology, such as a coal seam, that is thinner than the entire test interval. If a particular zone within the interval is accepting the majority of the water, the hydraulic conductivity for that zone is higher than the value reported for the entire interval. This method, despite its lack of precision, is useful for examining differences in order of magnitude among different strata classifications.

Estimates of the equivalent-porous-media hydraulic conductivity for each interval were calculated using the following formula (Hvorslev, 1951):

$$K = \frac{0 \times \ln(L / r)}{2\pi L H(t)} \text{ for } L > 5r$$

where:

K = hydraulic conductivity
Q = constant rate of flow into the injection interval over the test period
L length of test interval, in this case, 10 feet r
radius of borehole, in this case, 0.125 feet
H(t) = total head in the injection interval.

Head H(t) of this equation includes two components: pressure and elevation head. For our tests, pressure head is the pressure applied from the injection of water into the interval converted to equivalent feet of water. Elevation head is the distance between the point of applied pressure (injection-pump pressure gage) and the midpoint of the test interval. Therefore, total head, H(t), is the sum of the applied pressure in feet of water and the depth from the top of the water-injection point to the middle of the test interval.

Minimum reported hydraulic conductivity values are calculated from an interpolated injection rate of 0.01 gpm. Actual injection rates could be less; thus, the calculated conductivity would be even smaller.

Results of the pressure-injection tests for each core hole are shown in Figure 8. Highly conductive zones correlate with discrete fractures, fracture zones, and coal seams identified in the core logs. Conductivity differences of an order of magnitude or greater between

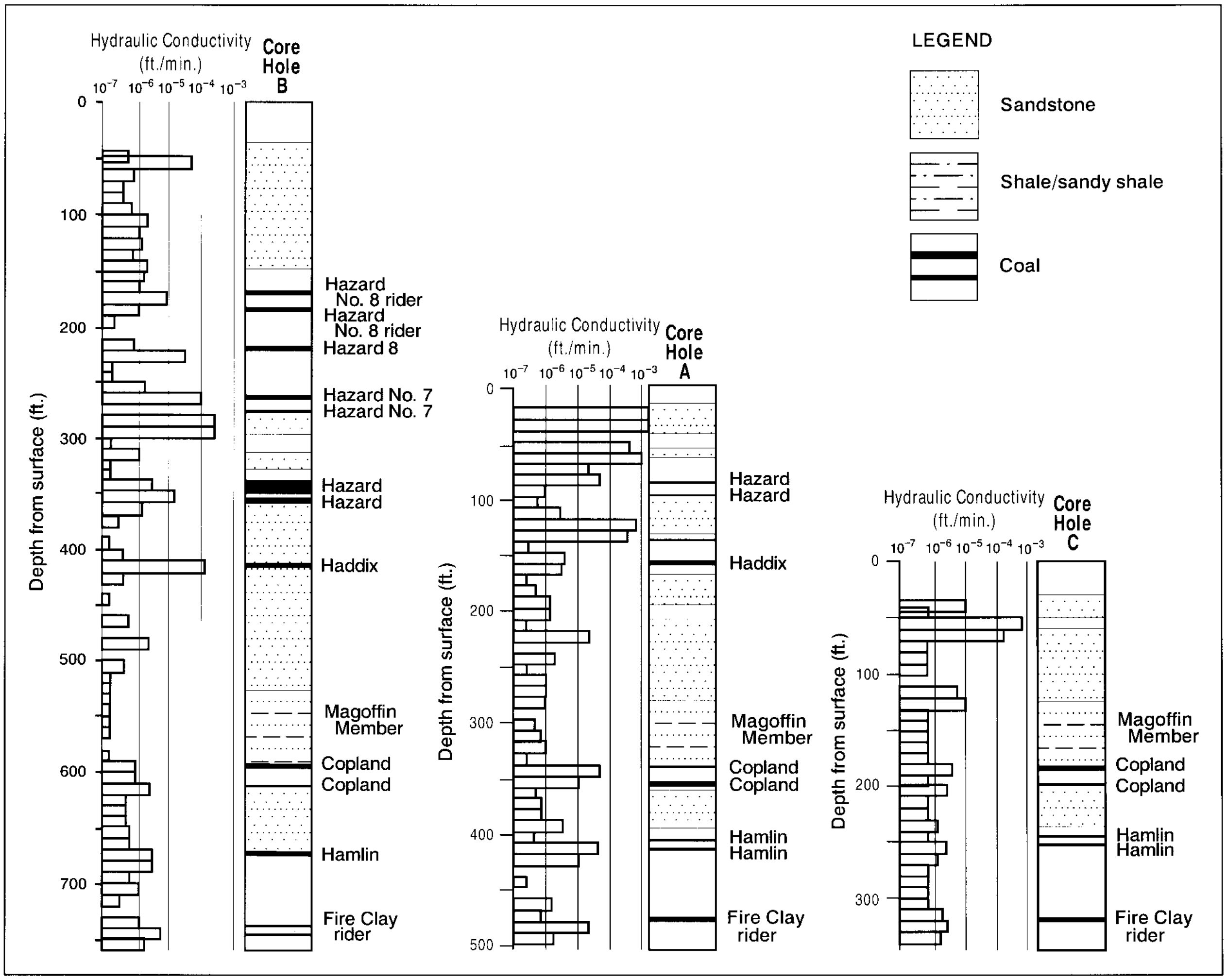


Figure 8. Geologic columns for core holes A, B, and C, showing hydraulic conductivity values.

test intervals are common. Intervals that do not contain coals or fractures have very low conductivity values.

Figures 9 through 11 show the variation in hydraulic conductivity with depth for core holes A, B, and C. The distribution of points indicates that hydraulic conductivity typically varies three or four orders of magnitude over the depth of a hole. Values range from I X 10-7 to 1 X 103 feet per minute. In general, the most conductive strata are near the ground surface, where open fractures are common. Strata deep within the ridge are the least conductive.

Conductivity values plotted in Figures 9 through 11 are differentiated according to lithology (sandstone, shale/sandy shale, interbedded sandstone and shale, and coal). Intervals that include major lithologic contacts are generally considered interbedded strata. Fractured zones are not differentiated by lithology. Coal beds and fractures stand out as highly conductive zones; however, below-drainage coal beds have conductivities that are smaller than those above drainage.

Unfractured sandstone, shale/sandy shale, and interbedded strata do not exhibit values that are markedly different from each other.

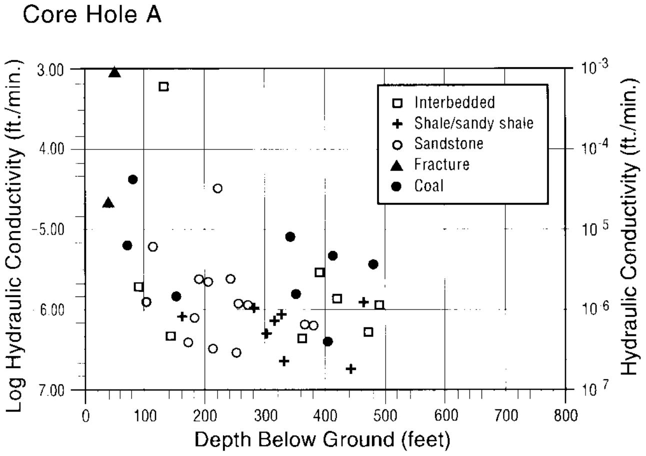


Figure 9. Distribution of hydraulic conductivity with depth for core hole A.

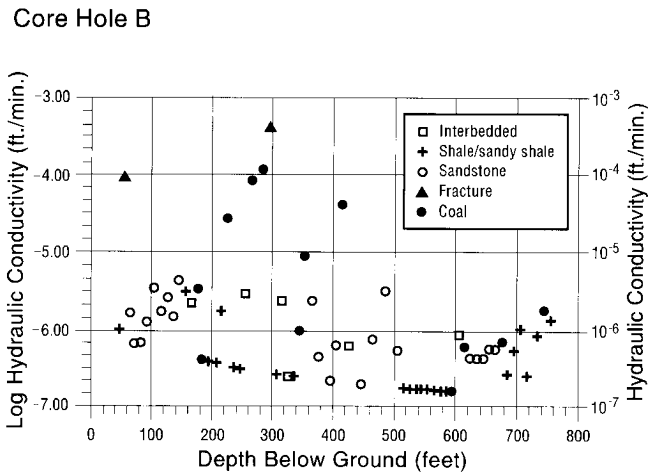


Figure 10. Distribution of hydraulic conductivity with depth for core hole B.

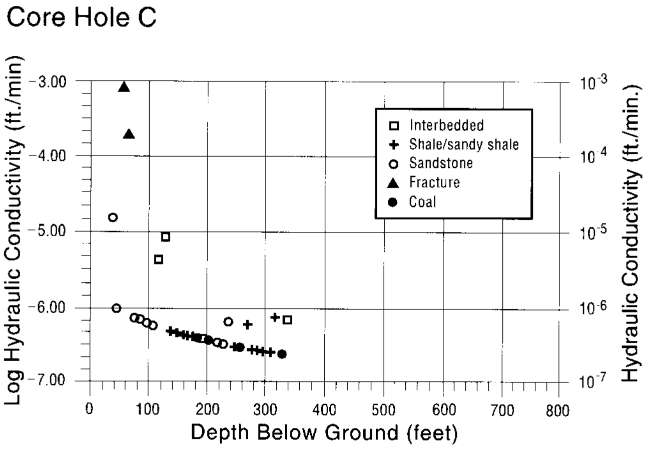


Figure 11. Distribution of hydraulic conductivity with depth for core hole C.

Table 1 summarizes conductivity relationships among different strata from coreholes A, B, and C. A total of 140 intervals in three holes is included. Fracture zones are the most conductive and have a median conductivity of 9 X 101 feet per minute (fpm). Intervals containing above-drainage coals are the second most conductive group, having a median conductivity of 9 X 101 fpm. Unfractured, noncoal strata have median conductivities between 4 X 107 and 1 X 10'fpm. Coal-bearing intervals below drainage have a median conductivity of 6 x 107 fpm, a value more like that for unfractured sandstone and shale than for above-drainage coal.

Time Domain Reflectometry

Time domain reflectometry is a technique to evaluate rock-mass breakage by identifying breaks or faults in coaxial cable grouted into a rock body Coaxial cables were grouted into coreholes, and pre-mining waveforms were obtained for the in-place cables. TDR will be used as an aid to evaluate the impacts of the undermining event on the strata above the mine. A description of the TDR installation in Edd Fork is contained in Appendix B.

Piezometers

Location

Twenty-four piezometers, distributed among three sites, were installed in the Edd Fork watershed (Figs. 6 and 12). These locations were designed to:

1. provide monitoring points in three different topographic positions: ridge top, valley side, and valley bottom

Table 1. Summary of calculated hydraulic conductivity values for core holes in Edd Fork watershed.

	Fracture	*Coal (Above Drainage)*	*Coal (Below Drainage)*	*Sandstone*	*Shale/ Sandy Shale*	*Interbedded*
Number of samples	10	11	13	45	43	18
Maximum value (ft./min.)	4E-03	2E-04	8E-06	3E-05	6E-04	6E-04
Minimum value (ft./min.)	2E-05	1E-06	2E-07	2E-07	3E-07	3E-07
Average value (ft./min.)	4E-04	9E-06	8E-07	1E-06	4E-07	2E-06
Median value (ft./min.)	9E-04	9E-06	6E-07	7E-07	4E-07	1E-06

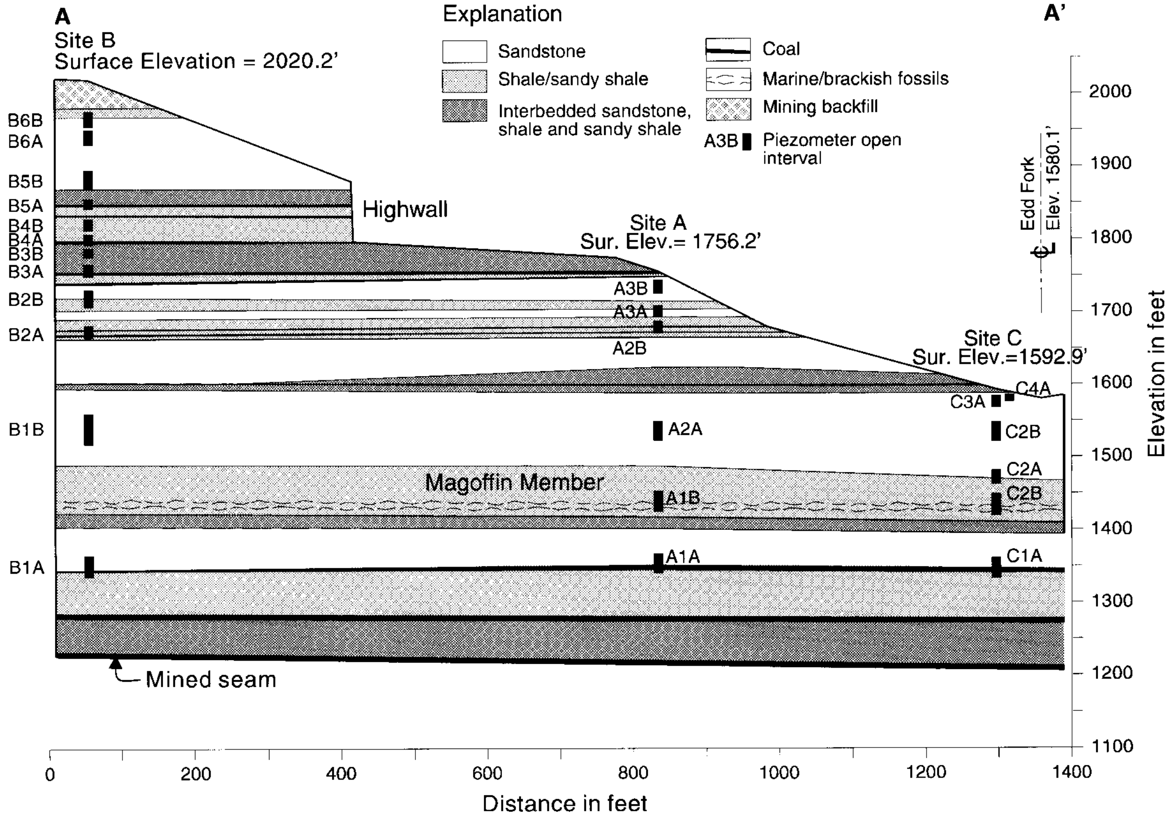


Figure 12. Piezometer locations along cross section A–A' (see Figure 6 for location).

