Hydrogeology, Groundwater Flow, and Groundwater Quality of an Abandoned Underground Coal-Mine Aquifer, Elkhorn Area, West Virginia

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with the West Virginia Department of Environmental Protection,
the West Virginia Department of Health and Human Resources,
and the West Virginia Geological and Economic Survey

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WVGES GEOLOGY UNDERLIES IT ALL

The picture on the cover of this report was taken by Kurt J. McCoy and is of the Ashland Company Store in Ashland, West Virginia. The original company store was built in the early 1900s, but was destroyed by fire in 1943. The existing store was built shortly thereafter and still exists today. The store is a local landmark and is characteristic of many similar stores owned and operated by coal companies to provide food, clothing, hardware and other day to day necessities for their employees due to inaccessibility by highways of many of the coal mining towns.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (feet)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (feet2)	929.0	square centimeter (cm2)
square foot (feet2)	0.09290	square meter (m2)
square mile (mi2)	259.0	hectare (ha)
square mile (mi2)	2.590	square kilometer (km2)
Volume		
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m3)
gallon (gal)	3.785	cubic decimeter (dm3)
Flow		
foot per day (feet/d)	0.3048	meter per day (m/d)
cubic foot per second (feet3/s)	0.02832	cubic meter per second (m3/s)
cubic foot per second per square mile [(feet3/s)/mi2]	0.01093	cubic meter per second per square kilometer [(m3/s)/km2]
cubic foot per day (feet3/d)	0.02832	cubic meter per day (m3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)
Radioactivity		
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
Hydraulic conductivity		
foot per day (feet/d)	0.3048	meter per day (m/d)
Hydraulic gradient		
foot per mile (feet/mi)	0.1894	meter per kilometer (m/km)
Transmissivity*		
foot squared per day (feet2/d)	0.09290	meter squared per day (m2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C=(°F-32)/1.8
Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88)
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)
Altitude, as used in this report, refers to distance above the vertical datum NAVD88.
***Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(feet3/d)/feet2]feet. In this report, the mathematically reduced form, foot squared per day (feet2/d), is used for convenience.** Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).
Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Local land mark – Prior St. Mary's Orthodox Church, Elkhorn, West Virginia, established in 1912.

Local land mark – U.S. Post Office in Elkhorn, West Virginia, established in 1888.

Hydrogeology, Groundwater Flow, and Groundwater Quality of an Abandoned Underground Coal-Mine Aquifer, Elkhorn Area, West Virginia

By Mark D. Kozar, Kurt J. McCoy, B. James Q. Britton, and Bascombe M. Blake, Jr.

Abstract

The Pocahontas No. 3 coal seam in southern West Virginia has been extensively mined by underground methods since the 1880's. An extensive network of abandoned mine entries in the Pocahontas No. 3 has since filled with good-quality water, which is pumped from wells or springs discharging from mine portals (adits), and used as a source of water for public supplies. This report presents results of a three-year investigation of the geology, hydrology, geochemistry, and groundwater flow processes within abandoned underground coal mines used as a source of water for public supply in the Elkhorn area, McDowell County, West Virginia.

This study focused on large (> 500 gallon per minute) discharges from the abandoned mines used as public supplies near Elkhorn, West Virginia. Median recharge calculated from base-flow recession of streamflow at Johns Knob Branch and 12 other streamflow gaging stations in McDowell County was 9.1 inches per year. Using drainage area versus mean streamflow relationships from mined and unmined watersheds in McDowell County, the subsurface area along dip of the Pocahontas No. 3 coal-mine aquifer contributing flow to the Turkey Gap mine discharge was determined to be 7.62 square miles (mi^2), almost 10 times larger than the 0.81 mi^2 surface watershed. Results of this investigation indicate that groundwater flows down dip beneath surface drainage divides from areas up to six miles east in the adjacent Bluestone River watershed. A conceptual model was developed that consisted of a stacked sequence of perched aquifers, controlled by stress-relief and subsidence fractures, overlying a highly permeable abandoned underground coal-mine aquifer, capable of substantial interbasin transfer of water. Groundwater-flow directions are controlled by the dip of the Pocahontas No. 3 coal seam, the geometry of abandoned mine workings, and location of unmined barriers within that seam, rather than surface topography.

Seven boreholes were drilled to intersect abandoned mine workings in the Pocahontas No. 3 coal seam and underlying strata in various structural settings of the Turkey Gap and adjacent down-dip mines. Geophysical logging and aquifer testing were conducted on the boreholes to locate the coal-mine aquifers, characterize fracture geometry, and define permeable zones within strata overlying and underlying the Pocahontas No. 3 coal-mine aquifer. Water levels were measured monthly in the wells and showed a relatively static phreatic zone within subsided strata a few feet above the top of or within the Pocahontas No. 3 coal-mine aquifer (PC3MA).

A groundwater-flow model was developed to verify and refine the conceptual understanding of groundwater flow and to develop groundwater budgets for the study area. The model consisted of four layers to represent overburden strata, the Pocahontas No. 3 coal-mine aquifer, underlying fractured rock, and fractured rock below regional drainage. Simulation of flow in the flooded abandoned mine entries using highly conductive layers or zones within the model, was unable to realistically simulate interbasin transfer of water. Therefore it was necessary to represent the coal-mine aquifer as an internal boundary condition rather than a contrast in aquifer properties. By representing the coal-mine aquifer with a series of drain nodes and optimizing input parameters with parameter estimation software, model errors were reduced dramatically and discharges for Elkhorn Creek, Johns Knob Branch, and other tributaries

were more accurately simulated. Flow in the Elkhorn Creek and Johns Knob Branch watersheds is dependent on interbasin transfer of water, primarily from up dip areas of abandoned mine workings in the Pocahontas No. 3 coal-mine aquifer within the Bluestone River watershed to the east. For the 38th, 70th, and 87th percentile flow duration of streams in the region, mean measured groundwater discharge was estimated to be 1.30, 0.47, and 0.39 cubic feet per square mile ($ft^3/s/mi^2$) respectively, and median measured groundwater discharge was estimated to be 1.49, 0.46, and 0.37 $ft^3/s/mi^2$, respectively. These values can be multiplied by the area of the surface that contributes recharge to groundwater discharge to estimate volumetric flow rates.

Introduction

The Pocahontas No. 3 coal seam has been mined in Mercer, McDowell, Raleigh, and Wyoming Counties in West Virginia as well as portions of Virginia and Kentucky. Coal mining began in the region in the 1880's and became a large scale industry in the 1920's. The Pocahontas No. 3 coal was, and still is, valued as a source of high-quality coal suitable for coking, a process which prepares the coal for use in blast furnaces.

Pocahontas No. 3 coal mines in the Elkhorn area of McDowell County, West Virginia, which were abandoned upon extraction of available coal in the 1920's and 1930's, have since provided a constant source of groundwater for public supply in the region. However, groundwater recharge to and flow within these prolific aquifers has not been fully documented, and additional information was needed to better understand the processes which control recharge to the aquifers, the residence time of groundwater within the aquifer, the hydraulic characteristics of the aquifer, and the quantities of water that may be expected during both average or drought conditions. To better understand recharge to and groundwater-flow processes in abandoned coal-mine aquifers, the U.S. Geological Survey (USGS) in cooperation with the West Virginia Department of Environmental Protection (WVDEP), the West Virginia Department of Health and Human Services, and the West Virginia Geological and Economic Survey (WVGES), conducted a three-year investigation of the geology, hydrology, geochemistry, and groundwater-flow processes within abandoned Pocahontas No. 3 coal mines used as a source of water for public supply in the Elkhorn area of McDowell County, West Virginia. Results of the quantitative analyses conducted as part of this study will provide information for local water-resource planners and managers to better protect the resource and predict the availability of groundwater for future use.

Purpose and Scope

This report presents the results of a three-year assessment of the hydrogeology of the Elkhorn area in West Virginia, and includes: (1) revision of the conceptual model of groundwater flow in the prolific abandoned Pocahontas No. 3 coal-mine aquifer (hereafeeter referred to as the P3CMA) that supplies the majority of water to residents in McDowell County; (2) discussion of borehole geophysical logs and water-level and water-quality data collected during the study; (3) presentation of data from detailed single well and straddle-packer aquifer tests conducted to determine hydraulic properties of the aquifer; (4) assessment of the impact of groundwater withdrawals on the yield and long term availability of water from existing mine outfalls; (5) analysis of the water quality and geochemistry of the coal-mine aquifer; and (6) results of a fluorometric dye tracer test conducted to ascertain average residence time of groundwater in the coal-mine aquifer.

Description of Study Area

The study area (Figure 1) is located in the eastern part of McDowell County, in the southernmost part of West Virginia's low-sulfur coalfield. The area is comprised of portions of three watersheds, a portion of Elkhorn Creek on the west and south, North Fork of Elkhorn Creek to the north, and a portion of the Bluestone River watershed to the east. The total study area encompasses 58.8 square miles (mi^2), but the area of specific interest, the Elkhorn Creek and North Fork watersheds, comprise only 37.0 mi^2. Approximately 21.8 mi^2 of the study area is topographically part of the Bluestone River watershed, although the majority of groundwater discharges to Elkhorn Creek, a tributary of the Tug Fork River. The groundwater recharge source area for the Elkhorn Creek watershed is much larger than its corresponding surface-drainage area, as the No. 3 Pocahontas coal-mine aquifer has been extensively mined in up dip areas east of the surface watershed, creating a groundwater recharge source area that extends well beyond the actual surface drainage divide for the study area (Figure 1).

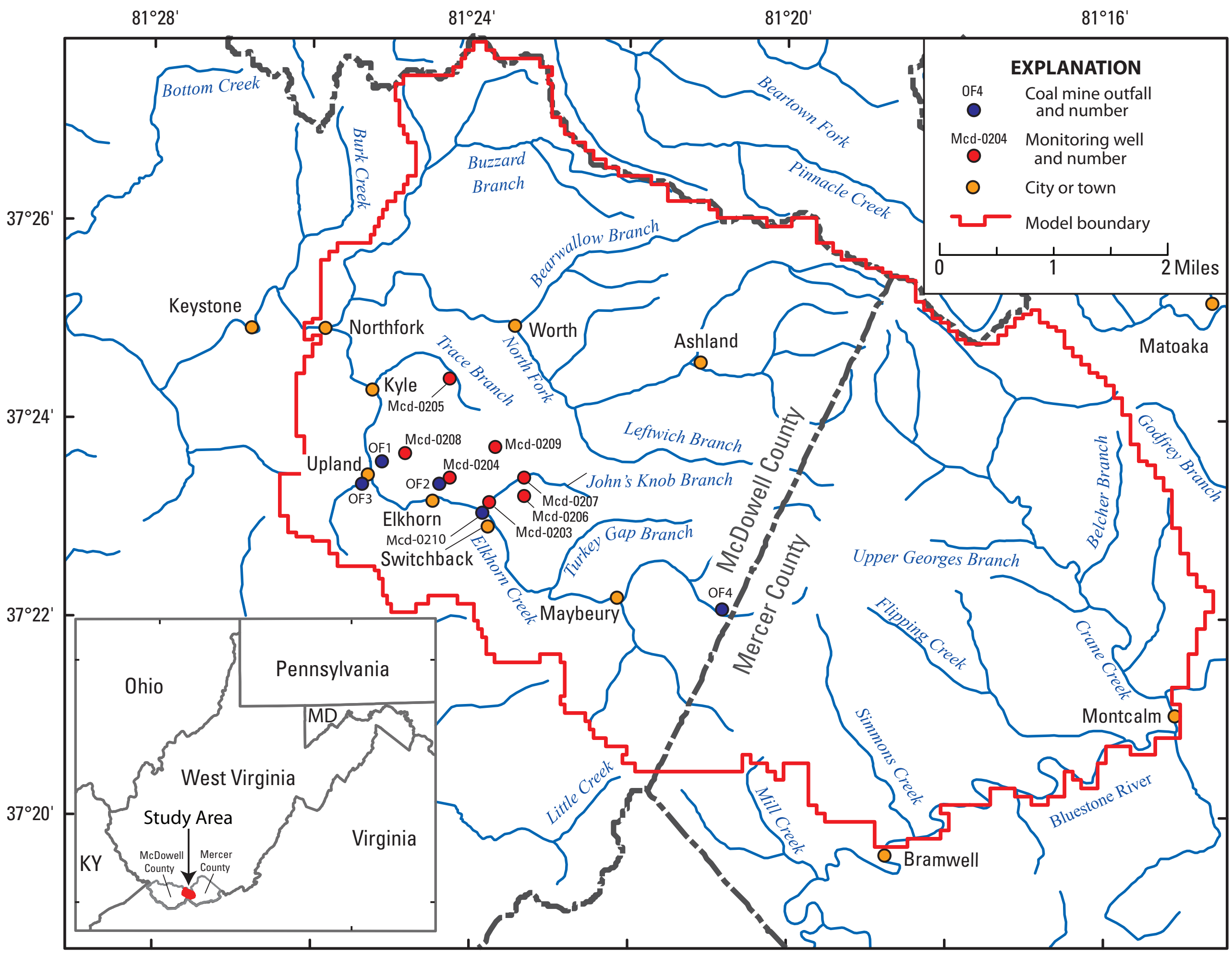


Figure 1. Map showing location of the study in the Elkhorn area, McDowell County, West Virginia.

This region of the Appalachian Plateaus is highly dissected with local topographic relief exceeding 1,000 feet. Regional dip is to the northwest at approximately 75 ft/mi. Coal seams in this part of West Virginia have been heavily mined, especially the Pocahontas No. 3 coal seam, for over 100 years.

Approach

A multi-phase investigation was undertaken to better understand the prolific abandoned coal-mine aquifers which supply the majority of water used for public supply in southern West Virginia. First, available mine maps and hydrogeologic data were obtained and a GIS database was created to evaluate potential study sites. The Elkhorn area was selected, after an extensive statewide search for suitable sites to conduct the research, for several reasons. First, the abandoned coal mines in the P3CMA in the study area are all above local drainage, which made quantification of the inflows to and outflows from the mines possible. Second, the Elkhorn area had fewer interactions with adjacent and overlying or underlying mines than most areas in West Virginia, which reduced the hydrogeologic complexity of the area to be studied.

The WVGES provided the mine maps which were used to assess and select the study area. Geologists from the WVGES also logged cuttings for wells completed as part of the study and correlated the strata with data from other well cores available for the study area. This information was used to prepare and update a structural contour map for the base of the Pocahontas No. 3 coal seam. This structural contour map was used to develop the principal aquifer layer within a numerical groundwater-flow model developed for the study area. WVGES geologists also helped prepare a stratigraphic column for the study area from logs of drilling cuttings and geophysical logging results.

Upon selection of the study area, seven monitoring wells were installed to (1) ascertain the depth to the P3CMA, (2) monitor water levels in the aquifer, (3) allow detailed borehole geophysical logging, (4) allow for single-well and straddle-packer aquifer tests to determine hydraulic properties, and (5) allow collection of water-quality samples for geochemical characterization of groundwater. The borehole geophysical logs were collected to ascertain the nature and extent of fractures and bedding planes within the P3CMA and overlying and underlying strata. Borehole geophysical logs included standard electrical logs (gamma, fluid resistivity, temperature, caliper, and spontaneous potential), acoustic televiewer logs, and borehole video logs. Acoustic televiewer and borehole video logs were used to ascertain the strike and dip of fractures and bedding planes that intersected the boreholes.

A streamflow gaging and precipitation monitoring station was installed on Johns Knob Branch to continuously monitor the discharge of that tributary, which is fed primarily by several outfalls from the P3CMA. The gage was installed to ascertain the response of the mine to precipitation and to quantify the amount of water discharging from the mine during various hydrologic conditions.

Monthly water-level measurements were made in each of the seven monitoring wells (appendix 1). Two wells were equipped with monitoring instrumentation to provide an hourly record of water levels within and below the P3CMA. Mcd-0204 monitored water levels in the strata underlying the P3CMA and Mcd-0207 monitored water levels in the P3CMA (well numbers are shown on figure 1).

Aquifer tests were conducted on two wells, Mcd-0203 and Mcd-0204, to better understand the impact of groundwater withdrawals on the multi-layered aquifer system, which is characterized by the interbedded coal-mine aquifers which act as the primary aquifers, and associated low permeability confining units comprised of shale and sandstone. Packer tests, using inflatable straddle packers, were conducted to ascertain hydraulic properties of specific coal-mine aquifers, sandstone, and shale layers.

Water-quality samples were collected from two sites, an outfall from the P3CMA (Mcd-0210), and from a well (Mcd-0204) that taps strata underlying the P3CMA, and includes the Pocahontas No. 2 coal aquifer. These two sites were sampled for a broad range of constituents, including common ions, trace metals, nutrients, indicator bacteria, volatile organic compounds (VOCs), and constituents for determining the age or residence time of groundwater (chlorofluorocarbons (CFCs), deuterium, and oxygen-18). These constituents were analyzed to assess general geochemistry of the aquifer, help understand the response of the aquifers to precipitation, and to determine whether the aquifers are affected by surface processes, and if so to what extent. A multi-parameter water-quality monitor was installed at Mcd-0210, an outfall from the P3CMA, to continuously measure the temperature, specific conductance, dissolved oxygen, and pH of the mine discharge. These data were used to ascertain how quickly the quality of mine water is affected by precipitation.

Petrographic analysis of several rock samples from the study area was conducted to provide a frame of reference for analyzing the geochemical data collected for the study. Knowledge of the mineral composition of typical sequences of rock in the study area helps to better understand the geochemical processes occurring within the aquifer. Specifically, samples were collected to ascertain why water quality samples from the P3CMA and the underlying Pocahontas No. 2 coal seam can have elevated concentrations of iron yet lack the acid mine drainage signature common for many coal seams.

A dye tracer test was conducted by injecting a fluorescent dye into a well (Mcd-0206) up gradient of the mine outfalls discharging to Johns Knob Branch. Several potential resurgences were monitored down gradient and along bedrock strike of the injection point to determine the average residence time of groundwater within the P3CMA. Elevation surveys were conducted along the south face of the P3CMA outcrop using a survey grade global positioning receiver (GPS) to document local variations in bedrock dip not readily apparent from the structural contour map developed for the study or from the digital elevation models (DEMs) available for the study area.

Finally, a numerical model of groundwater flow was developed to better refine and test the conceptual understanding of groundwater flow, and to provide estimates of the flux of water into and from the P3CMA under various hydrologic conditions. Such data may be used to assess present and future water availability.

Acknowledgements

The authors wish to thank the Arcelor Mittal Corporation and Midvol Coal Sales for allowing access to their property during the course of this study. The investigation could not have been completed without their support. The authors also wish to thank Mr. John E. “Jack” Caffrey and Mr. Charles R. Lavender, Jr. for their insight into current and past mining practices in the Pocahontas Coalfields of southern West Virginia.

Hydrogeology

The hydrogeologic setting is important in controlling groundwater flow in the study area. Both the type of rock and structural features such as the dip of bedrock strata, are important controls on groundwater flow. The following sections provide discussions of previous hydrogeologic investigations, and results of borehole geophysical logging, base-flow stream and mine-outfall discharge surveys, aquifer and straddle-packer hydraulic tests, petrographic analyses, and dye-tracer tests. These data provide the framework on which the conceptual model was revised and a numerical simulation of groundwater flow was developed for the Elkhorn area, McDowell County, West Virginia.

Previous Hydrogeologic Investigations

Groundwater flow in the Appalachian Plateaus is primarily controlled by the orientation and permeability of the gently dipping and moderately folded sedimentary rocks (Seaber and others, 1988). The bedrock aquifer system in the Plateaus is composed of regionally deposited cyclical sequences of sandstone, siltstone, shale, limestone, and coal. Groundwater flow in these rocks is primarily through fractures, bedding-plane separations, and in limestone or dolostone rock, through solution openings (Ferrell, 1988). Conceptual models of groundwater flow in the Appalachian Plateaus have been presented by Ferguson (1967), Wyrick and Borchers (1981), Harlow and LeCain (1993), and Sheets and Kozar (2000).

Wyrick and Borchers (1981) expanded upon Ferguson's (1967) original stress-relief model to describe groundwater flow in the Appalachian Plateaus as occuring primarily in near horizontal bedding-plane separations beneath valley floors and in nearly vertical stress-relief fractures along valley walls. Near-surface groundwater flow in valley and hillside settings is a result of a network of fractures formed by the unloading of compressional stresses. Harlow and LeCain (1993) found downward gradients driving flow in a stair-step pattern, alternating among vertical joints, faults, and fractures, and horizontal bedding-plane separations. Groundwater age-dating data support the model that recharge occurs primarily in topographically high areas (ridges) and flows laterally and downward toward valley floors (Figure 2) through shallow fractures in the bedrock (McCoy and Kozar, 2007; Sheets and Kozar, 2000). Groundwater ages for the study area (Figure 2) were based on earlier work in the region (Sheets and Kozar, 2000; Figure 3) and verfied with chlorofluorocarbon age data collected as part of this study.

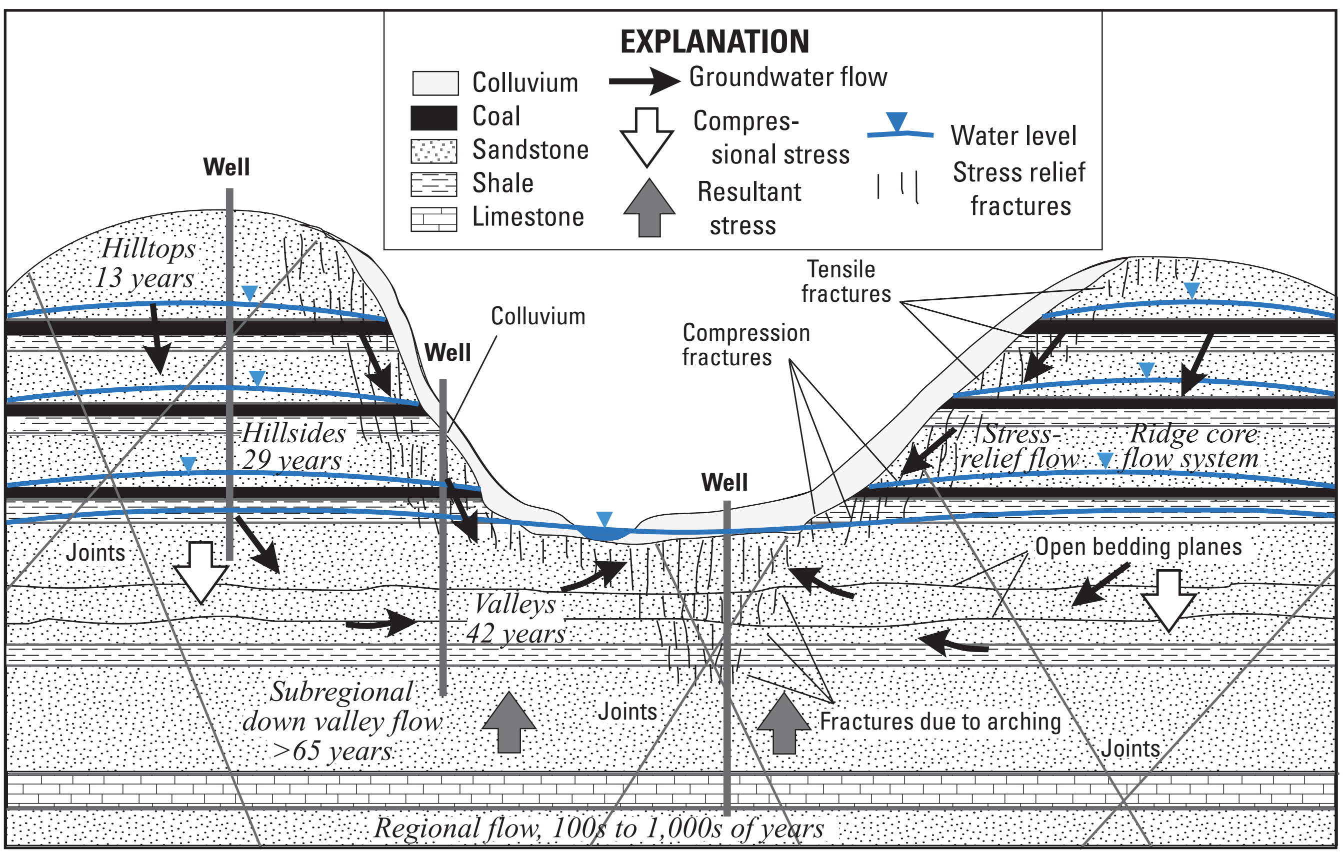


Fig. 2. Revised conceptual model of groundwater flow in an Appalachian Plateaus fractured bedrock aquifer, including apparent age of groundwater.