2. allow monitoring of stratigraphic zones in different topographic positions
3. facilitate construction of a cross section through panel 7
4. allow completion of above- and below-drainage piezometers.

Twelve piezometers, located in the site B ridge-top nest, were completed to depths ranging from 67 to 684 feet. Six piezometers located in the valley-side nest at site A and have completion depths from 35 feet to 417 feet. Six piezometers are located in the nest at site C adjacent to Edd Fork had completion depths ranging from 18 to 262 feet.

Screened intervals were based on the results of coring, geophysical logs, and pressure-injection tests. piezometers were installed as close as practical to the core hole at each site. The maximum distance of any piezometer from a core hole is approximately 75 feet. Individual boreholes were drilled approximately 15 feet apart to minimize interference among piezometers at any one site during drilling and construction. All piezometer locations were surveyed to the nearest 0.01 foot by a licensed surveyor. Elevations were rounded to the nearest 0.1 foot to be consistent with the level of accuracy of water-level measurements. The top of the protective casing was used as datum.

Piezometer Installation

Piezometer installation began in early May 1992, and was completed at the end of July 1992. Boreholes for piezometers were drilled using a downhole hammer, utilizing air as the circulation medium where possible. Water was added to assist cuttings removal when mud cakes formed around the bit or when air was no longer sufficient to lift cuttings from the hole. Twelve of 14 boreholes were 8-inch holes with 8-inch steel surface casing. Surface casing in these holes is set in a 10-inch hole drilled with a tri-cone bit. After surface casing was installed, holes were completed to the desired depths with a 77/8-inch-diameter air-percussion hammer. Two boreholes were 6-inch holes with 6-inch steel surface casing. Surface casing was set in an 8-inch hole drilled with a tri-cone bit. The two 6-inch holes were completed with a 6-inch hammer. Two drill rigs were utilized where possible in order to speed completion of boreholes. Drills used were a Driltech Model D40K, mounted on a crane carrier, and a Schramm T-64HP, mounted on a 5-ton M821 all-wheel-drive military truck. The required air volume for drilling deep 8-inch holes was obtained by connecting the compressors on the two drills.

All monitoring pipe was 2-inch flush-joint, PVC. The two deepest piezometers (684 feet and 492 feet) were constructed with schedule 80 riser and screen. Schedule 40 riser and schedule 80 screen were used for piezometers with depths between 300 and 415 feet. Piezometers shallower than 300 feet were constructed using schedule 40 pipe and screens. Piezometer installation followed accepted methodology, as described in Aller and others (1989). A typical piezometer installation is illustrated in Figure 13.

Each piezometer has a three-character alphanumeric identifier that designates location, hole number, and piezometer identification. The deepest piezometer in each hole is designated "A" and the shallowest piezometer is designated "B." Cross section A-A', shown in Figure 12, illustrates the location of screened intervals for all *piezometers. Piezometers* constructed for this study had open intervals that ranged from approximately 12 to 27 feet in length. Piezometers in coal seams had the shortest intervals. Deep piezometers in tight formations had longer intervals. Piezometer Bl B had an open interval of about 40 feet because of a problem during construction. Table 2 summarizes piezometer depths, open intervals, and monitored interval.

Water-Level Data

Water *levels* in *piezometers were measured using* a Slope Indicator, Inc., water-level indicator. Measurements were recorded to the nearest 0.1 foot. The measuring point for water levels was the top of the protective *steel* casing.

Water levels were measured at least every 2 weeks from August 1992 through December 1992, then monthly through June 1993. *Measurements were* taken to characterize both wet and dry periods. Twenty of the 24 piezometers had measurable water *levels* throughout the monitoring period. *Three shallow piezometers* remained consistently dry and one shallow piezometer contained water only after rainfall. A summary of water-level elevations is presented in Appendix C.

Fractures and highly conductive coal beds located within monitored intervals exerted a strong influence on static water levels. Fractures and coal seams may control water levels in the interval so that head is not a composite of the interval. Nonetheless, examination of *water-level elevations relative to interval* midpoints provided useful information of the distribution of hydraulic head with depth.

Graphs showing water-level elevation and piezometer-interval midpoint elevation for each piezometer within a nest are shown in Figures 14 through 16. The line of zero pressure head, where water level is equal to the elevation head of the interval midpoint, and the static water elevation for the core hole at each site are shown on each plot.

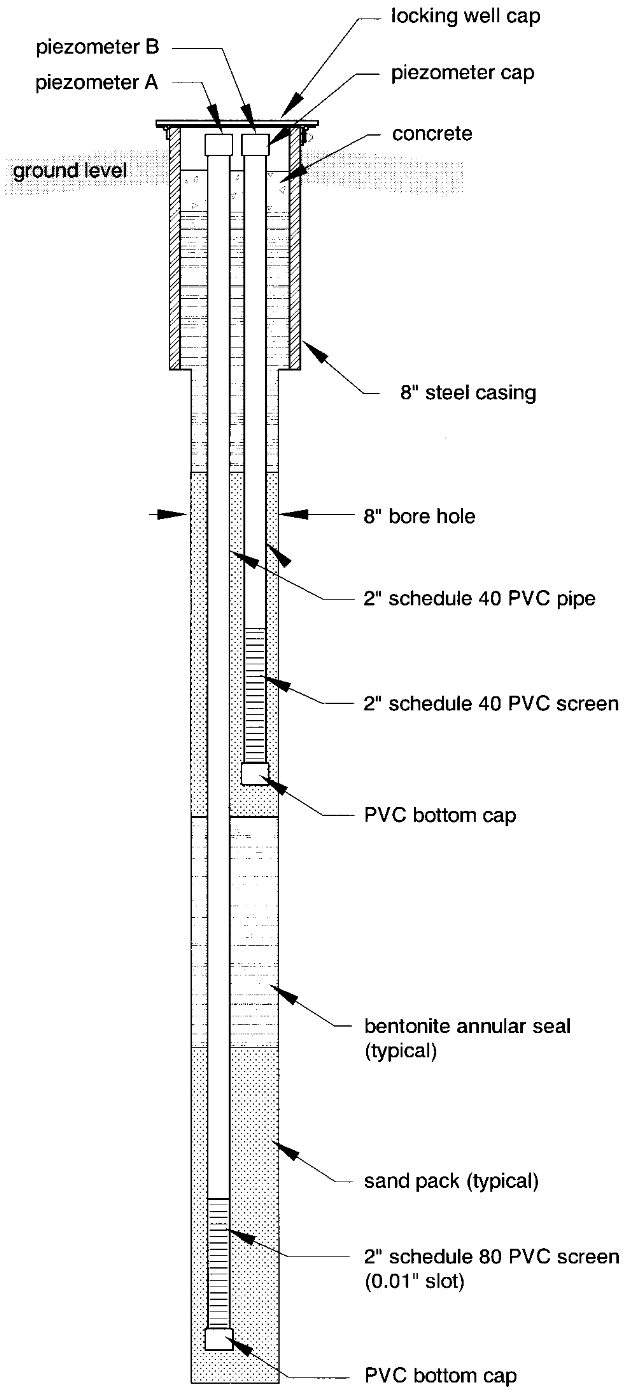


Figure 13. Typical double piezometer installation.

Figure 17, showing piezometer heads and interval depths for Edd Fork on one graph, displays the relationships among piezometers completed in the same stratigraphic intervals but in different topographic positions. Piezometers at the same elevation and those with similar heads are tightly clustered, indicating that heads were nearly equal for intervals screened at similar ele-

Table 2. Summary of screened intervals for piezometers in Edd Fork watershed.

Piezometer	*Total Depth (ft.)*	*Elev., Top of Open Interval (ft.)*	*Elev., Bottom of Open Interval (ft.)*	*Monitored Interval*
A1A	415.0	1367.0	1340.5	Interbedded
A1B	328.0	1453.0	1425.5	Shale (Magoffin Member)
A2A	233.5	1549.0	1523.0	Sandstone (>50%)
A2B	85.5	1687.0	1671.0	Hazard coal zone
A3A	65.5	1709.0	1693.5	Fractures
A3B	34.5	1744.0	1725.5	Fractures
B1A	684.0	1363.5	1336.5	Sandstone (>50%)
B1B	492.0	1560.5	1518.5	Sandstone (>50%)
B2A	354.5	1682.5	1665.5	Hazard coal zone
B2B	311.0	1731.5	1708.0	Fractures
B3A	269.0	1766.5	1750.0	Hazard No. 7 coal
B3B	243.5	1788.5	1776.5	Interbedded
B4A	227.0	1807.5	1793.5	Hazard No. 8 coal
B4B	205.0	1829.0	1813.0	Shale/sandy shale
B5A	179.0	1856.5	1843.5	Hazard No. 8 rider coal
B5B	149.5	1896.0	1870.5	Fractures
B6A	91.5	1952.0	1930.5	Fractures
B6B	64.0	1977.0	1956.0	Interbedded
C1A	260.0	1361.0	1333.5	Interbedded
C1B	173.5	1448.5	1419.5	Shale (Magoffin Member)
C2A	130.5	1481.0	1462.0	1/3 in Magoffin Member
C2B	70.5	1547.5	1521.0	Sandstone (>50%)
C3A	24.0	1583.5	1567.5	Fractures
C4A	17.0	1585.5	1567.0	Fractures

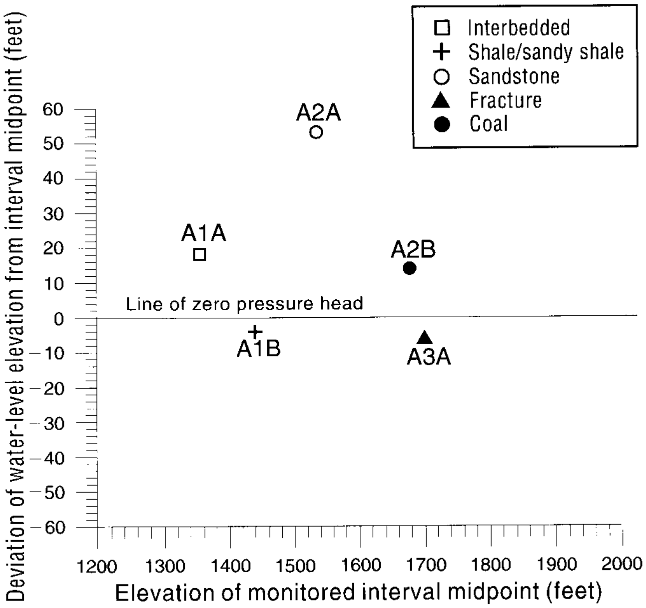


Figure 14. Water-level elevations plotted against piezometer midpoint elevation for piezometer nest A.

vations. Figure 18 shows head contours throughout the cross section, assuming the system is homogeneous and isotropic. The cross section shows an overall loss of head with depth. It does not reflect the presence of horizontal flow in individual beds or the third flow dimension parallel to Edd Fork.

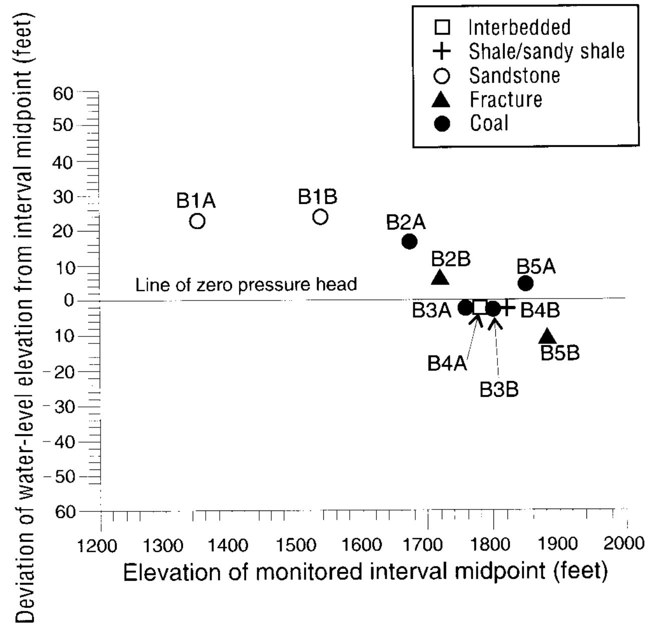


Figure 15. Water-level elevations plotted against piezometer midpoint elevation for piezometer nest B.

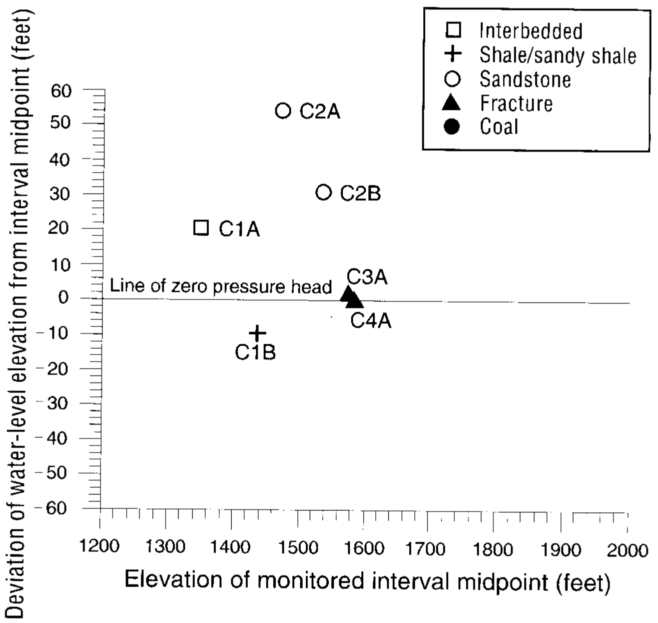


Figure 16. Water-level elevations plotted against piezometer midpoint elevation for piezometer nest C.