In cyclical coal sequences above regional drainage, coal underclays limit downward vertical leakage from permeable coals and result in a stacked sequence of perched aquifers (Abate, 1993; Figure 2). In unmined areas of the Plateaus, perched aquifers typically discharge as springs and seeps where permeable fractured rocks are located on top of claystones, shales, or coal underclays (Borchers and others, 1984). Multiple seepage faces develop in cyclical coal sequences where several low permeable units intersect the hillside (Minns, 1993).

Underground mining has the potential to impact the hydrology of aquifers in the Appalachian Plateaus on a relatively large scale (Callaghan and others, 1998). Post-mining hydrostratigraphy of underground mines is important in southern West Virginia where abandoned underground coal-mine aquifers are a resource for public supplies in areas where other groundwater resources are limited (Ferrell, 1992). At some time following mining, a caved zone of high permeability forms within the mine, as overlying strata fracture and subside from lack of support and pillars collapse or spall over time (Schubert, 1980; Su and Hasenfus, 1987; Hasenfus and others, 1988). These zones of intense fracturing have permeabilities several orders of magnitude higher than adjacent unfractured rocks and intact coal barriers (Schubert, 1980). The subsided area of increased permeability overlying the mine is suggested to extend to a height above the mine that is 3 to 6 times the thickness of the coal itself (Kendorski and others, 1979; Liu, 1996). Other studies indicate fracturing and caving sometimes extend to as much as 30 to 50 times the extracted coal thickness (Hill and Price, 1983; Booth, 1986). The highest observation of a fracture zone above a mine floor in West Virginia recorded by Hasenfus and others (1988) was 164 feet. Schubert (1980) suggested that water infiltration to underground mines occurs predominantly through vertical fractures in roof rock and was simulated in the subsidence models of Singh and Kendorski (1981), Parizek and Ramani (1996), and Liu (1996). Donovan and Fletcher (1999) outlined an expected hydrostratigraphic sequence following mining (from top to bottom):

- a surface subsided zone, likely hydraulically continuous with shallow water table aquifers (from 0 to 200 feet depth, depending on surface topography),
- a non-caved aquitard zone, from the surface-subsided zone down to an elevation 150-300 feet above the top of the coal,
- a caved aquifer zone, pronounced in the 13-39 feet above the coal but possibly extending up to 300 feet into a zone of bed separation,
- the mine aquifer itself, consisting of intact coal pillars, rubble from rock collapse, and mine openings, and
- the intact shale and underclay beneath the mine (inferred to be an aquitard).

Large volumes of water are stored in underground mines and the quality of water available from underground mines in southern West Virginia, eastern Kentucky, and southwest Virginia is generally suitable for public supply (Minns, 1993; Ferrell, 1992; Hobba, 1981). Ferrell (1992) found recharge to public water supplies in abandoned mines of McDowell County, West Virginia to have increased since the time active mining ceased. The increase in recharge was assumed to be groundwater inflow from adjacent mines. Coal-mine aquifers are the primary aquifers in the Plateaus (Harlow and LeCain, 1993) and mine inflow as leakage across intact coal barriers separating mines is common where head gradients develop between adjacent mines (McCoy and others, 2006). Interconnection between mines on a regional scale leads to groundwater recharge source areas that greatly exceed the boundaries of individual mines (Lopez and Stoertz, 2001) and may be difficult to trace without expensive monitoring (Aljoe and Hawkins, 1992).

Quantitative groundwater models have been developed to estimate groundwater inflow to abandoned mine workings (Banks, 2001; Winters and Capo, 2004; Goode, et al. 2011), route groundwater through interconnected mine entries (Adams and Younger, 2001), and assess residence times (Winters and Capo, 2004). Modeling of the complex hydrostratigraphy and mine-to-mine interaction in mine aquifer systems is difficult, but results can be used for regional-scale water budgets (Adams and Younger, 2001). Abate (1993) tested the hypothesis that the hydrostratigaphy of a stacked perched aquifer system in the Appalachian Plateaus can be simplified to three homogeneous units based on stratigraphic contrasts of permeability in (1) coal-mine aquifers, (2) underclays, and (3) overburden. This simplified conceptualization was validated using a finite-element model of a Plateau coal sequence in eastern Pennsylvania. Abate (1993) suggests the model is applicable in other areas of the Appalachian Plateaus with similar hydrostratigraphy, particularly in deeply incised areas.

Geology

Geologists with the Coal Program of the WVGES reviewed all available data in their files, and entered it into their state-wide coal resource Geographic Information System (GIS). In addition, available mine maps were reviewed, georeferenced, and mine footprints were digitized and entered into the GIS dataset.

Following review of existing data, initial geologic field work was conducted by WVGES geologists to add to the existing databases. Reconnaissance of the area was done to familiarize project members with road access to monitoring-well drill sites, as well as to locate outcrops, sample locations and potential hazards. The Pocahontas No. 3, Pocahontas No. 6, and Fire Creek coals have been extensively surface mined along contour and deep mined in the region, but coal exposures are largely inaccessible due to a combination of reclamation, thick vegetative cover, and post-mining mass wasting. Sandstones above some coals were exposed and accessible locally and these were examined for suitability for petrographic studies. Measuring and describing sections that extended for substantial intervals between stream valleys and ridge tops were not possible because of large zones concealed by vegetation. In addition, there was an initial expectation of obtaining available historic core samples and core logs.

Few historic cores, measured sections, and related data exist in the WVGES database within the footprint of the study area due to the early development of mining. WVGES possesses several versions of mine maps for the Keystone mining area, but none of these maps contained surveyed coal elevations, coal thicknesses, or structural contour lines. The lack of detailed coal elevation data made the generation of accurate structural contour maps difficult. Several coal and land companies contacted during the study were unable to provide historic coal mine maps. However, a structural contour map of the base of the Pocahontas No. 3 coal seam was developed for this study based on pre-existing data. The structural contour map was modified based on WVGES core data, borehole logs of the seven wells drilled for the study, and an elevation survey of the base of the Pocahontas No. 3 coal-mine strip bench. A structural flexure along the Pocahontas No. 3 outcrop was postulated due to localized higher groundwater discharge from Johns Knob Branch and results of the elevation survey.

Considerable time and effort was expended attempting to acquire complete or partial cores that penetrated the P3CMA in order to characterize the coals, roof, and floor rocks. Two cores drilled within approximately one mile east and west of the study area were eventually located but unfortunately, pertinent samples had been discarded. However, both core records assisted in the geologic assessment of the area. From these records it was found that the Pocahontas Nos. 2, 2 Rider, 3, 4, 6, 7, 8, and 9 coal seams are present in the study area.

WVGES geologists assisted with the supervision of the drilling process by logging the air rotary drill cuttings and providing target formation depths and other related information. Data were recorded into field books and were entered into WVGES's databases. Coal elevations obtained from seven USGS monitoring wells completed for the study were added to the database.

After all available data were reviewed and correlated, bed maps were produced for coal seams in the study area, including the Pocahontas Nos. 2, 3, 4, 5, 6, 7, 8, 9, Little Fire Creek and Fire Creek seams. Complete extents of these GIS layers can be viewed at www.wvgs.wvnet.edu/www/coal/cbmp/coalims.html including mining extent, structural contours and thickness grids. The bed maps are continually updated as new data are obtained. All mine maps utilized for the project can be accessed at http://www.wvgs.wvnet.edu/www/coal/MIDS_Index.htm which provides detailed company name, mine name, and location information, as well as links to download digital versions of the maps.

Stratigraphy

Names of geologic formations and groups within this report conform to the geologic nomenclature of the WVGES. Rocks within the study area are assigned to the Upper Mississippian Bluestone Formation and the Lower Pennsylvanian Pocahontas and New River Formations (Figures 3 and 4). Limited exposures due to steep relief, the lack of cultural development, heavy vegetation, and the withdrawal of the mining industry from the area due to resource depletion, greatly hampered geologic investigations. The Bluestone Formation underlies the entire study area, but does not crop out within the boundaries of the study area to any substantial degree, occurring a few feet below Elkhorn Creek and North Fork. The Bluestone Formation consists of red and green mud rocks and lithic sandstones, and in this part of West Virginia, the silty marine Bramwell Member occurs near the top of the formation, and may actually crop out along the railroad tracks at Keystone, where Hennen and Gawthrop (1915) describe a black, possibly marine fossil-bearing shale, overlying greenish sandy shales and sandstones. This monospecific assemblage of shells is comprised of flattened and crushed, thin-walled bivalves (Hennen and Gawthrop, 1915). This distinctive unit, named the North Fork Shale, has been found at many locations in the outcrop belt of McDowell and Mercer counties during geologic mapping (Beuthin and others, 2000; Blake and others, 2000; Beuthin and Blake, 2001; Blake and others, 2001; Beuthin and Blake, 2002a, 2002b; Blake and Beuthin, 2002) and reconnaissance field work. The brachiopod Lingula has been reported occasionally (Henry and Gordon, 1979; Blake and Beuthin, 2008). As this bed always overlies the interfluve Green Valley paleosol complex that marks the mid-Carboniferous unconformity (Beuthin, 1997; Blake and Beuthin, 2008), the lower Pocahontas sandstone that fills the paleovalley incised during the mid-Carboniferous eustatic event (Beuthin, 1994, 1997; Blake and Beuthin, 2008), or the

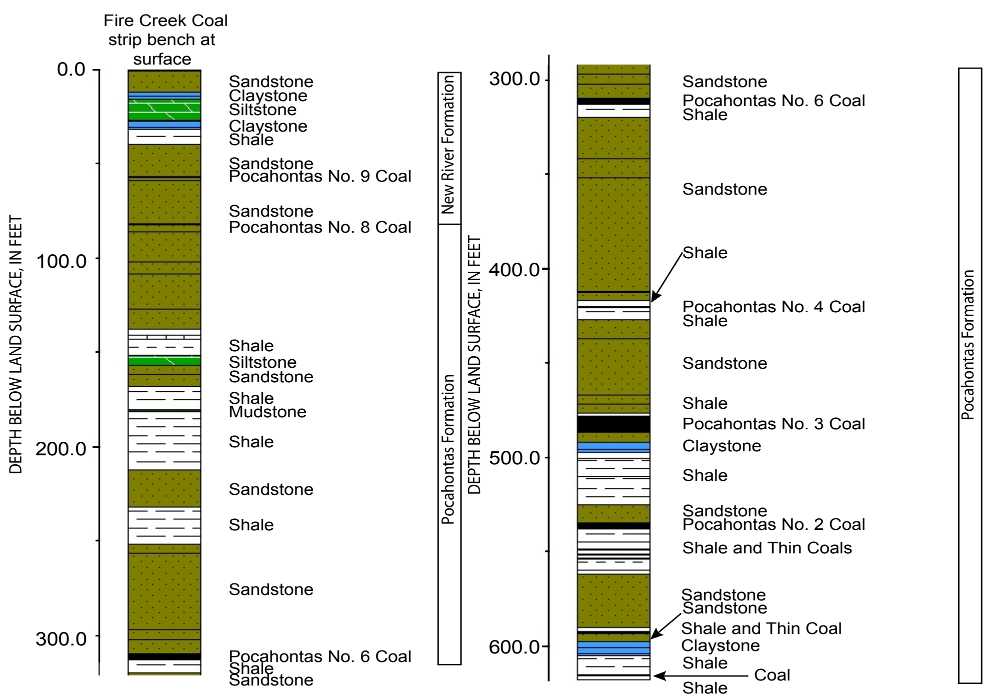


Figure 3. Stratigraphic column showing bedrock stratigraphy in the Elkhorn area, McDowell County, West Virginia.

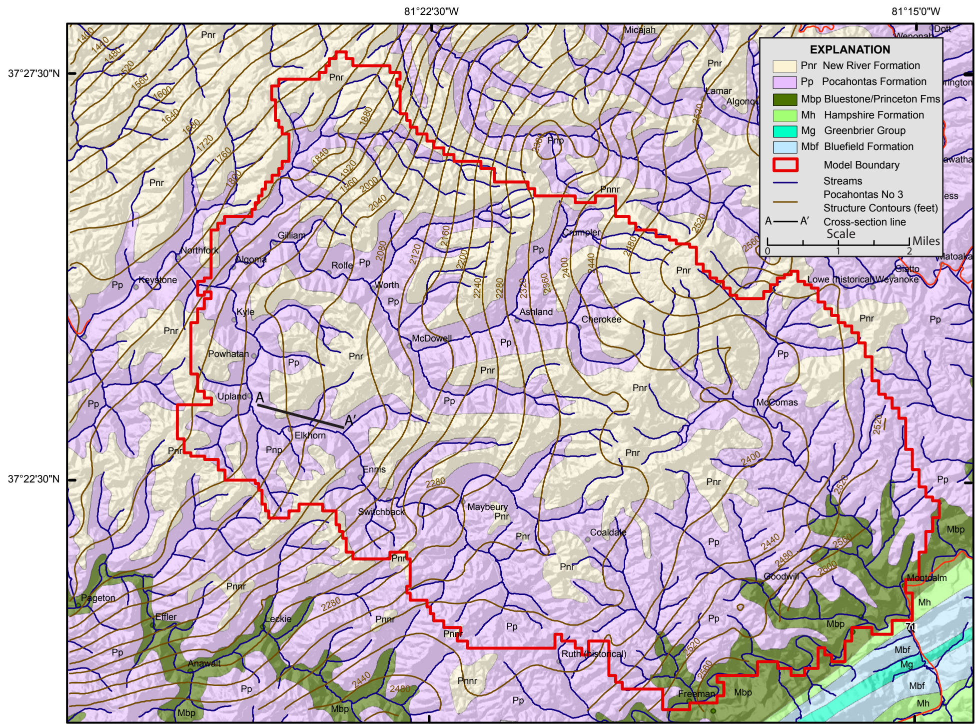


Figure 4. Geologic map of the study area showing geologic formations, structural contours for the base of the Pocahontas No. 3 coal seam, and the boundary for the groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

older upper member and Bramwell members of the Bluestone Formation (Beuthin, 1997; Blake and Beuthin, 2008) it is unlikely that Hennen and Gawthrop's (1915) unit is the Bramwell member. However, regional stratal relationships indicate that the top of the Bluestone Formation is present within a few feet below the streambed of Elkhorn Creek at Northfork.

The Lower Pennsylvanian Pocahontas Formation outcrops through the lower parts of the hills and along the stream valleys in the study area. Pocahontas strata consists of fluvial sandstones with lesser amounts of siltstones, shales, mudstones, and coal seams deposited in a series of coalescing delta lobes and associated coastal plain facies (Englund 1974, 1979; Englund and others, 1979; Englund and Thomas 1990; Blake and others, 2002). Minor siderite nodules and zones are present in marine-influenced deposits. Decimeter to meter scale ellipsoidal limestone nodules are present sporadically in tidally-influenced beds above the Pocahontas No. 1 coal seam. In contrast to the underlying Bluestone Formation, no red beds have been reported from the Pocahontas Formation (Blake and Beuthin, 2008; Blake and others, 2009). Peat accumulated on the topographically positive parts of the shelf exposed during eustatic sea level drops. The Pocahontas Formation thins north and northwestward from a maximum thickness of approximately 700 feet in southern West Virginia and adjacent parts of Virginia, wedging out approximately 30 miles to the north of the study area (Englund 1974, Englund and Thomas 1990). The Pocahontas is approximately 500-feet thick in the study area with the lower formation contact being placed at the base of the lower sandstone member (Englund 1974; Figure 1 in Blake and Beuthin, 2008; Blake and others, 2010), but in some areas the lower formation contact is problematic, and is placed above the stratigraphically highest red beds of the subjacent Bluestone Formation (Blake and Beuthin, 2008; Blake and others, 2010). In areas where the upper portion of the Pocahontas formation has not been truncated by Early Pennsylvanian erosion, the upper formation contact is placed arbitrarily at the base of the Pocahontas No. 8 coal seam (Englund, 1974, 1979; Englund and others, 1979; Englund and Thomas, 1990). Early Pennsylvanian erosion progressively truncated the Pocahontas Formation north-northwestward, a thinning trend possibly enhanced by non-deposition. This regional unconformity is located at the base of the Pineville Sandstone Member of the overlying New River Formation (Chesnut, 1993, 1994, Englund and Thomas, 1990) and has been named the Early Pennsylvanian unconformity (Chesnut, 1992).

There are at least ten named coal seams and splits in the Pocahontas Formation, with four reaching minable thickness in the study area: the Pocahontas Nos. 2, 3, 4 and 6. By far the Pocahontas No. 3 was the most valuable coal seam, being heavily mined within the study area in the early 1900's to the present. The lowest minable coal seam, the Pocahontas No. 2, has not been mined within the study area. Regionally the Pocahontas No. 2 has a thickness of between 2.2 and 2.6 feet, but its economic attractiveness was overshadowed by the thicker, higher quality, more continuous Pocahontas No. 3 seam less than 100 feet above. With resource depletion becoming an issue with previously mined beds, the Pocahontas No. 2 is increasingly being targeted to the northeast of the study area. The Pocahontas No. 3 generally ranges in thickness from 3.9 – 6.9 feet; underground resources within the study area have been totally exhausted, and its outcrop widely contour surface mined. The Pocahontas No. 4 seam, while not mined in the immediate study area, is heavily mined approximately 3 miles west of the town of Northfork. Available data indicates the Pocahontas No. 4 is not minable within the study area. The Pocahontas No. 6 seam occurs 180 to 200 feet above the Pocahontas No. 3. The Pocahontas No. 6 is more erratic in thickness than the Pocahontas No. 3 bed, but has been mined in areas adjacent to the study area. Several contour surface mines targeted the Pocahontas No. 6 within the footprint of the study area. Pocahontas coal seams from McDowell County are low volatile in rank, with an average sulfur content of 0.62 % (n=607; dry basis) and an ash yield of 5.04 % (n=607; dry basis).

The youngest rocks in the study area are assigned to the Lower Pennsylvanian New River Formation, which extends upward from the base of the Pocahontas No. 8 coal seam to the base of the Lower Douglas coal seam of Hennen and Teets (1919) (Englund, 1979; Blake, 1997; Blake and others, 2002), reaching a maximum preserved thickness of over 1,000 feet in its southern outcrop area and thinning to the north and west. Only about 500 feet of the lower part of the New River Formation is present within the study area due to erosion of the upper half. The New River Formation consists of sub-lithic to lithic arenites with lesser amounts of siltstones, shales, mudstones, and coal seams. Sideritic nodules and cm-scale beds are present in marine-influenced beds (Blake and others, 2002). Marine fossils are rare to absent; although non-marine to marginal marine bivalves are not uncommon (Henry and Gordon, 1979; Blake, 1997). In many areas the New River Formation is marked by prominent lenticular, quartzose sandstone bodies. These quartz arenites fill valleys incised during eustatic sea level falls and are unconformable with underlying and laterally equivalent strata (Houseknecht, 1980; Rice 1984, 1985; Rice and Schwietering, 1988; Blake, 1997; Blake and others, 2002; Blake and Beuthin, 2008). Paleocurrent data indicate a general northwest transportation direction from low-grade metamorphic highlands to the southeast for the lithic sandstones and a south-southwest transport direction from the stable craton towards the southern Appalachian region for the quartzose sandstones (Houseknecht, 1980; Donaldson and Shumaker, 1981; Chesnut, 1993, 1994; Archer and Greb 1995), and fill paleovalleys incised during eustatic sea level lows (Blake and others, 2002; Blake and Beuthin, 2008; Korus and others, 2008). Blake (1997) demonstrated that the New River Formation has a diachronous top due to miscorrelations of coal seams in the overlying Kanawha Formation, a thesis strongly supported by Blake and others (2002). The New River Formation thins rapidly to the north and northwest until in northern parts of the Appalachian region it is absent due to non-deposition and/or erosion. Within the footprint of the study area, the Fire Creek is the only New River coal seam mined. The Fire Creek seam averages 3.3 feet in thickness and occurs 500 to 530 feet above the Pocahontas No. 3 coal seam. The New River coal seams in McDowell County are low to medium volatile in rank, with an average sulfur content of 0.76 % (n=245; dry basis) and ash yield of 7.14 % (n=245; dry basis).

Petrography

Petrographic examination of sandstone units overlying the Pocahontas No. 3 seam was conducted in order to better characterize and define aquifer permeability at a micro scale and to assess the mineral composition of bedrock in the study area to aid interpretation of geochemical water samples collected for the project. Four rock samples were collected from the sandstone unit directly above the Pocahontas No. 3 seam at various locations within the study area. No samples were taken below the Pocahontas No. 3 seam due to non-exposure of any units within the sample area. Reclamation back filling followed by decades of mass wasting has rendered the Pocahontas No. 3 seam largely inaccessible without the use of excavation equipment which was unavailable for this project; however, samples would not have been collected below the Pocahontas No. 3 since underlying units were determined from core records to be claystone and shales. Samples were restricted to sandstones above the Pocahontas No. 3 seam, since this was the target seam for the project.

Samples were collected under overhangs where the exposed rock surfaces of outcrops were somewhat protected from weathering processes, although later microscopic examination revealed the samples to be heavily weathered. Large oriented hand samples were collected and described and were reduced to transportable samples. Final samples were trimmed with a masonry rock saw utilizing a diamond impregnated blade. Original orientations of samples were maintained to aid in the determination of sedimentary and diagenetic features.

Trimmed samples were sent to Applied Petrographic Services, Inc. in Greensburg, PA which processed standard 27 x 46 mm thin sections impregnated with blue epoxy to enhance pore spaces. No cover slips were added at the laboratory to allow possible further staining or etching at WVGES should these processes be deemed necessary.

Grain mineralogy was determined by examination, identification and classification of 300 grains per slide spaced over a predetermined grid using a mechanical stage. Counted categories included: monocrystalline quartz, polycrystalline quartz, cryptocrystalline quartz (chert), secondary quartz (cement), phyllosilicate grains, feldspars, primary porosity (intergranular), secondary porosity, muscovite, sericite (generally micro-muscovite), siderite, pyrite, rock fragments, kaolinite and clays, and a general classification of feldspar to clay. Trace amounts of other minerals were also recorded. Additional information about depositional, diagenetic and weathering history was collected through examination.

Photomicrographs were collected using a Pixera 150es digital camera attached to a Leitz polarizing petrographic microscope using a mechanical stage. Photomicrographs were collected of characteristic and interesting features. Grain size was determined by estimation of the size of framework grains in hand samples, as well as measurements calculated from the average size of 50 measured grains from thin sections utilizing a graduated ocular, while grain shape and sorting were ascertained by comparison with standard charts based on Pettijohn’s (1975) classifications.

Thin-Section Analyses

Sample McD-1 was collected across the access road from monitoring well Mcd-0203 in a sandstone unit approximately 4.3 feet above the Pocahontas No. 3 coal (which was concealed), directly overlying a medium gray 2.0 to 4.3-feet thick claystone. The sandstone unit weathers orange-brown and contains abundant plant fossils, stems and calamites, some of which are very well preserved.

Macroscopically, the sample is a very fine to fine-grained sandstone, gray to white, weathered to brown-orange on exposed surfaces, massive, hard and micaceous with abundant small, irregular, distinct siderite grains. The unit becomes planar bedded toward the top with 1 to 2.5 cm planar bed sets. The sample was collected oriented with the long axis of the thin section perpendicular to bedding.

Thin-section examination revealed abundant mono-and polycrystalline quartz grains comprising 61.33 percent of the total rock volume with abundant feldspar grains, ranging in quality from pristine to nearly completely dissolved grains with resultant ghost images. Original feldspar content was 16.33 percent of the total rock volume, with substantial alteration of most feldspars to clays or completely dissolved to secondary porosity. The majority of primary pore spaces were filled by compaction of ductile rock fragments, phyllosilicate grains (6.00%), micas (6.33%) and clays leaving a resultant 1.00% primary porosity (Figure 5). Later secondary pore spaces were generally unfilled with ductile grains indicating early compaction and deformation of the rock unit. Secondary quartz cement (0.67%) and trace amounts of pyrite and zircon were observed as well as chert grains (0.33%) and one tourmaline grain. Clays were derived primarily from feldspars altered to kaolinite or from 'micro' muscovite (sericite), much of which was finely ground into pore spaces although 0.33% of the clays were unidentified. Siderite, composing 7.67 percent of the total rock volume, was observed throughout the sample, commonly associated with clays which provided the iron staining of the hand sample. The sample was moderately well sorted with an average grain size of 0.21 mm and was sub-angular to sub-rounded, and determined to be a sub-arkosic sandstone. Based on the interconnectedness of pore spaces, porosity, and cementation, permeability was deemed to be low.