Water-Quality Data

One set of water-quality samples was collected from 19 of the 24 piezometers on the site. Piezometers were either pumped using a Grunfos Redi-flo 2-inch submersible pump or purged of standing water using a 2-inch stainless-steel bailer, depending on the depth and water-producing capabilities of each piezometer. Several piezometers produced little water and had to be purged, then sampled the following day. At least three well volumes were purged from 9 of the 19 piezometers sampled. Less than three well volumes were removed from the remaining piezometers with low yield.

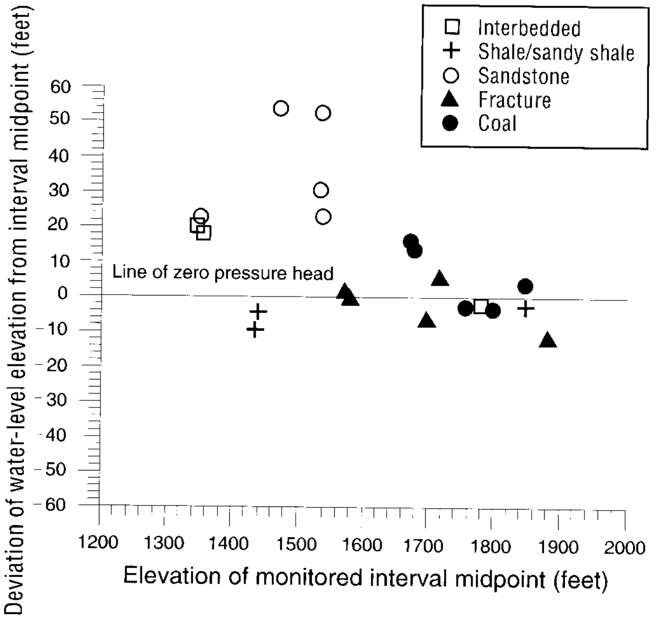


Figure 17. Water-level elevations plotted against piezometer midpoint elevation for all piezometers.

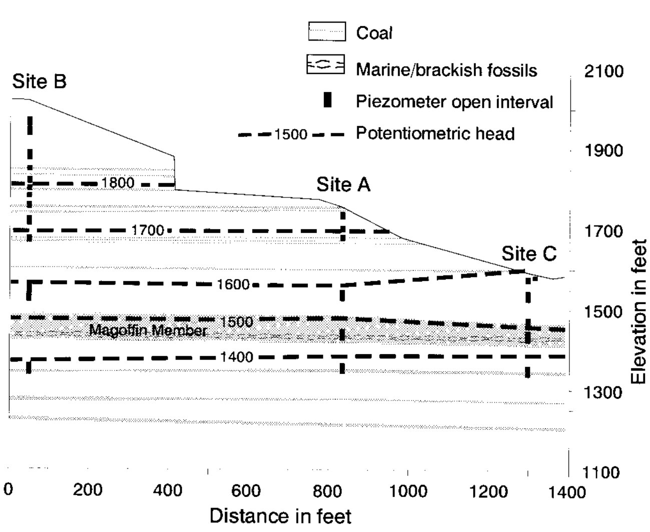


Figure 18. Water-level elevations for cross section A–A', assuming homogeneous and isotropic media (see Figure 6 for location).

Specific conductance, temperature, and pH were measured in the field during pumping and sampling using a YSI 3500 flow-through meter. Probes from the YSI meter were used for field measurements on bailed samples, but the airtight chamber was not used. The pH probes were calibrated at least daily using pH 7.0 and 10.0 standards. Specific conductance was measured with a Cole-Parmer 1481-55 temperature-compensating conductivity meter. The specific conductance meter was standardized at least once per day using 75 and 2,000 microsiemen (pS) standards. Field measurements were corrected using linear regression techniques.

Water for non-metals analyses was placed in certified clean polyethylene cubitainers. Samples for dissolved metals were field-filtered through a 0.45 micron cellulose-acetate filter, placed in certified clean 250 ml bottles, and preserved with I ml of 1:1 double-distilled water to nitric acid solution. All samples were stored in an ice chest after collection. Sampling equipment was thoroughly rinsed with deionized water between piezometers.

Laboratory analyses were performed by the Laboratory Services Section of the Kentucky Geological Survey. Metals were analyzed using a Thermal-Jarrell Ash Inductively Coupled Plasma Emission Spectrometer (ICAP).

Data from 14 piezometers were assumed to be representative of water quality in the formation. The remaining piezometers were not sufficiently developed for data to be representative of the formation water. Three criteria were used to determine if water quality was representative of the formation: (1) piezometers produced at least three well volumes when purged, (2) water exhibited quality characteristics of a sodium-rich "deep" water, or (3) little residual bentonite was present in the sample.

Springs

Thirteen springs and seeps located in the Edd Fork watershed are shown on Figure 19. A tabulation of spring data is included in Appendix D. Water-bearing horizons for each spring were determined where possible. Spring flow was estimated visually or by estimating flow into a beaker over time. Flow volumes were generally less than 1 gpm and generally represented seeps from coal beds or sandstone. The largest spring flow was apparently associated with the Hazard No. 8 coal.

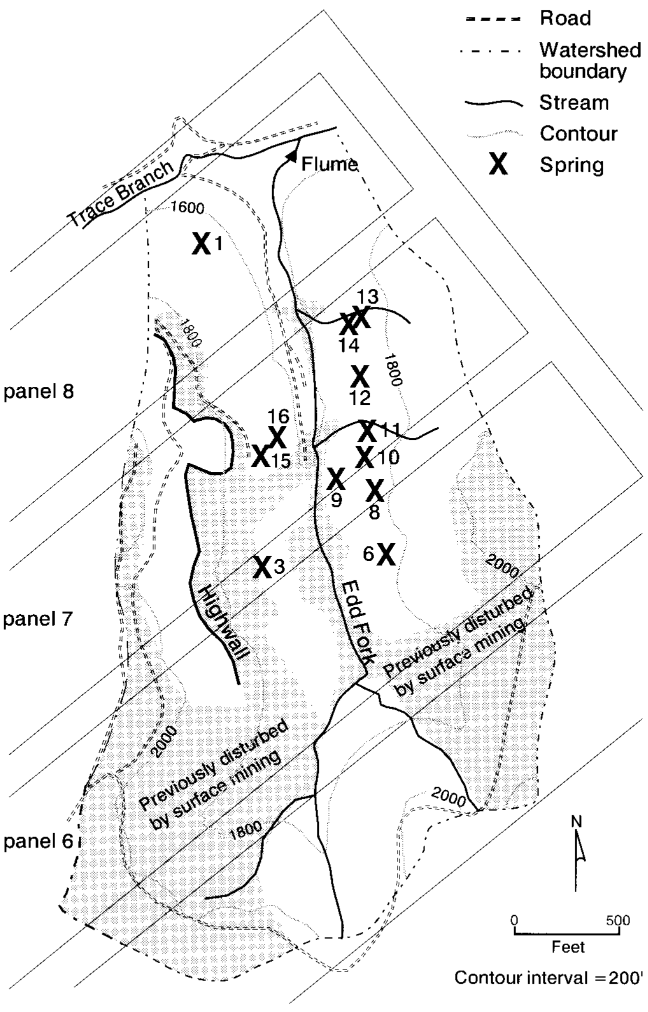


Figure 19. Spring locations in Edd Fork watershed.

Precipitation Monitoring

A tipping-bucket rain gage (WEATHERtronics) was located on a reclaimed, surface-mined area midway between the ridge-top and valley-bottom piezometer nests (Fig. 6). The rain gage was bolted to a 12-inchsquare concrete slab and leveled using shims under the bolts. Growth of weeds in the immediate vicinity of the rain gage was controlled by anchoring plastic and geofabric to the ground surface. A Telog pulse recorder automatically counted the number of bucket tips during each 10-minute interval. Each bucket tip registered 0.01 inch of rainfall.

Precipitation data were downloaded to a laptop computer monthly. Precipitation data reported from July 1, 1992, through June 30, 1993, are shown in Figure 20. Annual rainfall totaled 52.90 inches for this period, compared to a normal of 48 to 50 inches per year (Kentucky Water Resources Study Commission, 1959).

Streamflow Monitoring

A 3.0-foot, fiberglass H-flume was installed in Edd Fork approximately 30 feet above the confluence with Trace Branch. The flume was bolted to railroad ties secured into the stream bed with 3 /4-inch steel reinforcing rod. Plastic sheeting and bentonite were used to seal the entrance channel to minimize leakage under the flume. The sides were backfilled with dirt.

Stream stage was measured using a pressure transducer and a Telog data logger. Data were collected at 10-minute intervals as an average of interval measurements taken every second. A rating curve provided with the flume was used to relate stage to discharge.

The stream-monitoring station was activated May 1, 1992. The monitoring station was active from May I until June 3, and then was down (washed out) until July 19,1992. With the exception of brief periods of freezing on December 19, 1992, and March 13 through 15, 1993, continuous stream flow data were obtained during the period.

Summer storms produce sharply peaked runoff events (Fig. 20). Surface runoff from winter precipitation also produces fast-rising stream runoff, but saturated ground tends to sustain the flow for longer periods.

Selected precipitation and runoff statistics are given in Appendix E. Commensurate with annual rainfall, runoff was also higher than normal for the year, about 22 inches compared with a normal of 20 inches (Kentucky Water Resources Study Commission, 1959). Stream flow accounted for 44.9 percent of the rainfall falling on the watershed. The estimated surface, or quick, runoff averaged about 7 percent of storm rainfall. Comparing the estimated runoff with rainfall inches

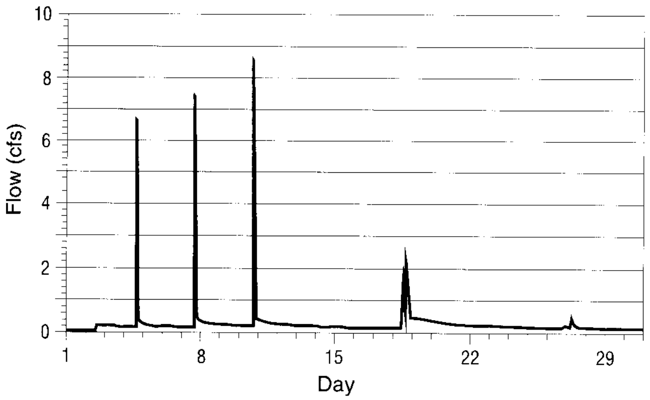


Figure 20. Hydrograph for Edd Fork showing storm responses during September 1992.

indicates Soil Conservation Service runoff curve numbers of around 62 during the growing season and about 82 in the dormant season. These values are reasonable for a forested eastern Kentucky watershed (Barfield and others, 1981).

Figure 21 is a flow-duration curve that indicates the probability that flows less than a given level will occur. Changes in the shape of the flow distribution may provide an indication of subsidence impacts, if those impacts are not otherwise obvious after mining.

A water sample was collected from Edd Fork adjacent to piezometer nest C at the same time wells were sampled.

Underground Mine Visit

In addition to surface investigations, a trip through the active longwall operation afforded the opportunity to directly observe mine conditions. Water was observed dripping from the mine roof in two areas. Several areas within the mine contained ponded water that either accumulated naturally or was pumped from other areas of the mine. A water sample from the ponded water was collected and analyzed (see Fig. 5 for location).

GROUND-WATER ZONES

Data collected from the site confirm the complexity of coal-field ground-water systems where flow is controlled by fractures and lithologic stratification. To simplify this complex system, zones that have similar characteristics can be identified and, consequently, general behavior can be described.

The ground-water flow system in Edd Fork may be categorized on the basis of hydraulic properties and water quality (Minns, 1993). Three zones are differentiated on the basis of fracture occurrence and hydraulic properties. They are (1) the shallow-fracture zone, (2) the elevation-head zone, and (3) the pressure-head zone. Ground water at the site can also be distinguished by water quality. There are two general hydrochemical facies, one being calcium-magnesium-bicarbonate-sulfate and the other being sodium bicarbonate. Figure 22 illustrates the location of these zones in Edd Fork. A description of these zones in the study area follows.

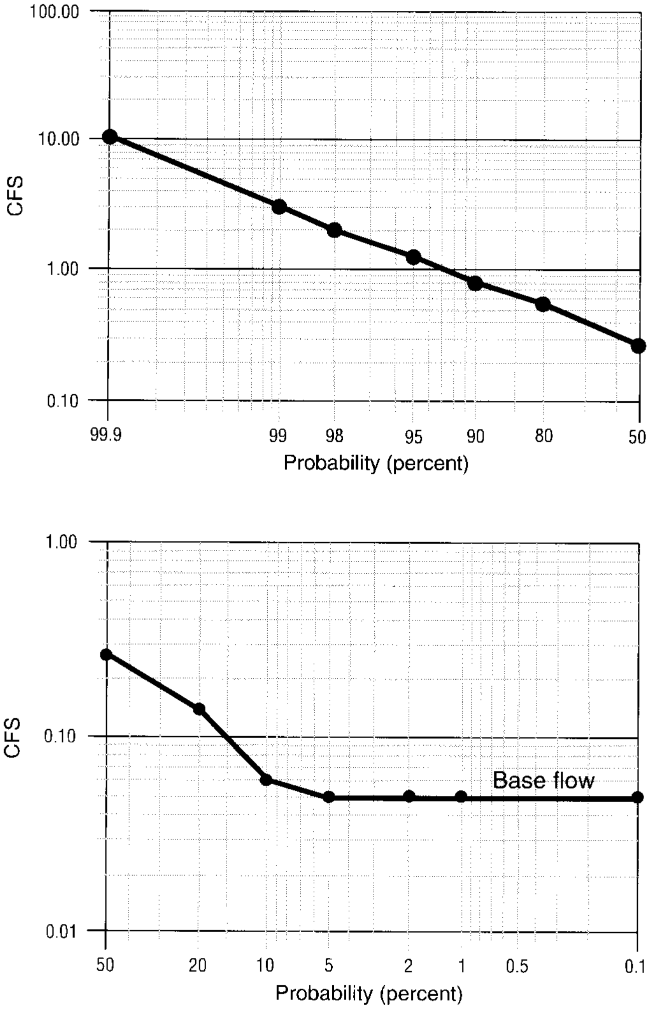


Figure 21. Probability of flows less than a given value for streamflow measures at the flume in Edd Fork, July 1992 through June 1993.