Sample McD-2 was collected approximately 200 feet to the east of well Mcd-0203. The base of this section was concealed, therefore the coal was not observed. A 6.9-feet thick medium dark gray, highly weathered claystone unit with scattered plant debris and calamites becoming fissile to the top appears to overlie the Pocahontas No 3 coal-mine aquifer. Fossil fragments increase to the top of the unit which forms a sharp contact with the overlying sandstone. Excavation was attempted to expose the Pocahontas No. 3 seam but was abandoned after the removal of 4.6 feet of loose debris revealed large rocks and boulders too large to be removed by hand, as was the case in most locations.

Overlying the claystone is a 2-feet thick light gray to white weathered brown-orange sandstone with shale and discontinuous coal streaks where the hand sample was collected. It is a very argillaceous, wavy to almost flaser bedded, very fine to fine-grained, micaceous sandstone, with 1 mm discontinuous coal streaks and a gradational upper contact with vertical fractures.

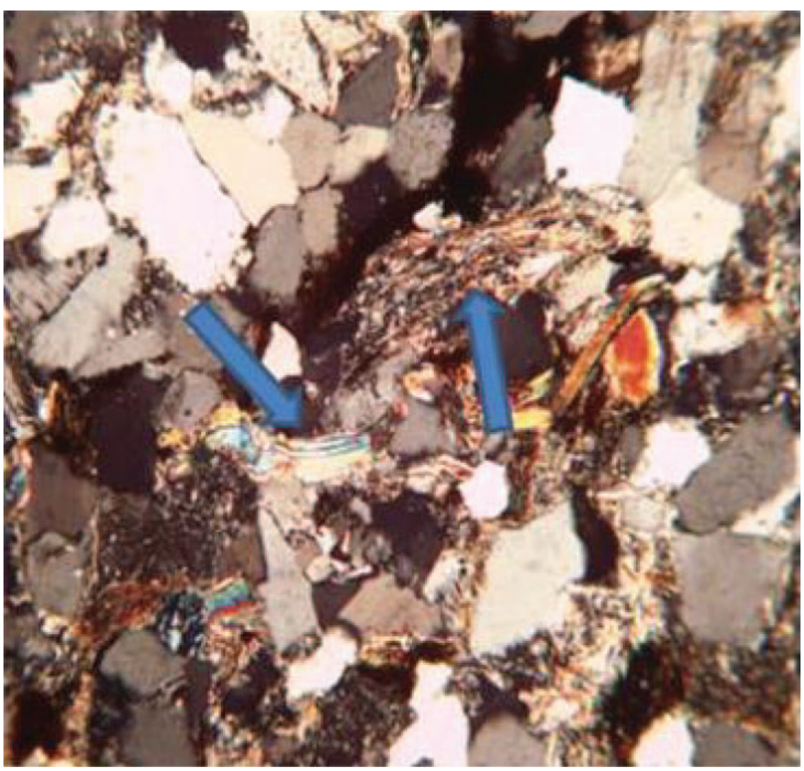


Figure 5. Photomicrograph of rock sample McD-1, collected near well Mcd-0203, in the Elkhorn area, McDowell County, West Virginia. [Abundant highly bifringement material (blue arrows) composed of muscovite, phyllosilicate, and sericitic grains filling all available pore spaces. Field of view approximately 1.1 mm.]

Above this unit is a 10- to 20-feet thick, medium-grained gray to white, weathered, slightly argillaceous sandstone with abundant plant debris and large scale trough bedding. The unit also exhibits large vertical fractures consistent with collapse structures due to undermining.

Macroscopically, hand sample McD-2 is a weathered, fine-grained, moderately sorted, light gray, planar-bedded sandstone with abundant grain voids and sub-millimeter coal streaks and micaceous streaks. Grain voids were particularly abundant associated with thicker micaceous streaks. Two samples were collected; the first oriented with the long axis parallel to bedding, the second was oriented with the long axis perpendicular to bedding.

Thin-section examination revealed abundant mono- and polycrystalline quartz grains comprising 54.67 percent of the total rock volume with the next most abundant constituent being rock fragments (13.67%) and original feldspar grains comprising 13.00 percent. Rock fragments are a mixture of shales, other reworked sedimentary fragments and a few metamorphic rock fragments. Phyllosilicate grains (0.33%) were scarce in this sample while micas comprised 8.34 percent of the rock volume with siderite comprising 2.33 percent and secondary quartz adding an additional 2.33 percent. Approximately 2.33 percent of the total rock volume was comprised of eroded or dissolved feldspar grains creating secondary porosity combining with 1.00 percent original porosity resulting in 3.33 percent total porosity (Figure 6) while an additional 3.33 percent (accounted for above) of the total rock volume was feldspars converted to clays. Pyrite (0.67%), chert grains (0.33%), kaolinite (0.67%) and unidentified clays (0.33%) were observed locally.

In both instances these components would have contributed relatively high porosity values due to the microporous nature of ductile micaceous grains and clays, however, through visual quantification, permeability was considered to be very low due to compaction of clays, ductile rock fragments and micas in existing pore spaces creating ‘log jams’, except in areas with microfractures or grain plucking. The sample was well sorted with an average grain size of 0.19 mm with sub-angular to angular grains, and was determined to be an arkosic arenite.

Sample McD-3 was collected from the sandstone above the Pocahontas No. 3 coal seam near well Mcd-0203. The sample is oriented with the long axis perpendicular to bedding. The sand unit was fine to medium grained with semi-rounded grains. The unit exhibits abundant accessory minerals, planar bedding with occasional very thin discontinuous coal streaks on ripple surfaces or brown iron stained, with scattered irregular coal clasts.

Macroscopically the hand sample is a very fine to fine grained, light gray to white argillaceous sandstone with semi

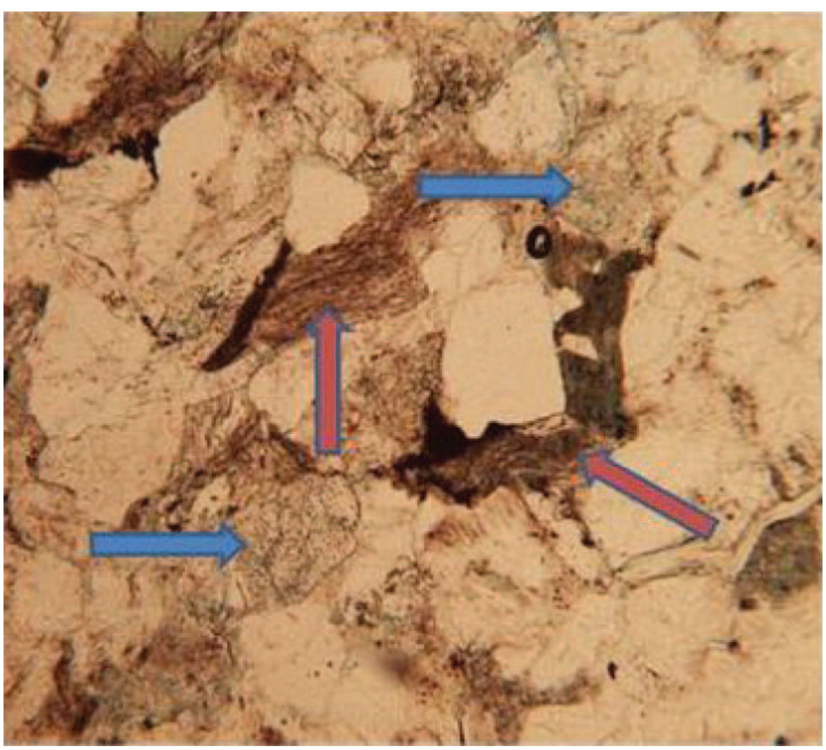


Figure 6. Photomicrograph of rock sample McD-2, collected near well Mcd-0203 in the Elkhorn area, McDowell County, West Virginia. [Feldspar grains have been corroded (blue arrows) increasing secondary porosity. Ductile phyllosilicate grains (red arrows) fill all available pore spaces creating a tight low primary porosity and permeability sandstone. Field of view approximately 1.1 mm.]

rounded grains, abundant accessory minerals, low angle to planar beds, few very thin discontinuous coal streaks, multiple brown, iron stained, approximately 1 mm x 1 mm clasts, and abundant thin, discontinuous siderite streaks.

Thin-section examination revealed abundant mono- and polycrystalline quartz grains comprising 60.00 percent of the total rock volume. The next most abundant constituents are rock fragments at 11.00 percent, siderite comprising 10.33 percent of the total rock volume followed by feldspar comprising approximately 9.00 percent. Siderite with occasional pyritic zones, are expressed as well defined discontinuous streaks. The sample contains abundant micas composed of muscovite (3.33 percent) and sericite (0.67 percent), shale fragments primarily of reworked sedimentary and, to a lesser amount, metamorphic origins, and other phyllosilicate grains all of which have infiltrated original pore spaces due to compaction (Figure 7). Remaining rock constituents include pyrite (0.67%), secondary quartz overgrowths (2.67%) and unidentified clays (0.33%). Porosity, measured as primary porosity at 2.00% is very low although secondary porosity does exist due to late stage dissolution of feldspar grains. Permeability is deemed to be very low due to clogged pore spaces and pore throats greatly reducing or eliminating pore to pore communication. The sample is fairly well sorted with an average grain size of 0.22 mm, with sub-angular to sub-rounded grains and was determined to be a sub-lithic arenite.

Sample McD-4 was collected approximately 0.25 miles west of monitoring well Mcd-0204 on the Pocahontas No. 3 coal seam strip bench. This was the only location where the Pocahontas No. 3 seam was actually observed, although abundant large tree roots prevented complete exposure of the coal, approximately 3.3 feet was uncovered.

An incomplete thickness of 3.3 feet of the Pocahontas No. 3 coal was uncovered showing a weathered, bright laminated coal, which was blocky in the upper section. Above this unit was 6 cm of dark gray carbonaceous shale with abundant plant debris that grades upward into a dark gray claystone. The claystone was 7.5-feet thick, medium to dark gray, very rooted, highly weathered with abundant stems, plant fragments and occasional well preserved specimens with a sharp upper contact. Above this is approximately 20 feet of broken and fractured, fine to medium grained sandstone with rounded grains, abundant accessory minerals, planar bedded, with thin coal streaks and wisps and abundant thin siderite streaks.

The hand sample is weathered brownish orange, internally massive, very fine to fine-grained sandstone with scattered micaceous grains. The hand sample (Figure 8) appears to exhibit increased porosity compared to other samples, perhaps due to dissolution and weathering of feldspars, clay and clay

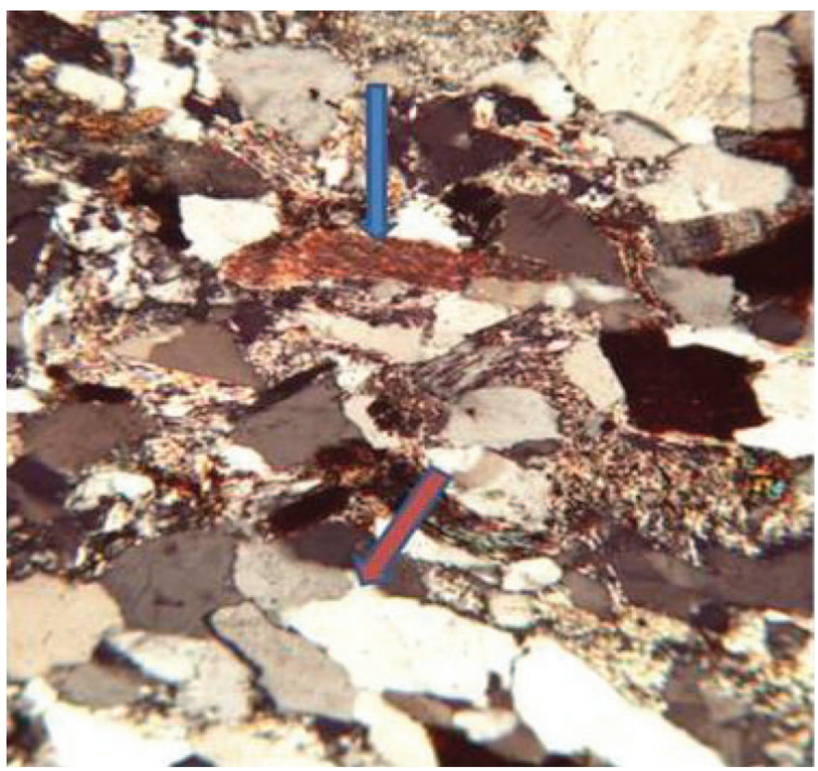


Figure 7. Photomicrograph of rock sample McD-3, collected near well Mcd-0203, in the Elkhorn area, McDowell County, West Virginia. [Abundant quartz grains exhibiting sutured grain boundaries (red arrows). Highly birefringent phyllosilicate grains fill all available pore spaces. Field of view approximately 1.1 mm.]

materials on the outcrop surface, since the surface from which the sample was collected was much less protected from the elements.

Thin-section examination again reveals mono- and polycrystalline quartz grains comprised the majority of the total rock volume at 61.00 percent. The next most prevalent constituent is siderite (14.33 percent) expressed as both small secondary siderite blebs and as staining of grain coatings, clay-sized material and phyllosilicate grains (Figure 8). Feldspar grains comprise 10.67 percent of the rock volume and are corroded. Rock fragments comprise 7.00 percent and are primarily sedimentary fragments with minor metamorphic fragments. Porosity comprising 2.67% of rock volume is primarily secondary, composed of ground up micas and clay material filling primary pore spaces and dissolved feldspars. The remainder of the sample is composed of various micas (2.67%), clays (1.33%) and minor secondary quartz overgrowths (0.33%) scattered throughout. The sample is well sorted with an average grain size of 0.17 mm, with sub-angular to sub-rounded grains and was determined to be a subarkose.

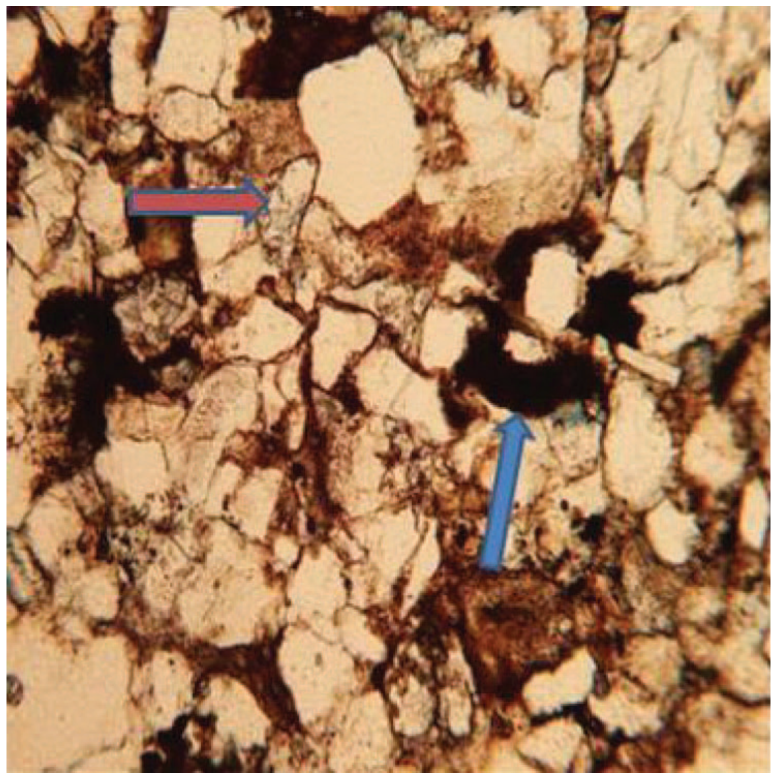


Figure 8. Photomicrograph of rock sample McD-4, collected approximately 0.25 mi west of well Mcd-0204, in the Elkhorn area, McDowell County, West Virginia. Abundant monocrystalline quartz grains exhibiting sub-rounded to locally sub-angular nature. Siderite stains many phyllosilicate grains while pyrite (blue arrows) fills occasional pore spaces. Feldspar grains have been corroded (red arrow) adding secondary porosity. Field of view approximately 1.1 mm.

Petrographic Results

Monocrystalline and polycrystalline grains composed the majority of framework grains in all samples. Quartz grain boundaries were often sutured possibly with secondary quartz cement which was difficult to identify without cathode-ray luminescence or clay grain coatings.

All samples contained large amounts of rock fragments, feldspar grains and accessory minerals ranking the sandstones as subarkose to arkosic arenites. Primary permeability of the sandstone overlying the P3CMA is low due to clogged pore throats, dissolution of feldspar grains into clays, and abundant ductile phyllosilicate grains which fill pore spaces. Porosity remains fairly high due to abundant micro-porosity associated with ductile micas and phyllosilicate grains and grain coatings and dissolution of feldspar grains. The remainder of macro-secondary porosity as observed in thin section occurred post-compaction of the unit as evidenced by the lack of ductile material within secondary pore spaces.

Structural Geology

Pocahontas strata have been slightly folded within the study area with a gradual rise from north-west to south-east exhibiting few folds throughout the county. The nearest named structural features are the Dry Fork Anticline to the south and the Mullens Syncline to the north, neither of which directly affect the study area. The bedrock dip within the study area is to the northwest and is slight, being almost impossible to measure by inclinometer. A geologic map for the study area includes structure contours for the Pocahontas No 3 coal seam (Figure 4) and shows a general north-west to south-east rise of approximately 250 feet from Elkhorn to Maybeury, which is an average of only 83 ft/mi.

Although large-scale regional structures such as anticlines, synclines, or faults are not present in the study area, there are some subtle folds which are not apparent when examining the geologic map or the structure contours for the Pocahontas No. 3 coal seam (Figure 9). These subtle folds are important controls on groundwater and mine discharge in the study area. The cross section (Figure 9) is based on survey grade GPS elevation data collected along the Pocahontas No. 3 strip-mine bench (line of section shown on Figure 4). Local dips (topographic lows) in the structure of the Pocahontas No. 3 coal seam typically intersect with local headwater streams. Stream base-flow surveys conducted for the study show groundwater discharge from abandoned underground Pocahontas No. 3 mine adits generally coincides with the topographic lows along the Pocahontas No. 3 coal strip-mine bench.

Abandoned mine workings in the P3CMA, which is comprised of mine entries filled with collapsed overburden strata and coal pillars which have collapsed or spalled over time, serves as the water reservoir for public supply in the study area, and where undisturbed by mining is a natural aquifer. The sandstone(s) above the Pocahontas No. 3 coal are highly weathered at the outcrop and vertically fractured due to subsidence and settling following mining allowing communication with higher water sources.

Abandoned mine workings extend for many miles with regional dip to the west allowing large quantities of potable water to be available for public consumption, exiting mines through abandoned mine portals (adits) or other openings. A possible structural flexure is postulated to exist creating a roll in the mined out portion of the Pocahontas No. 3 seam near Elkhorn which serves to channel mine waters towards Johns Knob Branch. This assumption cannot be proven by geologic data, but hydrologic data collected during this project strongly supports this theory.

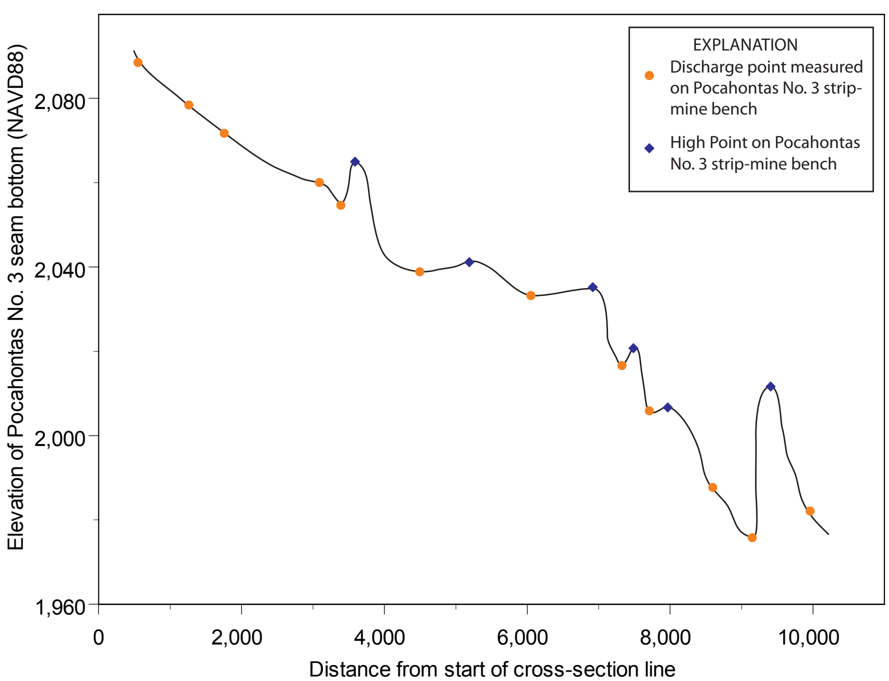


Figure 9. Cross section of elevation along a portion of the Pocahontas No. 3 coal strip-mine bench, showing local variations in geologic structure in the Elkhorn area, McDowell County, West Virginia.

Borehole Geophysical Methods

In the Appalachian Plateaus, bedrock aquifer complexities are the result of hydraulic interaction between intricate networks of fractures. The distribution of fracture networks in Plateau aquifers is largely dependent on lithology and response of respective lithologies to valley stress-relief or mining induced subsidence. For this study, description of lithologies and fracturing observed in the Elkhorn area is based upon drilling and borehole logs from a network of seven monitoring wells (Figure 1). Borehole geophysical logs were collected in August 2009 from wells Mcd-0203, Mcd-0204, Mcd-0205, Mcd-0206, Mcd-0207, Mcd-0208, and Mcd-0209 (Appendix 2).

Borehole logging activities were designed to evaluate the distribution, orientation, and flow properties of various lithologies and associated subsurface fractures at depth. Borehole logging included collection of caliper, natural gamma, resistivity, heat-pulse flow meter, focused electromagnetic induction (EM), and acoustic televiewer (ATV) logs. General methods of borehole log interpretation are outlined in Keys (1990).

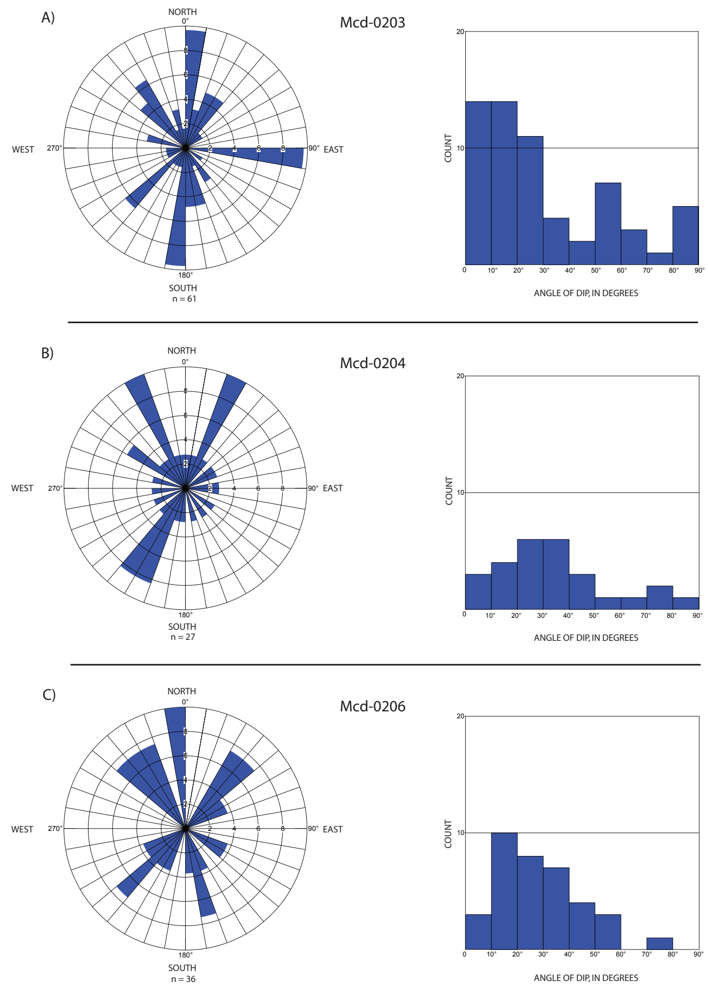
Results of Borehole Geophysical Logging

Lithologic interpretations for this study were based primarily on use of resistivity and EM logs. The driller's logs provide supplemental information on rock type penetrated by the borehole, and the resistivity and EM logs show typical responses for various rock types. In general, sandstones occur in intervals showing increased resistivity values. Conversely, finer-grained shales and coals result in lower resistivity values. EM logs record the conductance of lithologies surrounding the borehole and are inversely related to resistivity logs. Natural gamma logs indicate the intensity of naturally occurring radiation as a function of sediment mineralogy and are shown in Appendix 2 as supportive information. Coal typically has a pronounced low-gamma signature which makes gamma logs particularly useful in locating coal-mine aquifers penetrated by the borehole.