Shallow-Fracture Zone

The shallow-fracture zone is made up of highly fractured strata that parallel the land surface to a depth of 50 or 60 feet. The exact mechanism of fracture development is unknown; however, it is likely a combination of tectonic jointing, overburden unloading, and surficial weathering processes. Possibly, stress from overburden unloading is released along existing joint planes. Surficial weathering may enhance fracture openings. Fractures, both in outcrops and drill holes, have

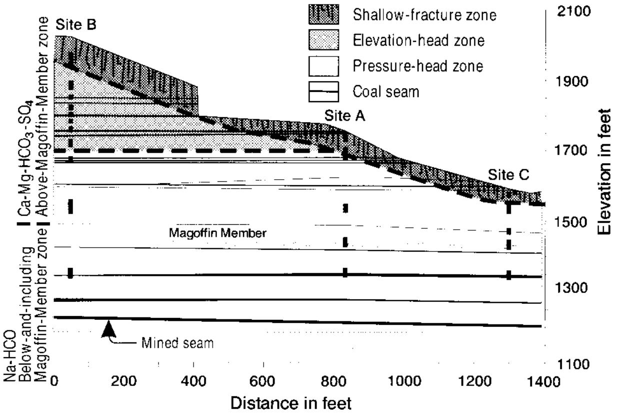


Figure 22. Location of ground-water zones in Edd Fork watershed.

near-vertical orientations. At least one orthogonal set attributable to tectonic forces is present. Near-horizontal bedding plane fractures also occur. Fracture spacing generally differs among lithologies, and fractures may terminate at lithologic boundaries.

Hydraulic conductivity values that are higher in the shallow-fracture zone than in deeper rock are directly attributable to fractures. In general, the equivalent-porous-media-hydraulic conductivity calculated from pressure-injection tests is approximately 1,000 times greater in rock where fractures were observed in cores than in strata where fractures were not apparent. Fracture frequency is greater in the shallow-fracture zone than in deeper strata, as noted in drill logs, increasing the likelihood of intercepting a conductive fracture during hydraulic testing. Intervals in the shallow-fracture zone that do not intercept fractures have hydraulic conductivity values similar to deeper strata, indicating that conductivity is fracture dependent.

Depth to the water table in the shallow-fracture zone is variable, and is affected by rainfall, topography, fracture location, fracture orientation, and previous surface disturbances. The water table is probably irregular, being higher where recharge is more direct and lower where less direct infiltration occurs or flow is more rapid. Shallow valley-side piezometers A3A and A313 show evidence of water moving through the monitored interval, but water probably drains rapidly to a lower level. Piezometer response to individual precipitation events is rapid and transient (Fig. 23). A storm in August 1992 caused a rise in water level over a 24-hour period in valley-bottom piezometers C4A and C3A of I foot and 3 feet, respectively. Abrupt water-level increases in valley bottoms result from increase in head in the shallow-fracture system. Water levels decline during periods of no rainfall as water discharges through fractures to adjacent streams.

Information on the depth of the shallow-fracture zone in Edd Fork is available from core- and borehole data. Drill data show that the upper 40 feet of the fracture zone on ridge tops surrounding Edd Fork has been removed by surface mining. Approximately 40 feet of mine spoil covers what is left of the shallow-fracture zone in these areas. Sandstone immediately below the mine spoil contains a weathered and fractured zone

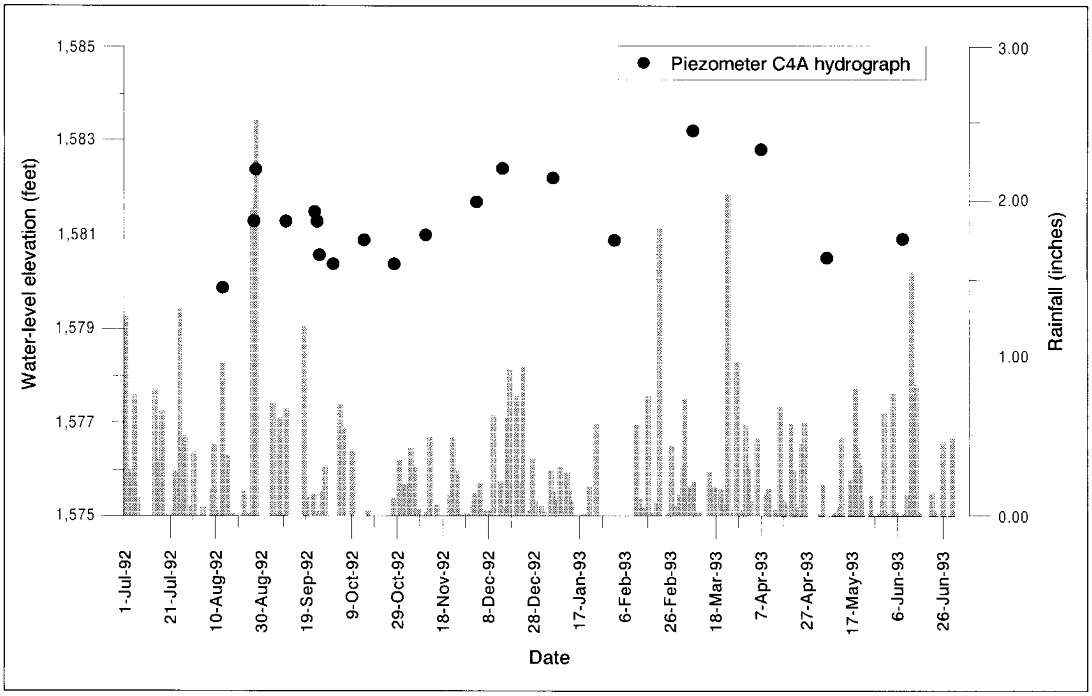


Figure 23. Response of piezometer C4A in shallow-fracture zone to rainfall.

at a depth between 50 and 60 feet below the top of the sandstone. In core hole B, only the interval between 50 and 60 feet accepted injected water. Drill cuttings from six piezometer boreholes at site B show lateral and vertical variations in the extent of weathering.

The valley-side location shows numerous fractured and weathered zones extending to the base of a sandstone unit 60 feet below the surface. Fractures are mostly high-angle and weathered bedding planes. Drilling circulation was lost in a high-angle fracture at 30 feet during coring. An open fracture with an aperture of approximately 6 inches was observed in borehole A2 at a depth of 21 feet.

Fractures at site C, adjacent to Edd Fork, extend to a depth of approximately 60 feet. The upper 30 feet is highly weathered. Because the shallow-fracture zone is defined on the basis of hydraulic characteristics, the lower boundary of this zone may not extend into the deeper fractures at 50 to 60 feet. Water-level data, discussed later in this section, indicate that deeper fractures may be associated with regional flow. The lower boundary of the shallow-fracture zone, however, is transitional.

Shallow fractures less than 60 feet deep are shown by pressure-injection data to be the most conductive zones in the study area. The fracture-dependent flow in this system is apparent from the variation in conductivities in adjacent test intervals.

Elevation-Head Zone

The elevation-head zone, located above drainage, is defined as a region where the head in a piezometer is approximately equal to the elevation of the midpoint of the piezometer open interval. This zone is characterized by a downward head loss over the entire zone of approximately I foot per foot. The near-vertical downward gradient is attributable to hydraulic stratification resulting from highly conductive coal beds that are interbedded with poorly conductive sandstone, shale, and claystone.

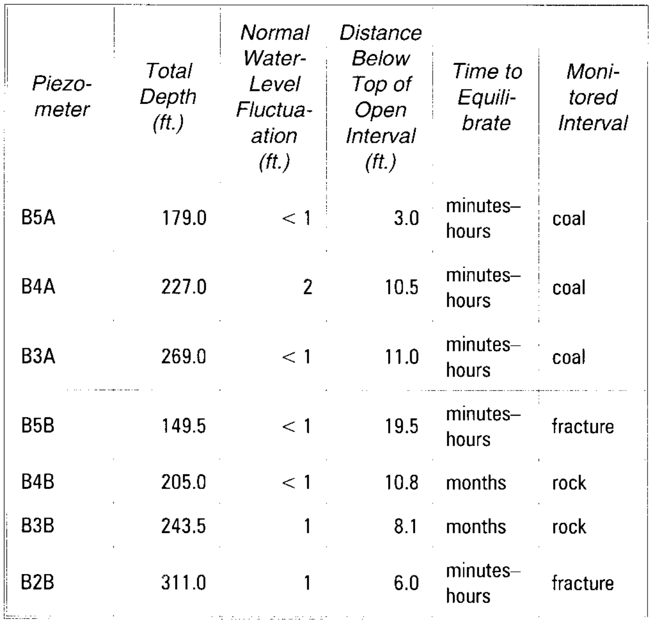
The elevation-head zone in Edd Fork lies below the shallow-fracture zone and extends into the sandstone unit below the Hazard No. 7 coal. The boundaries of the elevation-head zone are transitional, but in general are located at the approximate elevation where pressure head becomes a part of the total head. The location of the bottom boundary is determined in part by the position of the Hazard No. 8 coal seam, indicating this coal bed's role as an efficient drain. Vertical distance above drainage may also be a factor. Maximum depth to the bottom of this zone from the ridge top is approximately 300 feet (see Fig. 22).

The elevation-head zone in Edd Fork contains three main coal beds, the Hazard No. 8 rider through Hazard No. 7 coal seam (see Fig. 7), that are sandwiched between less conductive strata. Coal-bearing intervals in core hole B have conductivities that range from 1 X 10-4 fpm to 4 X 10-7 fpm. The lowest conductivities were calculated for two thin splits of the Hazard No. 8 rider coal. Coal-bed intervals having a coal thickness of at least 1.9 feet have equivalent-porous-media hydraulic conductivities that range from 1 X 10-4 to 3 X 10-5 fpm. These values are at least 10 times greater than the horizontal conductivity of surrounding sandstone and shale. Lithologic stratification creates hydraulic stratification where conductivity differences between coal beds and other strata may be four orders of magnitude or more. Such conductivity extremes between coal beds and non-coal strata cause flow to be nearly vertical in the non-coal strata and nearly horizontal in the coal beds.

Fractures are present in the elevation-head zone although they are less frequent than in the shallow-fracture zone. Loss of drilling circulation in this zone and fracture-controlled heads indicate that fractures influence flow locally in this zone, but the net impact of fractures throughout the elevation-head zone is unknown.

Water levels in the elevation-head zone near the ridge interior are generally stable, seldom varying by more than a foot (Table 3). Response to purging indicates that coal beds and fractures equilibrate more rapidly than piezometers in unfractured sandstone and

Table 3. Summary of piezometric data for the elevation-head zone.



Piezometer	*Total Depth (ft.)*	*Normal Water-Level Fluctuation (ft.)*	*Distance Below Top of Open Interval (ft.)*	*Time to Equilibrate*	*Monitored Interval*
B5A	179.0	< 1	3.0	minutes–hours	coal
B4A	227.0	2	10.5	minutes–hours	coal
B3A	269.0	< 1	11.0	minutes–hours	coal
B5B	149.5	< 1	19.5	minutes–hours	fracture
B4B	205.0	< 1	10.8	months	rock
B3B	243.5	1	8.1	months	rock
B2B	311.0	1	6.0	minutes–hours	fracture

shale. Figure 24 shows a hydrograph for a typical coalbed piezometer in the elevation-head zone. This piezometer generally shows an increase in water level during winter months and a decrease during dry months. This response is in contrast with the hydrograph for piezometer 13413 (Fig. 25), located in an interval just above piezometer 134A. The hydrograph for piezometer 13413 indicates the piezometer is not directly affected by seasonal rainfall patterns. Instead, piezometer B4B indicates a gradual decline in water level immediately following installation in August. The water level was abruptly lowered by purging on two different occasions. Water levels appear to have equilibrated after the second purging. Had purging not occurred, water levels would have taken many months to reach equilibrium with the surrounding strata.

Even though the elevation-head zone lies below the shallow-fracture zone, open fractures are not uncommon in the elevation-head zone. Fractures, however, are less directly connected to the surface here, as indicated by subdued changes in water levels. The distribution and interconnection of fractures among lithologic units undoubtedly play an important role in vertical groundwater flow.

Pressure-Head Zone

The pressure-head zone extends downward from the base of the elevation-head zone (or the shallow-fracture zone near valley bottoms). Eleven piezometers (see Fig.12 for locations) were used to define the boundaries. The upper boundary of the pressure-head zone in Edd Fork is located just above the Hazard coal bed. Conductivity differences between coal beds and other lithologic units in the pressure-head zone are less than in shallower rocks. Lowest calculated horizontal values for this zone are approximately 1 X 10-7 fpm.

Equilibration rates for piezometers in the pressure head zone are dependent on the hydraulic conductivity of the surrounding strata. Piezometers in above-drainage coal beds equilibrate within minutes to weeks (Table 4). Piezometers deep in the ridge interior take a month or longer to stabilize after stressing. The two piezometers in the Magoffin Member tend to remain at the levels to which they were purged (see Fig. 26 for piezometer Al B hydrograph). Whether or not these two piezometers ever equilibrated with the surrounding strata over the course of this investigation is uncertain.

Ground-water flow in the pressure-head zone is generally downward in the ridge interior at this site. Vertical head drops adjacent to Edd Fork are an order of magnitude greater than apparent horizontal gradients, indicating at least some part of the flow is moving vertically downward below the level of Edd Fork into a more regional flow system. Ground-water gradients in this zone depend on location within the flow system.

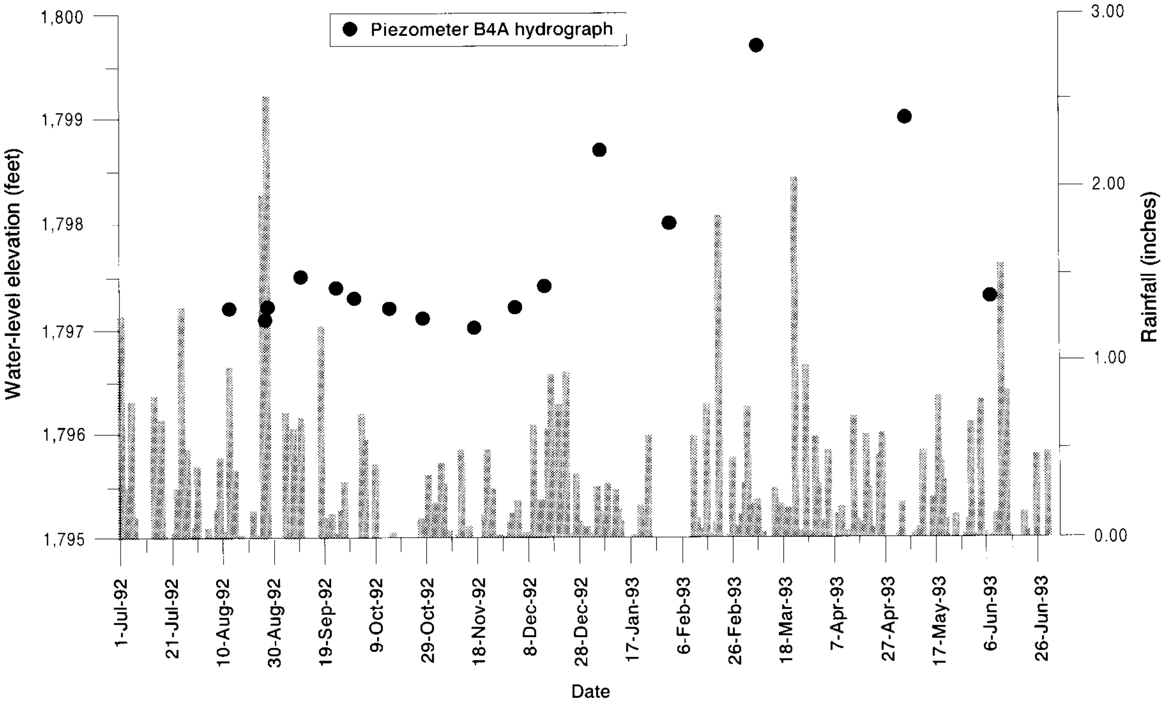


Figure 24. Hydrograph for coal-seam piezometer B4A in the elevation-head zone.

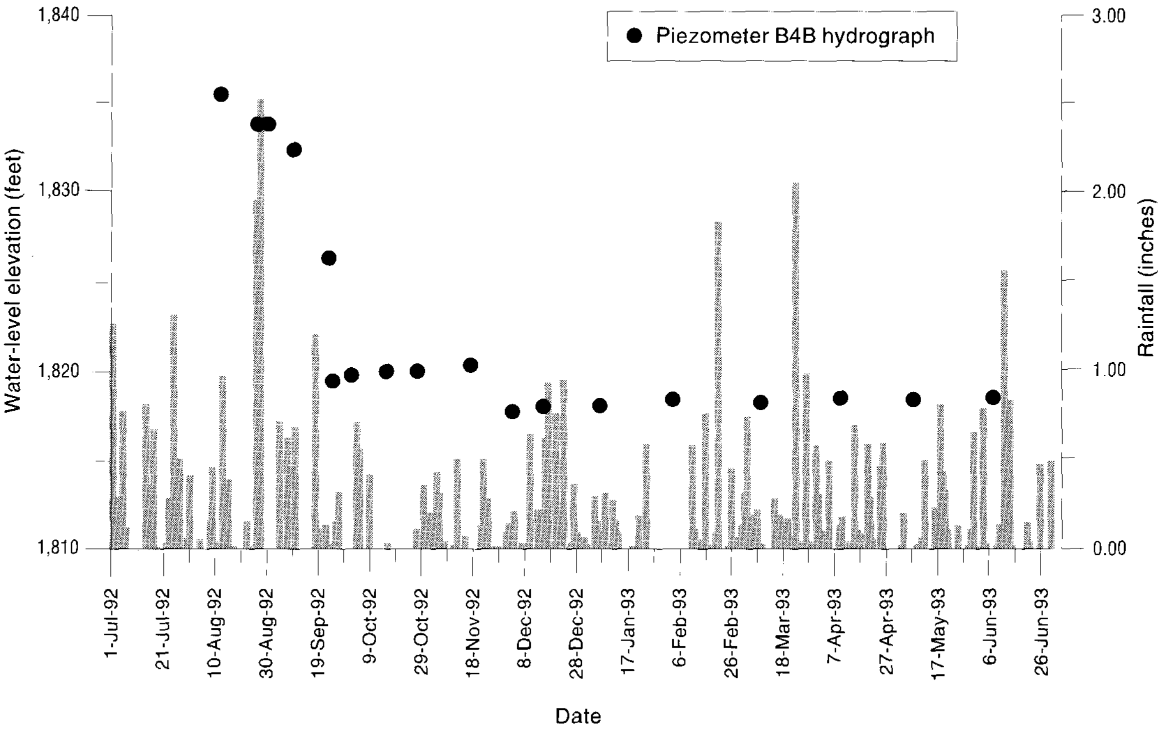


Figure 25. Hydrograph for piezometer B4B, completed in rock above piezometer B4A in the elevation-head zone.

Table 4. Summary of piezometric data for the pressure-head zone.

Piezometer	*Total Depth (ft.)*	*Normal Water-Level Fluctuation (ft.)*	*Distance Below Top of Open Interval (ft.)*	*Time to Equilibrate*	*Monitored Interval*
B2A	354.5	1	7.0	weeks	coal
A2B	85.5	1	5.0	days	coal
B1B	492.0	?	0.3	> 6 mos.	sandstone
A2A	233.5	1	40.0	days	fracture
C2B	70.5	1	18.0	minutes	fracture
C2A	130.5	1	45.0	minutes	fracture
A1B	328.0	1	(−18)	> 6 mos.	Magoffin
C1B	173.5	?	(−24)	month	Magoffin
B1A	684.0	1	9.1	> 6 mos.	below Magoffin
A1A	415.0	1	5.0	month	below Magoffin
C1A	260.0	1	8.0	month	below Magoffin

Calcium-Magnesium-Bicarbonate Sulfate Zone

(Above-Magoffin-Member Zone)

Coal-bearing strata located above the Magoffin Member typically yield calcium-magnesium-bicarbonate or calcium-magnesium-sulfate-type ground water. Analyses of water samples from nine piezometers, shown on the Piper diagram in Figure 27, illustrate representative water quality for this zone. Maximum and minimum constituent values measured in piezometers completed above the Magoffin Shale are included with the Piper diagram. Water quality is obviously variable over short vertical and horizontal distances in this zone.

Sodium-Bicarbonate Zone

(Below-and-including-Magoffin-Member Zone)

The sodium-bicarbonate zone encompasses strata from the top of the Magoffin Member to the saline/fresh-water interface. Below the interface, water is a sodium-chloride type. The location of the interface is inferred to be at an elevation between 1,000 and 1,200 feet above mean sea level (Hopkins, 1966) in the vicinity of the study area. This elevation is probably realistic for Beech Fork, where salty water is documented in wells

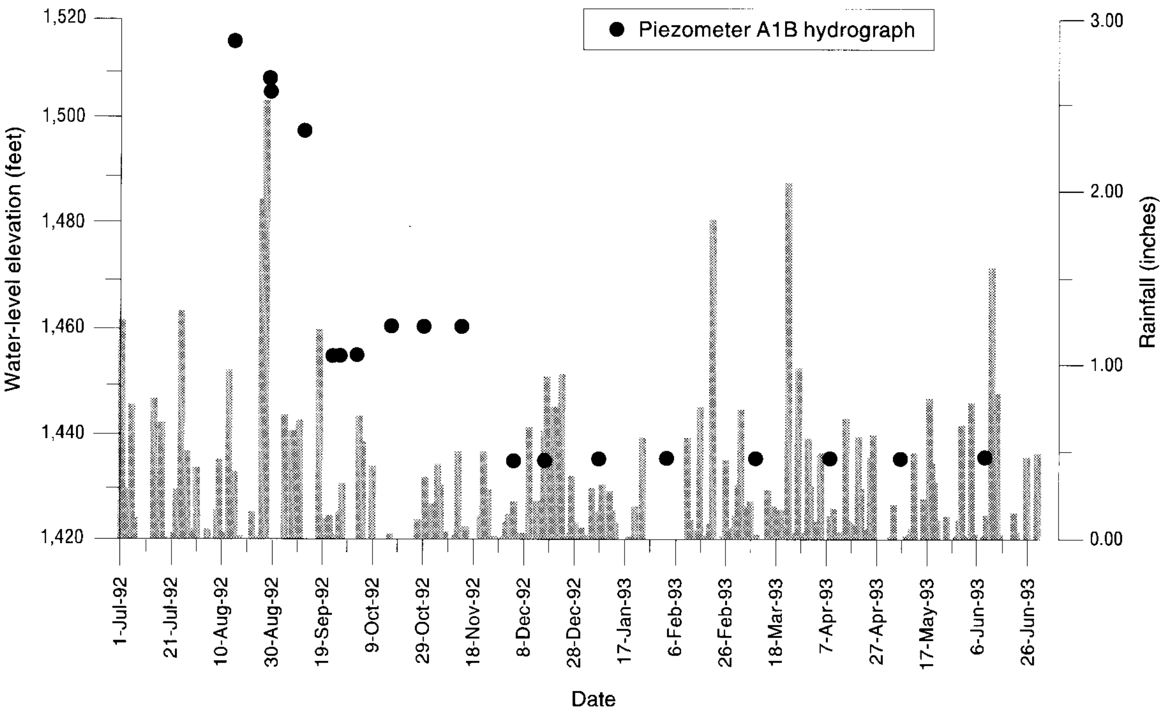


Figure 26. Hydrograph for piezometer A1B in the pressure-head zone.

drilled adjacent to Beech Fork, downstream of the study area. The elevation of the interface beneath the Edd Fork watershed is not documented.

Water-quality data are available for two piezometers within the Magoffin Member and for three piezometers below the Magoffin Member. The Piper diagram (Fig. 27) contrasts the sodium-bicarbonate-type water with the calcium-magnesium-sulfate-bicarbonate-type water obtained from strata above the Magoffin Member. Maximum and minimum constituent values are also listed in Figure 27. In general, water quality in the sodium-bicarbonate zone shows less variation in composition and total dissolved constituents than ground water at shallower depths.

GROUND-WATER FLOW SYSTEM

The ground-water flow system in the Edd Fork watershed can be described in terms of the zones discussed above. Boundaries separating these zones are transitional but can be approximated from water-level and water-quality data. The shallow-fracture zone functions as both a recharge zone and a discharge zone. Recharge from precipitation infiltrates vertically through the soil layer into the underlying fracture system. Water migrates vertically downward and laterally through the upper, unsaturated part of the fracture system as gravity drainage. Some percolating water exits the valley wall as springs where fractures or coal beds intersect the surface. Discharge from springs re-infiltrates into the ground-water system downslope or continues as surface flow.

A water table that intersects Edd Fork in the valley bottom is present within the shallow-fracture zone along the valley slope between site A and site C. The water-table surface fluctuates seasonally, as well as in response to specific rainfall events. Past mining activity in the watershed has probably depressed the elevation of the saturated zone in the ridge tops and on hill slopes beneath mining benches. A similar effect was documented at a mined area in Knott County, where the water level in a well downslope of an active contour cut declined in response to diversion of water along the bench (Kipp and Dinger, 1991).

Flow to Edd Fork is sustained by discharge from the shallow-fracture zone. Mine spoil throughout the watershed undoubtedly stores and releases water that helps to sustain flow during dry periods. Because ground-water flow is three dimensional, another component of flow in this zone is approximately parallel to Edd Fork and may discharge downstream to Edd Fork or to Trace Branch.

Water that does not discharge through the shallow fracture zone percolates into the elevation-head zone, partially through vertical fractures and partially through intergranular flow. The elevation-head zone is saturated except for the Hazard No. 8 coal bed. Flow throughout this zone is nearly vertical downward in

Ranges (mg/L)

Above Magoffin	**pH**	**TDS**	**Ca**	**Mg**	**Na**	**K**	**SO_4**	**HCO_3**	**Cl**
Maximum	7.46	1610	191	149	52.8	11.2	1050	193	4.59
Minimum	5.73	30	2.30	1.58	0.914	1.82	9.59	11	1.00
Below and Including Magoffin									
Maximum	8.87	652	4.0	1.45	232	3.47	159	552	11.0
Minimum	8.34	384	1.04	0.377	155	2.05	5.36	377	5.36

Note: Maximum/minimum data do not include mine no. 2 data.