Caliper and ATV logs are used to define the location and orientation of fractures intersecting the borehole. Fracture orientations were determined from ATV logs of three wells (Mcd-0203, Mcd-0204, and Mcd-0206). These three wells were the only wells in which submergence of the ATV probe in water could be achieved, a requirement for use of the ATV probe to image the borehole. In all three wells, fracture mapping was completed in strata below the P3CMA. A total of 124 fractures were mapped and plotted on compass-rose diagrams to show fracture orientation (Figure 10). The dominant orientation trends are N-S and NE-SW. The trends are generally aligned with strike of bedding. Most of the fractures are strike-parallel joints and cleavage which dip generally from 15 to 60 degrees (Figure 10). By right-hand rule convention, the compass-rose diagrams indicate that most fractures are dipping to the northwest and southeast. Caliper logs generally show that the larger fractures coincide with bedding plane contacts between units of varying lithology (Appendix 2). Bedding plane fractures noted in caliper logs have shallower dips and are less frequent than the dominant trends shown by joint and cleavage fractures. Hydrologically active high-angle joints and cleavage likely provide important pathways for groundwater flow linking them to more horizontally oriented bedding-plane partings. Bedding, joint, or cleavage related fracturing, however, rarely penetrates massive sandstones separating thinner coal and shale units (Appendix 2). Sandstones are less frequently fractured than the surrounding finer grained units and typically show no response in caliper logs. No relation between fracturing and proximity to the P3CMA was noted in caliper, ATV, or driller's logs.

Heat-pulse flow-meter logging was conducted at Mcd-0204 under ambient conditions to evaluate interaction of hydrologically active fractures at various depths within the borehole. Under ambient conditions, results of the flow-meter logging indicate that flow enters the borehole at a fracture

Figure 10. Compass-rose diagrams showing strike direction, and histograms showing dip angle, of dominant fracture trends identified from ATV logs of wells (A) Mcd-0203, (B) Mcd-0204, and (C) Mcd-0206 in the Elkhorn area, McDowell County, West Virginia.



approximately 32-33 feet bls and exits the borehole near the top of a coal seam at 56 feet bls at the same rate (Appendix 2 Figure 2; caliper log). Drilling logs indicate a sandstone unit from 38-52 feet bls separates the coal seam from an overlying shale unit. Several fractures were identified in the sandstone unit from acoustic televiewer logs (Appendix 2 Figure 2; fracture dip angle), although, none are noted in the caliper log. The flow meter, ATV, caliper, and driller's logs suggest sandstones at Elkhorn are poorly fractured and limit vertical flow between more permeable yet finer grained units. No additional flow was noted by heat-pulse flow-meter logging from fractures identified from 55 - 150 feet bls.

Hydrology

Groundwater-flow processes in sequences of sandstone, shale, and coal typical of the southern Appalachian coal fields in West Virginia were investigated by Wyrick and Borchers (1981). The study area for this earlier research was at Twin Falls State Park, less than 20 miles from the study area for this project near Elkhorn, West Virginia. Wyrick and Borchers (1981) proposed that groundwater flow in the Appalcahian Plateaus occurs predominantly along stress-relief fractures at the periphery of hillsides, and along bedding-plane partings, predominantly within coal strata. Multiple perched water zones, mostly in coal-mine aquifers and massive sequences of sandstone, are separated by less permeable shale layers which act as confining layers. Upward arching sections of bedrock along bedding planes in valley settings caused by stress relief, are also preferential flow paths. Flow within the core of ridges was theorized to be a slower and less dominant mechanism. Harlow and Lecain (1993) documented the importance of coal-seams as aquifers in a nearby study area in southwestern Virginia. These two studies laid the ground work for understanding groundwater flow in the region prior to this study.

However, the earlier studies investigated primarily natural processes and did not fully explore the effects of underground coal mining. Within the study area, abandoned underground coal mines are a dominant pathway for groundwater flow. Abandoned underground mines short-circuit natural fracture-flow processes in significant ways, and can aggregate groundwater flow over large areas, even from adjacent surface-water drainages. Research conducted as part of this investigation was centered on linking the natural groundwater-flow processes in bedrock due to stress-relief fracturing within the major coal-mine aquifers with flow processes that occur as a result of man-made effects of large, regional, underground abandoned coal-mine complexes.

Groundwater Levels

Groundwater-level data were used to evaluate seasonal trends, measure response from storm events, and define post-mining hydrologic conditions within and below the P3CMA. Groundwater levels were continuously monitored in and below the P3CMA for the period August 2009 through September 2010 (Figure 11; Mcd-0207 and Mcd-0204). Continuous water levels recorded in the P3CMA at Mcd-0207 (Figure 11) were supplemented with monthly monitoring up-dip at Mcd-0206 and down-dip at Mcd-0205 and Mcd-0208 (Figure 12). Water levels in strata below the P3CMA were measured continously at Mcd-0204 (Figure 11) and supplemented with monthly monitoring at Mcd-0203 (Figure12). Damage to well Mcd-0203 shortly after drilling precluded the use of the well for monitoring during most of the study period.

In general, water levels from all wells showed minimal change over the duration of the study. The hydrographs and water-level cross section in Figures 11 and 12 suggest that mine-aquifer water levels are not influenced by seasonal climate patterns, but rather are controlled primarily by the elevation and dip of abandoned mine workings in the P3CMA. During drilling of the seven monitoring wells for the project in the summer of 2009 very little water was encountered in the 150 to 525 feet of strata overlying the P3CMA, and water typically was not encountered until the wells penetrated abandoned mine workings in the Pocahontas No. 3 coal seam. Monthly measurements of water levels were made over the 15 month period from August of 2009 though October of 2010. Except for three occasions, the water-level measurements (53 of 56 measurements) made at the seven wells verified the trend noticed during drilling, that of minimal water entry in the open boreholes from overlying strata. The only exceptions to this trend were at well Mcd-0206 in March of 2010 and again in June of 2010, and at well Mcd-0205 in February of 2010. The February 2010 spike in well Mcd-0205 was the result of a

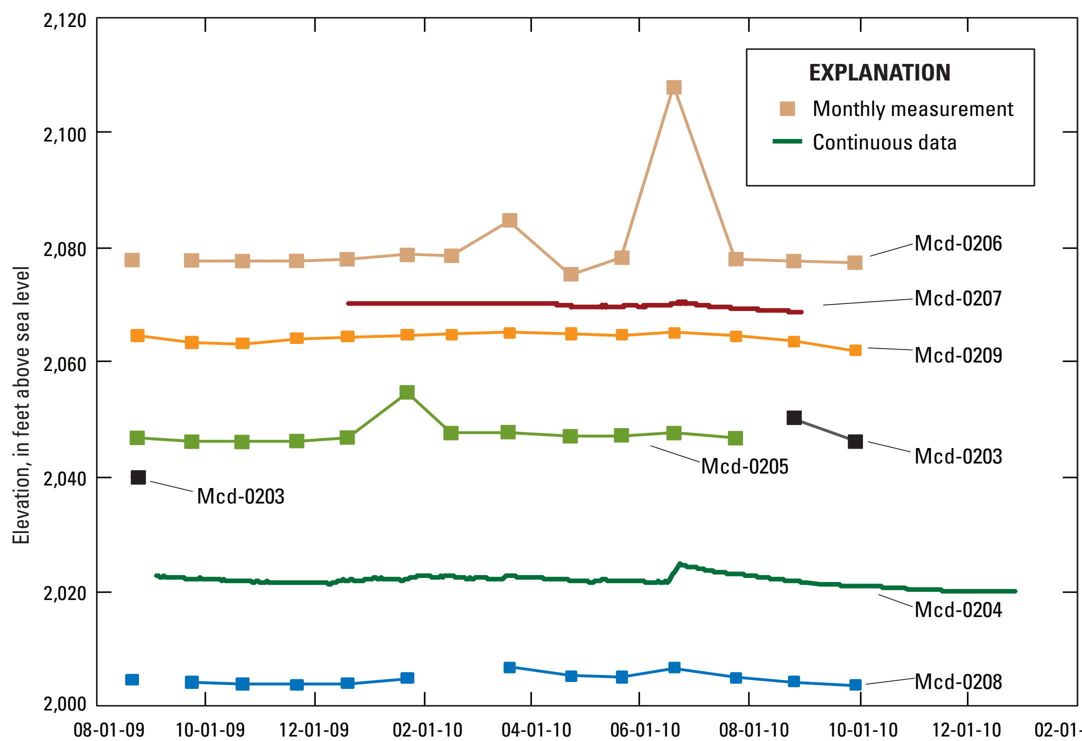


Figure 11. Water-level hydrographs for seven wells located in the Elkhorn area, McDowell County, West Virginia.

substantial snow melt event. Short-term peaks in water levels in March and June of 2010 correlate with individual storm events. Within the abandoned workings of the P3CMA, the heterogeneous water-level response to storm events is evident in the hydrographs of wells Mcd-0205, Mcd-0206, Mcd-0207, and Mcd-0208. A storm event on June 6, 2010 resulted in a 29.90 feet rise in water level in Mcd-0206, the furthest updip site. The next highest measured water-level rise in the P3CMA was associated with the same event and was 1.61 feet at Mcd-0208, the furthest down-dip site. Wells Mcd-0205 and Mcd-0207 both show less than 1 foot change in response to the storm. The hydrograph of well Mcd-0205 also shows a water-level peak on Jan. 19, 2010 that is not present in any of the other hydrographs. Water levels in Mcd-0204 in strata below the P3CMA rose 3.11 feet and peaked 12 days after the June 2010 event. Following the June 2010 event water levels from all wells receded to their lowest levels during the period of study.

A cross-section of water levels through the Elkhorn area (Figure 12) shows the hydraulic gradient within the P3CMA approximates the regional dip of the Pocahontas No. 3 coal seam. The absence of steep horizontal gradients along the dip of the P3CMA suggest the barriers between the mines are likely breached or that collapsed strata provide continuous pathways for groundwater flow from east to west. Within the P3CMA, unconfined heads range from about 2 feet (Mcd-0209) to about 13 feet (Mcd-0208) above the mine floor and are perched over a thin unsaturated zone just below the base of the P3CMA. Water levels just below the P3CMA reflect the top of the next perched or confined aquifer. Above the P3CMA, strata are generally unsaturated or are locally perched and unconfined. Seasonal development of perched aquifers was noted by ephemeral seepage faces along strip benches associated with the Pocahontas No. 6 and Fire Creek coal seams.

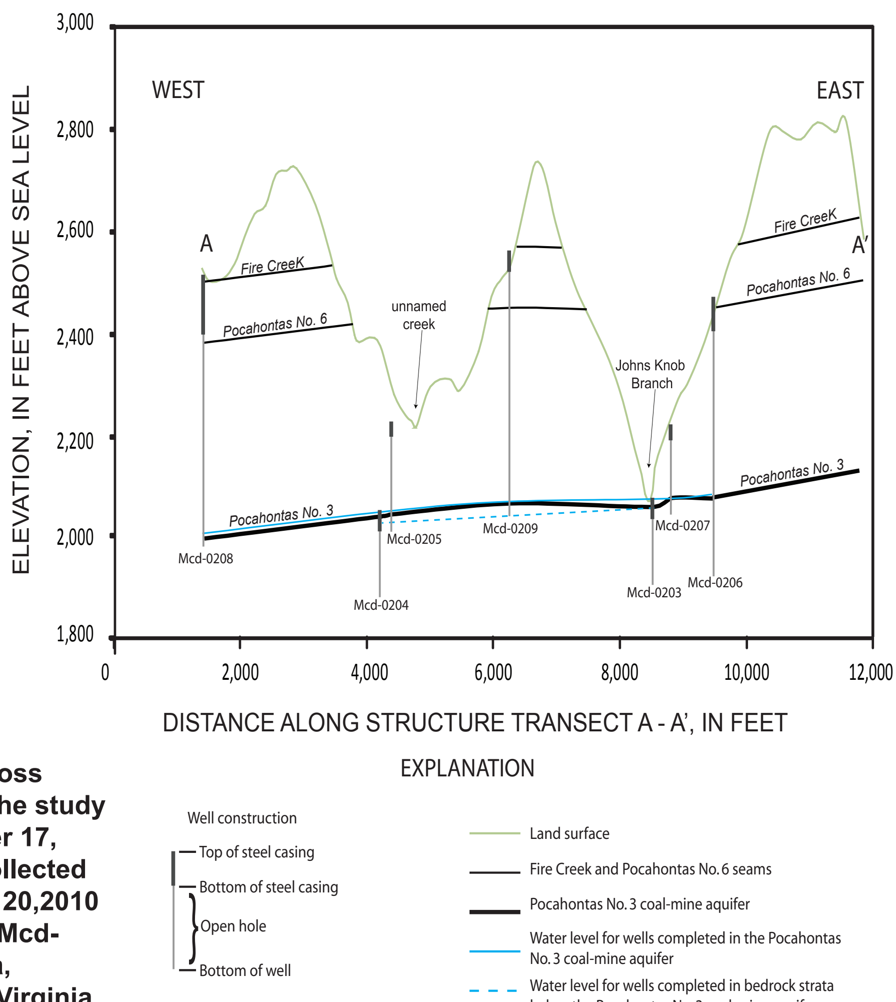


Figure 12. Water-level cross section for a portion of the study area, based on December 17, 2009 water-level data collected for six wells and August 20,2010 water level data for well Mcd-0203, in the Elkhorn area, McDowell County, West Virginia.