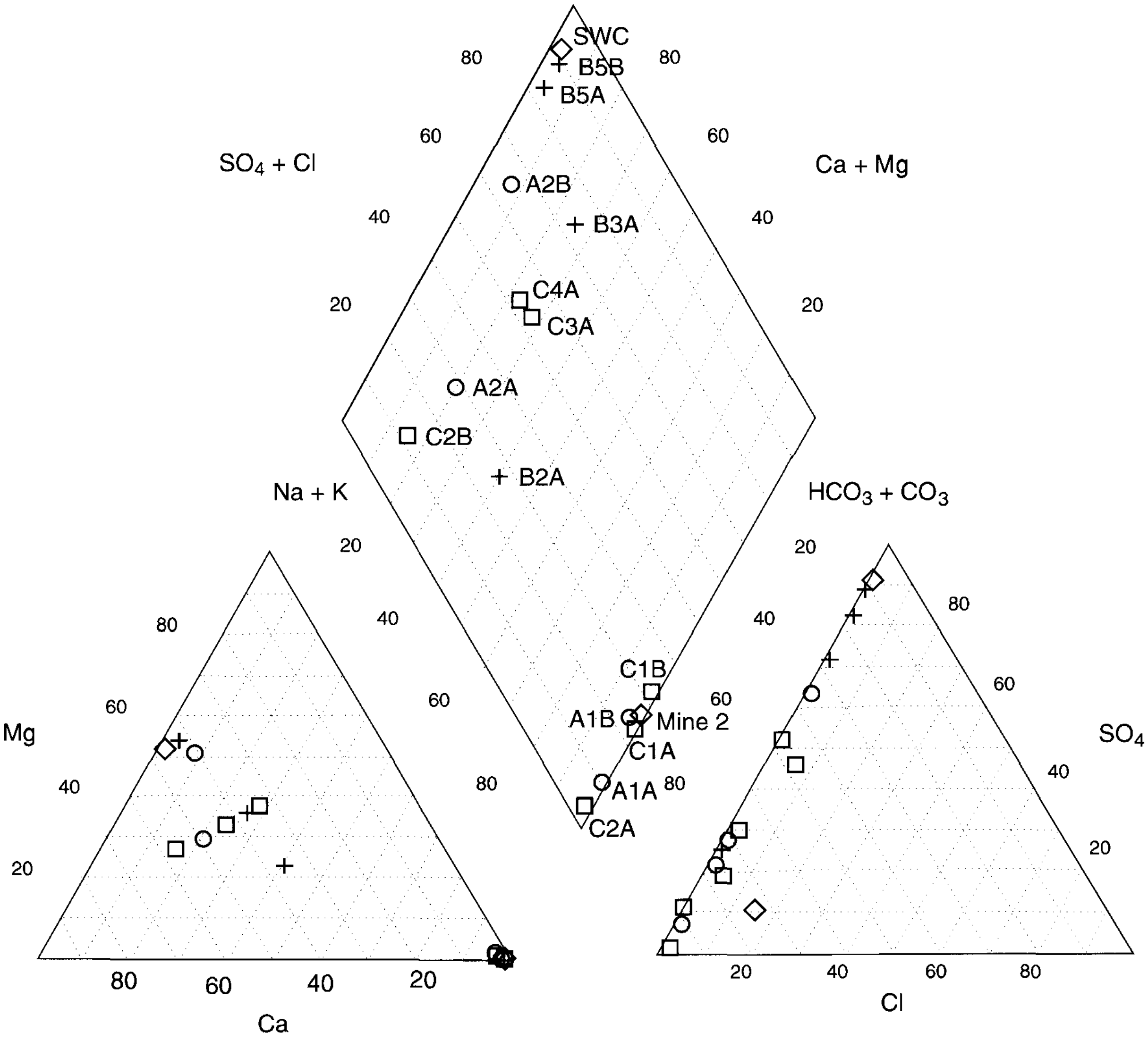


Figure 27. Water types present in the Edd Fork watershed.

non-coal rock, but is more nearly horizontal in coal beds. Near-vertical, downward gradients in rock are in response to more conductive coal beds that divert part of the flow horizontally toward valley walls. Water either discharges as springs, as evidenced by sustained flow from the Hazard No. 8 coal seam at the base of the highwall, or it re-enters the shallow-fracture zone. Saturated conditions in the ridge core indicate that some water moves downward to recharge deep strata. Vertical fractures above drainage probably provide recharge conduits and promote greater flow than would occur intergranularly.

Below the elevation-head zone, ground water is confined. The top of the pressure-head zone extends to about 150 feet above the level of Edd Fork (Fig. 22). Upper boundaries are the elevation-head zone or the shallow-fracture zone. Vertical gradients in the pressure-head zone are less steep than in the elevation-head zone, but flow has a strong downward component. Head data from the valley-bottom sandstone indicate a regional system, flowing downward and laterally to the east that does not discharge to Edd Fork. Because flow is three dimensional, a third probable component of flow in this sandstone is parallel to Edd Fork, toward Trace Branch.

The Magoffin Member, a thick, shale/sandy shale sequence, is located below the level of Edd Fork. Because strata are saturated below the Magoffin, some flow must pass through the Magoffin to recharge the regional flow system. The Magoffin, therefore, is a leaky, confining unit. Because it is laterally extensive and has a steep downward gradient, significant quantities of water may pass through this unit. Ground water below the Magoffin Member is sodium-bicarbonate type. As a result of this water-quality difference, two ground-water zones are distinguishable. Figure 28 illustrates the typical ground-water flow of the site.

SUBSIDENCE EFFECTS ON GROUND-WATER RESOURCES

A considerable body of existing research documents the observed short-term hydrologic impacts of rapid subsidence associated with longwall mining. A rather comprehensive review of this information is included in a report prepared by the Virginia Center for Coal and Energy Research (Roth and others, 1990). In general, fracturing and sagging of strata caused by subsidence

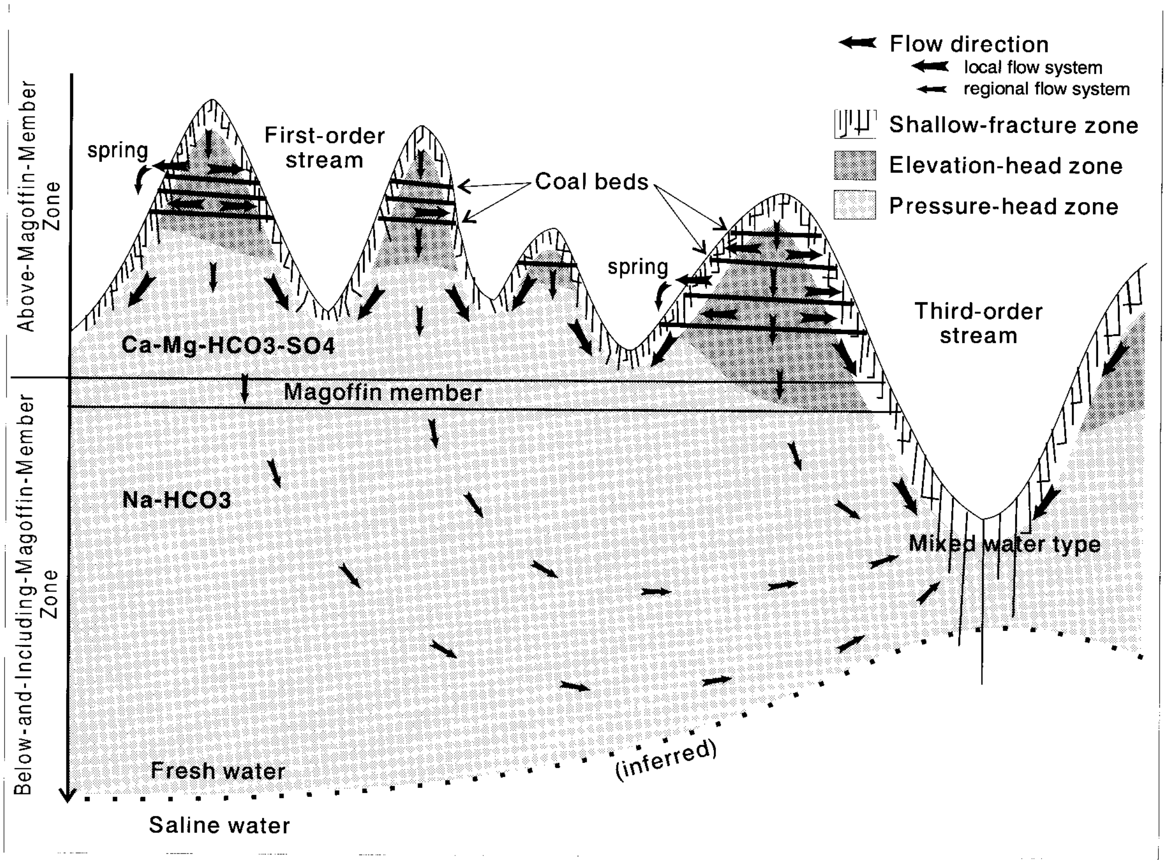


Figure 28. Conceputal model of local and regional ground-water flow, showing ground-water zones typical of Edd Fork watershed and vicinity.

over mined panels 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.

Water levels in wells over and immediately adjacent to the subsided area commonly fall, at least temporarily, following mining. Later, settlement and compression apparently lead to reductions in permeability and storativity, and partial recovery of water levels in some wells. Springs may change position, typically moving to lower elevations in steep terrain. Small surface streams immediately over the mined area often experience reduced discharge during base-flow conditions, particularly if the mined seam is at shallow depth or at an elevation above major regional drainage. However, base flow of larger regional streams draining extensive undermined areas may increase as the result of enhanced infiltration and a reduction in evapotranspiration due to subsidence.

Surface subsidence over longwall mines has also been extensively studied and is fairly well documented. The geomechanics and hydrogeology of overburden associated with mined panels is more difficult to investigate. Mining engineering concepts of strata movement and direct observations, however, indicate that 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. Figure 29 shows subsidence zones described by Coe and Stowe (1984).

Above the totally caved zone, a transitional zone of highly fractured rock reportedly reaches 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, an additional zone may exist above the extensively fractured bedrock in the subsidence trough. The majority of rock movement in this zone apparently occurs as minor horizontal slippage between strata. As a result, the strata in this zone

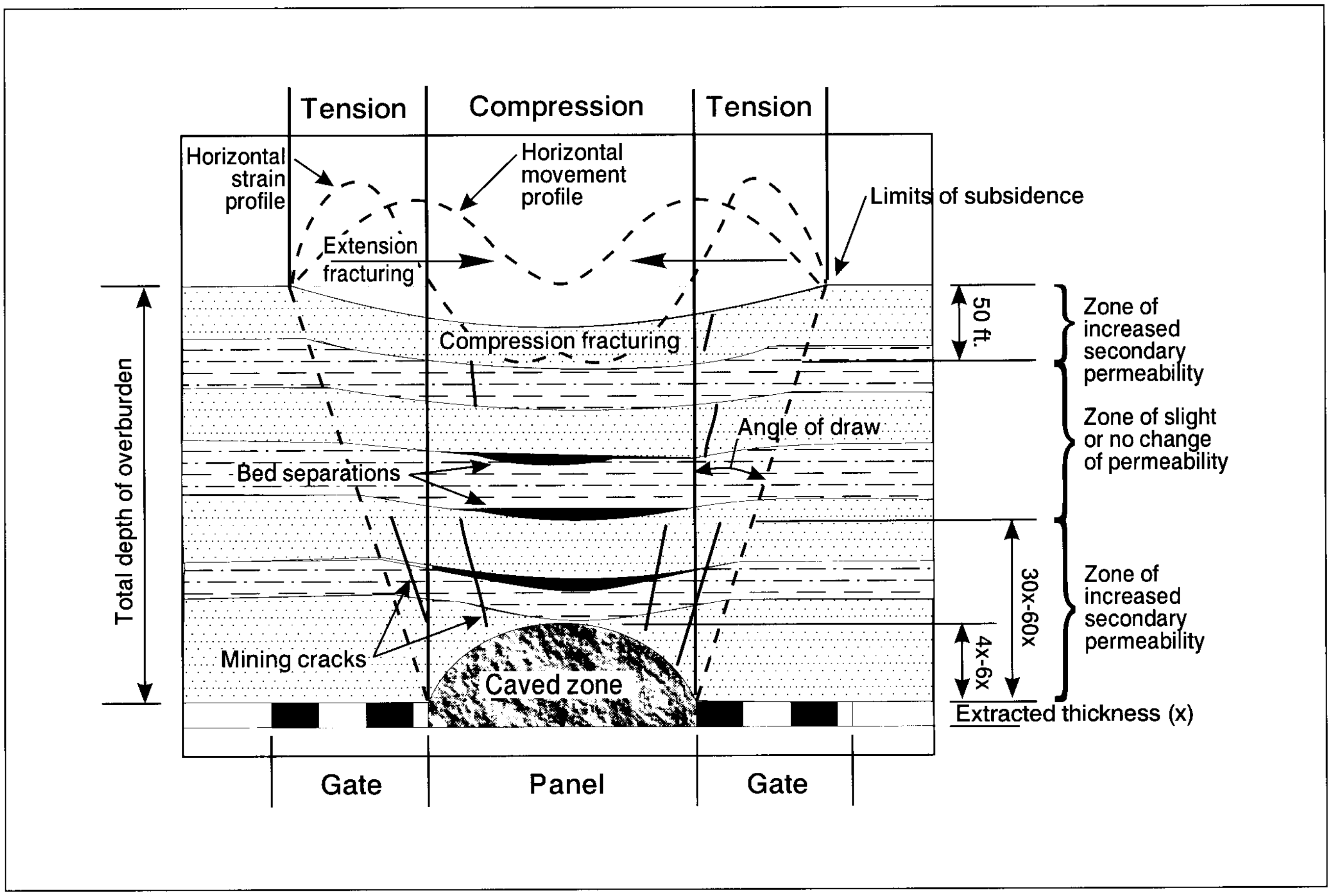


Figure 29. General subsidence effects related to longwall mining (modified from Coe and Stowe, 1984).

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

Near-surface strata (generally at depths up to about 50 feet) are susceptible to fracturing and movement during subsidence. Although water levels in shallow wells often decline slightly due to increases in porosity and permeability associated with subsidence, these changes may actually result in an increased availability of ground water from shallow wells.

Wells completed directly over mined longwall panels normally show the greatest effects from dewatering, often with precipitous water-level declines in the fractured zones. Smaller changes in water levels can also extend horizontally off of the panel area, with an angle of dewatering influence up to approximately 40' (Cifelli and Rauch, 1986). This angle is defined as the angle between a vertical line projected upward from the edge (rib or end) of a longwall panel and a line projected to the farthest point of dewatering effects from the longwall panel. The extent of hydrologic effects depends on several site-specific factors, including lithology, topography, stratigraphy, and pre-existing joints or fractures. The depth, location with respect to regional drainage, dimensions, and timing of the mining operation can also influence the nature, extent, magnitude, and duration of changes in the ground-water flow system over a longwall mine.

Water-quality changes sometimes occur in response to mining because fracturing often changes the existing flow pattern and exposes new mineral faces to weathering. In many wells, the only observed change in water quality is a minor increase in the concentration of dissolved solids. In situations where water quality varies significantly prior to mining, the chemistry of water from a single well may change dramatically in response to changes in ground-water flow associated with subsidence.

ANTICIPATED HYDROLOGIC EFFECTS FROM LONGWALL MINING AT EDD FORK

Based on reported observations from other studies, fracturing from subsidence may extend upward from the mine and pass through the Magoffin Member at the Edd Fork study site. If extensive fracturing extends only 30 times the extracted thickness, fractures should not reach the earth's surface (Fig. 30). In this case, a zone of lower hydraulic conductivity (the aquiclude zone) should remain between the mine and water flowing on the surface or in the shallow-fracture zone. As a result, a minimal amount of water would move into the mine from the surface.

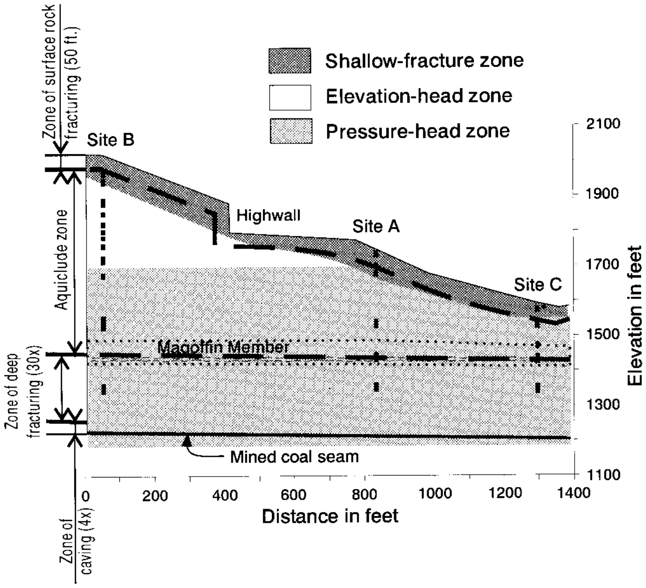


Figure 30. Minimum expected extent of subsidence effects in the Edd Fork watershed.

If the zone of fracturing is thicker (up to 60 times the extracted thickness), the aquiclude zone would only be present on the ridge tops, and the shallow-fracture zone in the valley bottom and lower slopes would be directly connected to the mine (Fig. 31). If this happens, more water will flow from the surface to the mine, and calcium and magnesium water from the shallow groundwater flow system will enter the deeper ground-water system, where sodium is currently the dominant cation. In either case, fracturing is generally not expected to extend into the elevation-head zone of the pre-mining flow system.

Fracturing will likely lead to decreases in water levels in the pressure-head zone. Rocks in this zone at Edd Fork are relatively tight and apparently do not provide sufficient water to support domestic water-supply needs. As a result, subsidence should have only limited impact on potential ground-water supplies in the area. If fracturing associated with subsidence does not breach the Magoffin Member, very little change in the existing flow system will occur above the Magoffin Member in the pressure-head zone.

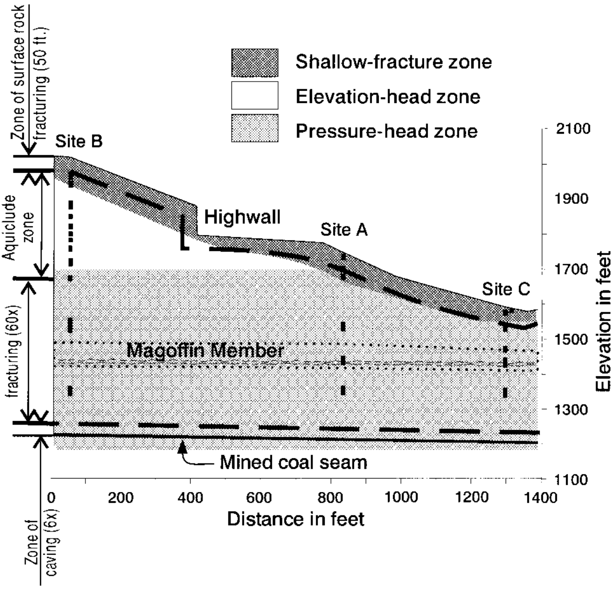


Figure 31. Maximum expected extent of subsidence effects in the Edd Fork watershed.

In all likelihood, flow in the elevation-head zone will not be greatly affected by subsidence. The coal seams are apparently presently able to act as drains to effectively move water laterally in this flow zone. This leads to a nearly vertical downward gradient in strata between the coals. Major fracturing due to subsidence is not expected to extend into the elevation-head zone in the Edd Fork study basin because of its vertical separation from the mined seam.

The shallow-fracture zone will probably undergo changes in response to subsidence associated with mining. Water levels in near-surface wells commonly decline temporarily after mining as a result of increased permeability. Water levels should rebound, however, as the additional void spaces become saturated. Piezometers less than about 150 feet deep at the ridge top site will be included within a 40' angle of potential dewatering influence from the edge of the previous adjacent panel. Frequent measurements during the mining of panel 7 should also provide additional insight into hydrologic influence as the working face approaches each set of piezometers on that panel.

Previous investigators have documented total loss of some piezometers during longwall mining (Booth, 1992). Depending on the vertical extent of intense fracturing, 5 to 12 of the 24 piezometers may be severely affected by subsidence at the Edd Fork site. TDR data should provide additional information on the thickness of the zone of fracturing and any relationship to piezometer loss or damage. Large variations in mining depth (because of topographic relief) as well as variations in stratigraphy and the extent of existing fracturing due to natural processes will likely influence the extent of fracturing related to subsidence. The thickness of the zone of intense fracturing will very likely vary significantly, causing a high degree of variability in hydrologic response along the longwall panel.

Mining personnel have reported that increased water influx to the mine is observed on a delayed basis shortly after (12 to 18 hours) precipitation events exceeding about 1 inch in magnitude. This has not been documented by flow measurement for specific precipitation events. Other than this observation, increased water influx to the mine has not been noted, indicating that little water is being released from the rock mass above the mine. Approximately 45 percent of the overlying rock section is shale or sandy shale, and these rocks are apparently not capable of releasing large quantities of water on a short-term basis.

Preliminary surface subsidence data indicate that only about 0.7 to 1.5 feet of subsidence is occurring on the centerline of the longwall panels. This represents only about 10 to 20 percent of the extracted thickness, which is considerably less than the maximum of 55 to 70 percent commonly reported for mines in the Appalachian Basin (Peng, 1992). Factors controlling the final surface deformation include the physical properties of the overburden strata, mine opening size (width and length of panel), mining depth, topography, and time. Continued monitoring of the TDR cables, piezometers, rain gage, flume, and surface subsidence monuments will provide evidence to evaluate if the response of the hydrologic system in the Edd Fork study area is similar to results from investigations at other research sites where the effects of longwall mining have been previously studied.

REFERENCES CITED

Aller, L., Petty, R., Lehr, J.H., Nielson, D., and Denne, J.A., 1989, Handbook for suggested practices for the design and construction of ground-water monitoring wells: National Water Well Association, 398 p.

Barfield, B.J., Warner, R.C., and Haan, C.T., 1981, Applied hydrology and sedimentology for disturbed areas: Stillwater, Ok., Oklahoma Technical Press, 603 p

Bauer, R.A., Dowding, C.H., Van Roosendaal, D.J., Mehnert, B.B., Su, M.B., and O'Connor, K., 1991, Application of time domain reflectometry to subsidence monitoring: U.S. Department of Interior, Office of Surface Mining Reclamation and Enforcement, Technical Report 598, 48 p.

Booth, C.J., 1992, Hydrogeologic impacts of underground (longwall) mining in the Illinois Basin, in Peng, S.S., ed., Proceedings, Third Workshop on

Surface Subsidence Due to Underground Mining: Morgantown W.Va., June 1992, p. 222-227.

Chesnut, D.R., 1981, Marine zones of the upper Carboniferous of eastern Kentucky, in Cobb, J.C., Chesnut, D.R., Hester, N.C., and Hower, J.C., eds., Coal and coal-bearing rocks of eastern Kentucky (Guidebook and roadlog for Coal Division of Geological Society of America Field Trip No. 14): Kentucky Geological Survey, ser. 11, p. 57-66.

Cifelli, R.C., and Rauch, R.W., 1986, Dewatering effects from selected underground coal mines in north-central West Virginia, in Proceedings of Second Workshop on Surface Subsidence Due to Underground Mining: West Virginia University, Morgantown, W.Va., p. 249-263.

Coe, C.J., and Stowe, S.M., 1984, Evaluating the impact of longwall mining on the hydrologic balance, in Graves, D.H., and DeVore, R.W., eds., Proceedings, 1984 Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation: University of Kentucky, Lexington, December 1984, p. 395-403.

Ferm, J.C., and Melton, R.A., 1977, A guide to cored rocks in the Pocahontas Basin: Carolina Coal Group, Department of Geology, University of South Carolina, 90 p.

Hopkins, H.T., 1966, Fresh-saline interface map of Kentucky: Kentucky Geological Survey, ser. 10, Scale 1:500,000.

Hvorslev, M.J., 1951, Time lag and soil permeability in ground water observations: U.S. Army Corps of Engineers, Waterways Experiment Station, Bulletin 36, 50 P.

Kentucky Water Resources Commission, 1959, Kentucky water resources study: Kentucky Department of Conservation, Division of Flood Control and Water Usage, 109 p.

Kipp, J.A., and Dinger, J.S., 1991, Stress-relief fracture control of ground-water movement in the Appalachian Plateaus: Kentucky Geological Survey, ser. 11, Reprint 30, 11 p.

Leist, D.W., Quinones, Ferdinand, Mull, D.S., and Young, M., 1982, Hydrology of Area 15, Eastern Coal Province, Kentucky and Tennessee: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-80, 81 p.

Minns, S.A., 1993, Conceptual model of local and regional ground-water flow in the Eastern Kentucky Coal Field: Lexington, University of Kentucky, Ph.D. Dissertation, 299 p.; Kentucky Geological Survey, ser. 11, Thesis Series 6, 194 p.

Minns, S.A., Kipp, J.A., Carey, D.I., Dinger, J.S., and Sendlein, L.V.A., 1994, Hydrologic impact of below drainage mines in Kentucky: Pre-mining conditions: Field data: Kentucky Geological Survey, Open-File Report OF-94-09, 224 p.

Morse, W.C., 1931, Pennsylvanian invertebrate fauna [of Kentucky]: Kentucky Geological Survey, ser. 6, v. 36, p. 293-348.

Peng, S.S., 1992, Surface subsidence engineering: Littleton, Colo., Society for Mining, Metallurgy, and Exploration, Inc., 161 p.

Quinones, Ferdinand, Mull, D.S., York, K., and Kendall, V., 1981, Hydrology of Area 14, Eastern Coal Province, Kentucky: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-137,82 p.

Rice, C.L., Sable, E.G., Dever, G.R., Jr., and Kehn, T.M., 1980, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States-Kentucky: U.S. Geological Survey Professional Paper 111 0-F, 32

Rice, D.D., 1975, Geologic map of the Helton Quadrangle, southeastern Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-1227.

Roth, R., Randolph, J., and Zipper, C., 1990, High-extraction mining, subsidence, and Virginia's water resources: Virginia Center for Coal and Energy Research, Virginia Polytechnic Institute and State University, Blacksburg, Va., p.

Tektronix, 1987, Tektronix metallic TDR's for cable testing: TEK 1500B series metallic cable TDR's application note: Beaverton, Ore., 16 p.

APPENDIX A: KENTUCKY GROUND-WATER DATA BASE RECORD NUMBERS

Field ID No. (Piezometer No.)	*Data Base Record No.*
A1A	13856
A1B	13857
A2A	13858
A2B	13859
A3A	13860
A3B	13861
B1A	13862
B1B	13863
B2A	13864
B2B	13865
B3A	13866
B3B	13867
B4A	13868
B4B	13869
B5A	13870
B5B	13871
B6A	13872
B6B	13872
C1A	13874
C1B	73875
C2A	13876
C2B	13877
C3A	13878
C4A	13879

APPENDIX B:
TIME DOMAIN REFLECTOMETRY

Time domain reflectometry (TDR) is a method for locating and identifying strain or breaks in any type of dual conductor cable. Ultra-fast pulses of electrical energy are sent through the cable, and any change in the impedance of the cable causes some of the energy to be reflected back. The TDR testing unit measures the time that it takes for the pulses to travel out to and be returned from a reflector. Using this time value and the known velocity of propagation for the cable, the TDR evaluates the distance to each reflector. Magnitude of the reflected energy is then displayed on the TDR screen with a distance scale indicating the locations of reflections as visible irregularities in the displayed trace (Tektronix, 1987).

The shape of a TDR trace indicates the nature of irregularities in the cable that are causing the reflections. Inductive faults (areas with higher resistance than the normal cable impedance) cause reflections in-phase with the initial voltage step. Capacitive faults (areas with lower resistance than the normal cable impedance) cause out-of-phase reflections. As a result, a large positive (upward) reflection indicates an open circuit (the end of the cable or a break along the length of the cable). A crimp or short in the cable causes a negative reflection, which is indicated as a large dip in the trace. TDR instruments are very sensitive to cable damage, and even minor crimps or abrasions of the cable normally produce changes in resistance that are evident on the resulting cable traces.

TDR was originally developed to locate faults in coaxial power transmission cables. However, the technique has also been adapted for monitoring deformation of cable grouted into rock masses. By monitoring changes in cable reflection signatures using TDR, both local extension and shearing of the cable as a result of rock mass deformation related to coal-mine subsidence can be documented (Bauer and others, 1991).

Cable installation and measurements for monitoring rock mass movements are relatively inexpensive and simple. Coaxial cable is lowered into a borehole, which is then filled with an expansive grout to bond the cable to the surrounding rock. Any changes in the distance between the inner and outer conductors of the cable, breaks in either conductor, or shorts caused by the conductors touching produce changes in the TDR trace. These changes can indicate the location and nature of deformation occurring as a result of mine subsidence.

One-half-inch-diameter FOAMFLEX FXA 12-50 unjacketed coaxial cable was installed in each of the three core holes at the Edd Fork study site for monitoring by TDR. This cable consists of a copper-clad aluminum center conductor, a low-loss cellular polyethylene foam dielectric (a material that does not conduct a current, but does permit the passage of the lines of force of an electrostatic field), and a smooth-wall aluminum outer conductor. FXA 12-50 has a velocity of propagation of 0.81 percent and an impedance of 50 ohms.

Prior to installation, crimps were placed in each cable at regular intervals, providing known reference points to improve distance evaluation. The bottom end of each cable was coated with epoxy and then wrapped with electrician's tape to seal out water. A section of 1-inchdiameter black iron pipe was attached to the lower end of each cable with clamps to serve as a weight and a guide to assist in the vertical installation of the cable in the core holes. The pipe also provides an anchor for the base of the cable in the cement grout. Cables were lowered down 3-inch-diameter NX core holes to refusal.

Grout was mixed in the ratio of 65 percent weight of water to cement (7.6 gallons of water per 94-pound bag of cement). Intrusion-Aid Type 3-C was added at 2 percent by weight. This material is an expansive agent that enhances cable/ grout/ rock contact and also improves pumping of the grout by lowering its viscosity. Grout was placed in each hole using a tremie pipe so that slurry filled the hole upward from the bottom, thus displacing any ground water and limiting dilution of the grout by standing water. Grout was pumped into each hole until it returned to the surface. The cables were then cut off above ground surface, and locking covers were installed.

An N-type 50-ohm cable connector was attached to the top of each cable so that the TDR tester could be connected using a short 50-ohm precision cable with a BNC adaptor. A TEKTRONIX 1502C metallic time domain reflectometer was used to test the cables. This unit has an LCD display, operates under field conditions on an internal DC power source, and includes a chart recorder to provide hard copy of the test results. The chart recorder can be removed and replaced by an SP232 serial interface package to provide the ability to store digital waveforms on computer diskette. Waveform storage allows for the comparison of recorded traces from an individual cable to directly indicate the location and nature of changes.

Initial waveforms were obtained from each cable at the time of installation. Additional waveforms were later recorded after the grout had cured. Changes in the TDR signatures were observed in these later waveforms that were evidently the result of differential expansion and contraction of the grout rather than actual rock mass movement (for example, changes in TDR response were noted in the cased portion of core hole B where the cable is protected by a steel casing to a depth of 39 feet).

Grout samples collected in 3-inch-long sections of 1-inch-diameter PVC pipe during cable installation varied between slight expansion (0.1 inch) and contraction of up to 0.55 inch. These differences were probably the result of inconsistent mixing of the grout from batch to batch. As a result, rock mass response due to mining will be based on the comparison with the waveforms obtained after the grout had cured.

APPENDIX C:
WATER-LEVEL ELEVATIONS FOR PIEZOMETERS

Site A						
Date	*A1A Elev. (ft.)*	*A1B Elev. (ft.)*	*A2A Elev. (ft.)*	*A2B Elev. (ft.)*	*A3A Elev. (ft.)*	*A3B Elev. (ft.)*
27-Aug-92	1384.4	1508.2	1589.0	1691.9	1695.3	dry
28-Aug-92	1383.8	1506.6	1589.4	1692.2	1695.3	dry
10-Sep-92	1381.5	1498.4	1589.1	1692.7	1695.5	dry
23-Sep-92	1373.5	1455.1	1589.8	1692.8	1695.0	dry
24-Sep-92	1373.5	1455.1	1588.8	1692.8	1695.4	dry
25-Sep-92	1373.5	1455.1	1588.8	1692.8	1695.5	dry
1-Oct-92	1371.3	1455.4	1588.7	1692.5	1695.3	dry
15-Oct-92	1372.0	1460.6	1588.7	1692.7	1695.0	dry
28-Oct-92	1372.1	1460.7	1588.7	1692.3	1695.5	dry
12-Nov-92	1372.2	1460.8	1589.1	1692.4	1695.0	dry
3-Dec-92	1370.7	1434.6	1589.4	1692.7	1695.0	dry
15-Dec-92	1370.8	1434.7	1589.7	1693.0	1695.5	dry
6-Jan-93	1371.2	1434.9	1589.2	1693.4	1695.9	dry
2-Feb-93	1371.7	1435.0	1589.1	1693.2	1695.5	dry
9-Mar-93	1372.2	1435.1	1589.6	1693.8	1695.7	dry
8-Apr-93	1372.2	1435.1	1589.5	1693.8	1695.7	dry
6-May-93	1372.2	1435.2	1589.1	1693.7	1695.7	dry
8-Jun-93	1372.3	1435.3	1589.0	1693.2	1695.3	dry
8-Jul-93	1372.2	1435.3	1588.6	1692.6	1695.3	dry

Site B						
Date	*B1A Elev. (ft.)*	*B1B Elev. (ft.)*	*B2A Elev. (ft.)*	*B2B Elev. (ft.)*	*B3A Elev. (ft.)*	*B3B Elev. (ft.)*
27-Aug-92	1377.3	1637.3	1688.4	1725.8	1755.4	1785.4
28-Aug-92	1377.3	1636.6	1688.7	1725.8	1755.4	1785.5
10-Sep-92	1376.5	1627.2	1689.2	1725.8	1755.4	1785.5
23-Sep-92	1375.9	1619.9	1690.7	1725.8	1755.4	1783.4
24-Sep-92	1375.9	1619.9	1690.7	1725.8	1755.4	1783.4
25-Sep-92	1375.9	1579.8	1690.7	1725.8	1755.4	1783.4
1-Oct-92	1373.2	1582.1	1690.7	1725.6	1755.4	1783.3
15-Oct-92	1374.2	1586.0	1690.7	1725.6	1755.4	1783.4
28-Oct-92	1374.5	1588.5	1690.8	1725.9	1755.4	1783.5
17-Nov-92	1374.1	1590.1	1690.7	1725.6	1755.3	1783.4
3-Dec-92	1374.2	1582.1	1688.1	1725.7	1755.3	1780.4
15-Dec-92	1373.9	1583.7	1688.9	1725.6	1755.4	1780.5
6-Jan-93	1373.5	1583.4	1689.1	1725.6	1755.4	1780.5
2-Feb-93	1373.3	1580.1	1689.5	1725.7	1755.4	1780.5
9-Mar-93	1373.3	1574.0	1689.7	1725.7	1755.4	1780.5
8-Apr-93	1372.9	1566.7	1690.5	1725.7	1756.1	1780.5
6-May-93	1372.6	1566.7	1690.7	1725.6	1755.4	1780.5
8-Jun-93	1372.7	1562.9	1690.3	1725.6	1755.4	1780.5
8-Jul-83	1372.6	1560.2	1690.2	1725.6	1755.3	1780.5

Site B (Continued)

Date	*B4A Elev. (ft.)*	*B4B Elev. (ft.)*	*B5A Elev. (ft.)*	*B5B Elev. (ft.)*	*B6A Elev. (ft.)*	*B6B Elev. (ft.)*
27-Aug-92	1797.1	1833.7	1853.4	1877.2	dry	dry
28-Aug-92	1797.2	1833.7	1853.5		1931.4	dry
10-Sep-92	1797.5	1832.2	1853.5	1877.5	1931.3	dry
23-Sep-92	1797.4	1826.2	1853.5	1876.8	dry	dry
24-Sep-92	1797.4	1826.2	1853.5	1876.8	dry	dry
25-Sep-92	1797.4	1819.3	1853.5	1876.8	dry	dry
1-Oct-92	1797.3	1819.6	1853.4	1876.7	dry	dry
15-Oct-92	1797.2	1819.8	1853.4	1876.6	dry	dry
28-Oct-92	1797.1	1819.9	1853.3	1876.3	1931.6	dry
17-Nov-92	1797.0	1820.0	1853.5	1876.5	dry	dry
3-Dec-92	1797.2	1817.7	1853.4	1876.5	dry	dry
15-Dec-92	1797.4	1817.9	1853.6	1876.8	dry	dry
6-Jan-93	1798.7	1818.0	1853.6	1876.8	dry	dry
2-Feb-93	1798.0	1818.2	1853.5	1876.9	dry	dry
9-Mar-93	1799.7	1818.2	1854.0	1877.5	dry	dry
8-Apr-93	1800.2	1818.3	1854.3	1878.6	dry	dry
6-May-93	1799.0	1818.3	1854.0	1878.4	dry	dry
8-Jun-93	1797.3	1818.3	1853.5	1877.0	dry	dry
8-Jul-93	1797.1	1818.3	1853.1	1875.4	dry	dry

Site C						
Date	*C1A Elev. (ft.)*	*C1B Elev. (ft.)*	*C2A Elev. (ft.)*	*C2B Elev. (ft.)*	*C3A Elev. (ft.)*	*C4B Elev. (ft.)*
27-Aug-92	1370.8	1562.1	1525.8	1567.0	1579.8	1581.3
28-Aug-92	1370.8	1562.1	1526.2	1567.4	1582.8	1582.4
10-Sep-92	1370.3	1562.0	1526.2	1567.3	1577.1	1581.3
23-Sep-92	1370.0	1528.3	1526.4	1566.7	1576.4	1581.5
24-Sep-92	1343.8	1425.4	1526.1	1566.7	1576.5	1581.3
25-Sep-92	1356.7	1425.4	1526.4	1567.1	1577.0	1580.6
1-Oct-92	1368.1	1425.7	1526.3	1566.5	1576.5	1580.4
15-Oct-92	1368.6	1425.6	1526.5	1566.5	1576.5	1580.9
28-Oct-92	1368.9	1427.7	1526.4	1566.5	1576.8	1580.4
11-Nov-92	1368.9	1525.7	1526.5	1566.2	1577.3	1581
3-Dec-92	1367.1	1424.5	1526.5	1566.2	1577.2	1581.7
15-Dec-92	1367.6	1424.5	1526.7	1566.7	1579.6	1582.4
6-Jan-93	1367.7	1424.6	1526.5	1566.2	1578.7	1582.2
2-Feb-93	1368.2	1424.6	1526.3	1565.8	1577.2	1580.9
9-Mar-93	1368.2	1424.6	1526.7	1566.5	1581.6	1583.2
8-Apr-93	1368.2	1424.8	1526.7	1566.4	1580.9	1582.8
6-May-93	1368.1	1424.8	1526.3	1565.5	1576.6	1580.5
8-Jun-93	1368.0	1424.9	1526.1	1565.4	1576.9	1580.9
8-Jul-93	1367.9	1425.1	1525.6	1564.9	1575.2	1579.2

APPENDIX D: SPRING DATA FOR EDD FORK

Spring No.	*Source*	*Date*	*Flow Rate (gpm)*	*Conductivity (mmhos)*	*Comments*
1	sandstone	05/01/91	< 1	72	
		04/08/92	< 1	not sampled	
		12/15/92	< 1	51	
2A	Hazard No. 8 coal	04/08/92	2	not sampled	
3	Hazard No. 8 coal	04/08/92	< 1	not sampled	
6	?	04/08/92	3	not sampled	
8	?	04/08/92	2	not sampled	
10	?	04/08/92	1	not sampled	
11	sandstone	04/08/92	< 1	not sampled	
12	?	04/08/92	< 1	not sampled	
13	?	04/08/92	1	not sampled	
14	sandstone	04/08/92	1	not sampled	
15	Hazard No. 7 coal	12/15/92	< 1	328	iron stained
16	sandstone	12/15/92	< 1	187	

?=origin of spring not apparent

APPENDIX E:
PRECIPITATION AND RUNOFF STATISTICS FOR EDD FORK WATERSHED JULY 1992 THROUGH JUNE 1993

Month	*Year*	*Precipitation (inches)*	*Runoff (Inches)*	*Percent Runoff*	*Average Runoff (cfs)*	*Average Runoff (csm)**	*Maximum Runoff (cfs)*	*Minimum Runoff (cfs)*
July**	1992	2.71	0.092	3.4	0.053	0.196	0.66	0.05
August	1992	6.80	0.495	7.3	0.116	0.430	11.38	0.05
September	1992	4.04	1.031	25.5	0.250	0.924	8.56	0.05
October	1992	2.48	0.840	33.9	0.197	0.728	2.08	0.10
November	1992	2.57	0.945	36.8	0.229	0.847	0.85	0.11
December	1992	5.48	3.256	54.9	0.763	2.824	6.36	0.20
January	1993	2.22	1.956	88.1	0.459	1.697	1.53	0.28
February	1993	4.00	2.528	63.2	0.656	2.428	14.82	0.18
March	1993	6.18	5.419	87.7	1.270	4.700	14.82	0.32
April	1993	4.04	2.889	71.5	0.700	2.589	4.06	0.37
May	1993	3.53	0.966	27.4	0.227	0.838	1.79	0.10
June	1993	4.50	1.402	31.2	0.340	1.257	20.04	0.07
TOTALS		48.55	21.819	44.9	0.457	1.690	20.04	0.05

* cfs/square mile (watershed area=173 acres)

** July 19 through July 31

Mission Statement

The Kentucky Geological Survey at the University of Kentucky is a State mandated organization whose mission is the collection, preservation, and dissemination of information about mineral and water resources and the geology of the Commonwealth. KGS has conducted research on the geology and mineral resources of Kentucky for more than 150 years, and has developed extensive public data bases for oil and gas, coal, water, and industrial minerals that are used by thousands of citizens each year. The Survey's efforts have resulted in topographic and geologic map coverage for Kentucky that has not been matched by any other state in the Nation.

One of the major goals of the Kentucky Geological Survey is to make the results of basic and applied research easily accessible to the public. This is accomplished through the publication of both technical and non-technical reports and maps, as well as providing information through open-file reports and public data bases.