Table 1. Streamflow and mean groundwater recharge rates estimated from base-flow recessions at streamflow gaging stations in McDowell County, West Virginia.

[mi^2, square miles; in/yr, inches per year; ft^3/s, cubic feet per second; %, percent of streamflow contributed by groundwater discharge]

USGS Station Number	Station name	Period of record	Watershed area (mi^2)	Mean daily streamflow (ft^3/s)	Base flow (in/yr)	Base flow (ft^3/s)	Base flow/drainage area ($ft^3/s/mi^2$)	Base flow index (%)
03212558	PUNCHEONCAMP BRANCH AT LECKIE, WV	1981	1.36	1.01	8.1	0.81	0.60	80.2
03212567	FREEMAN BRANCH NEAR SKYGUSTY, WV	1981	0.3	0.16	4.5	0.1	0.33	63.6
03212580	LEFT FORK SANDLICK CREEK AT ELBERT, WV	1981	1.7	1.27	9.0	1.12	0.66	87.9
03212585	RIGHT FORK SANDLICK CREEK NEAR GARY, WV	1981	1.21	0.51	3.2	0.29	0.24	56.2
03212600	TUG FORK AT WELCH, WV	1979-1980	85.9	103.53	12.0	76.04	0.89	73.4
03212640	JOHNS KNOB BRANCH AT ELKHORN, WV *	2009	0.81	5.43	89.8	5.35	6.60	98.5
03212700	ELKHORN CR AT MAITLAND, WV *	1979	69.9	149.83	23.9	123.19	1.76	82.2
03212703	ELKHORN CREEK TRIBUTARY AT WELCH, WV	1981	0.63	0.32	3.7	0.17	0.27	54.7
03212750	TUG FORK AT WELCH, WV	1986-1992	174	198.63	12.3	157.78	0.91	79.4
03212750	TUG FORK AT WELCH, WV	1997-2008	174	196.24	12.3	157.29	0.90	80.2
03212980	DRY FORK AT BEARTOWN, W. VA.	1986-1992	209	224.91	9.5	146.35	0.70	65.1
03212980	DRY FORK AT BEARTOWN, W. VA.	1997-2009	209	219.22	9.1	140.42	0.67	64.1
03212985	DRY FORK AT AVONDALE, WV	1979-1980	225	295.65	11.4	189.43	0.84	64.1
03213000	TUG FORK AT LITWAR, WV	1931-1983	504	555.44	9.1	338.86	0.67	61
03213495	CRANE CREEK NEAR PANTHER, WV	1981	0.54	0.44	6.2	0.25	0.46	56.6
03213500	PANTHER CREEK NEAR PANTHER, WV	1947-1985	31	35.17	7.4	16.83	0.54	47.8
03213500	PANTHER CREEK NEAR PANTHER, WV	2003-2008	31	36.17	7.5	17.06	0.55	47.2
		mean	101.1	119.1	14.1	80.7	1.04	68.4
		median	31.0	36.2	9.1	17.1	0.67	64.1

* Sites known or suspected to be impacted by interbasin transfer of groundwater

Groundwater Recharge

Groundwater recharge is an essential component for assessing groundwater availability, calculating water budgets, and parameterizing groundwater-flow models. To provide an initial estimate of groundwater recharge for the study and to provide base-flow discharge data for assessing typical base flow yields per unit contributing area, streamflow records for nearby streams were evaluated using the hydrograph separation program PART (Rutledge, 1998). PART separates streamflow into its base-flow and surface-runoff components. Under steady-state conditions, groundwater discharge as base flow to streams is equivalent to the rate at which groundwater is replenished or recharged (Fetter, 2001). The volumetric rate of base flow is divided by an assumed surface area of recharge to convert to units of inches per year. This assumption may not be applicable in areas with extensive underground mining, and depends on the geometry of abandoned workings and integrity of mine barriers and subsided overburden strata. Substantial interbasin transfer of groundwater via abandoned mine workings could result in mine discharges that potentially comprise as much as 50-80 percent of streamflow in receiving streams (Borchers and others, 1984). Regardless, Nelms and Moberg (2010) concluded that dividing the average base flow from PART by the surface-water drainage area provides a first-order estimate of recharge in areas where the location of groundwater divides are uncertain.

Streamflow data from 14 historic continuous gaging stations in McDowell County, West Virginia (Table 1) were evaluated to provide data (1) from which initial estimates of groundwater recharge could be made for model development and calibration, and (2) to assess average rates of base flow per unit contributing area which can be expected for watersheds near the study area. The drainage basins for the gages ranged in size from 0.3 to 504 mi^2, providing a range of basin size from which to assess variability in recharge. Relative percentage of streamflow attributable to groundwater base flow discharge are also represented as a base flow index in Table 1. The Johns Knob Branch at Elkhorn has a drainage area of 0.81 mi^2, and the gaging station was installed in February 2009 to measure streamflow primarily from mine discharge from the abandoned Turkey Gap and adjacent mines. Mine outfall discharges along Johns Knob Branch constitute the majority of flow in the stream. Because hydrologic connection between older mines is common (Borchers and others, 1984), the large volume of mine discharge to

Johns Knob Branch is assumed to originate from a groundwater contribution area much larger than the area of the surface watershed.

Base flow estimates of recharge estimated from the hydrograph analysis of the gaging stations ranged from 3.2 in/yr to 89.8 in/yr, and the base flow index ranged from 47.2 to 98.5 %. Generally, watersheds greater than 10 mi^2 in area had higher recharge estimates than those less than 10 mi^2. The median recharge estimate for all stations was 9.1 in/yr; a value equivalent to that estimated for Tug Fork at Litwar, WV, the largest watershed in the dataset with the longest period of record. Recharge calculated from streamflow data for the Elkhorn Creek at Maitland, WV was approximately two and one half times the median value for all sites. Elkhorn Creek at Maitland may receive mine discharge from interbasin transfer of groundwater, which would explain the higher than average recharge rate calculated for that gage. Unfortunately, no mine discharges were documented during the period of gage operation.

Kozar and Mathes (2001) estimated a slightly higher average recharge rate of 11.2 in/yr for two streams in McDowell County using the computer program RORA (Rutledge, 1998), which is based on the recession-curve displacement method (Rorabaugh, 1964). The RORA method does not account for losses due to riparian evapotranspiration (RET), a process that consumes 1 to 2 in/yr of groundwater in the Appalachian Valley and Ridge province from Alabama to New Jersey (Rutledge and Mesko, 1996). Assuming the RET rates for the Appalachian Plateaus to be comparable to those of the Valley and Ridge (Rutledge and Mesko, 1996), decreasing the recharge values obtained by Kozar and Mathes (2001) by 1 to 2 in/yr would result in similar results to those obtained using PART.

PART analysis of streamflow data for a 12-month period from March 2009 through February 2010 resulted in a median value of 9.1 in/yr of base flow for streams in the region, which is a rough approximation of groundwater recharge for the study area (Table 1). The base flow per unit surface drainage area and base-flow index (proportion of streamflow attributed to groundwater discharge) for the Johns Knob Branch watershed is anomalously high (6.60 $ft^3/s/mi^2$ and 98.5% respectively) compared to the median calculated for other stations in the region (0.67 $ft^3/s/mi^2$ and 64.1% respectively), and is

Table 2. Literature-cited values of coal hydraulic conductivity, from McCoy and others (2006).

[K, hydraulic conductivity; ft/day, feet per day; b, bituminous; sb, sub-bituminous; l, lignite]

Authors	K_{min} (ft/d)	K_{max} (ft/d)	K_{median} (ft/d)	Seam	Coal Rank	Formation/Group	Depth (ft)	Method	State
Isotropic K									
McCoy and others (2004)	0.10	0.49	0.30	Pittsburgh	b	Monongahela Group	900-1,500	modeling	WV
Luo and others (2001)		0.23					1,200	modeling	
Minns and others (1995)	2.9E-04	1.2E-02	8.6E-04	Fireclay	b	Breathitt Formation	300-900	packer tests	KY
Harper and Olyphant (1993)	0.20	11	4.9	Mariah Hill	b	Mansfield Formation	69-90	slug tests	IN
Harlow and LeCain (1993)	1.1E-04	6.6	0.017		b	Early to Middle Pennsylvanian**	0-900	packer tests	VA
Aljoe and Hawkins (1992)			0.36		b			well tests	WV,PA
McCord and others (1992)	3.3	0.033			b	Fruitland Formation	2,250	heat flux	CO,NM
Hobba (1991)	11	14		Upper Freeport	b	Allegheny Group	60	well tests	WV
Dames and Moore (1981)	1.0	4.9					300-600	modeling	
Rehm and others (1980)			2.8		l,sb	Fort Union Group		aquifer tests	ND,WY,MT
Rehm and others (1978)			1.1		l	Fort Union Group		aquifer tests	ND
Dabbous and others (1974)	2.9E-03	0.036		Pittsburgh	b	Monongahela Group		laboratory	PA
Miller and Thompson (1974)	0.72	3.1	0.98	Upper Freeport, Lower Kittaning	b	Allegheny Group	30-90	packer tests	PA
Anisotropic K	Range K_{min} (ft/d)	Range K_{max} (ft/d)							
McCoy and others (2004)	0.066 - 0.30	0.23 - 0.98		Pittsburgh	b	Monongahela Group	900-1,500	modeling	WV
Chadwick (1981)	1.0	8.2		D1 upper seam	l,sb	Fort Union Group		well tests	MT
Stoner (1981)	0.75 - 1.1	1.6 - 2.4		Sawyer A, Anderson	l,sb	Fort Union Group	120	well tests	MT,WY
Vogwill (1979)	1.2	2.8						well tests	Alberta
Stone and Snoeberger (1977)	0.49	0.89			l,sb	Wasatch Formation		well tests	WY

**(Lee, Pocahontas, New River, Norton, and Wise Formations, Gladeville Sandstone) due to interbasin transfer of water through abandoned mine workings up-gradient and structurally up dip within the P3CMA. Water discharging from the Turkey Gap mine into Johns Knob Branch potentially originates from up-dip areas extending as far as the Pocahontas No. 3 seam outcrop, six miles to the east in the adjacent Bluestone river watershed.

Hydraulic Properties

Coal is typically the most permeable of the rock types found in the Appalachian Plateaus (Harlow and LeCain, 1993). Harlow and LeCain (1993) found groundwater flow in coal-mine aquifers of the Appalachian Plateaus to be a result of higher hydraulic conductivity of the strata in the horizontal direction, rather than a result of vertical connections with adjacent sandstone, siltstone, or shale layers. The range of hydraulic conductivity of undisturbed coal from 18 studies was summarized by McCoy and others (2006) (Table 2). They found that coal hydraulic conductivity ranges over five orders of magnitude, from 0.00011 to 14 ft/d, and displays strong anisotropy that is ascribed to its systematic jointing, termed cleats. Hobba (1991) found that anisotropic ratios ranged from 2 to 15, with a median of 3.4, in the Upper Freeport coal of West Virginia. Schubert's (1980) summary of several studies indicate anisotropy of 2 to 10 in West Virginia coals, and that anisotropy in Plateaus rocks overlying coal-mine aquifers ranges from 1:2.6 in sandstones and 1:14.9 in siltstones. Lithologies possessing well-developed joint systems serve as aquifers with higher conductivity than lithologies with poorly developed joint systems (Abate, 1993). Permeability in all rock types of the Appalachian Plateaus decreases with depth as overburden pressures decrease the frequency and distribution of fractures (Callaghan and others, 1998).

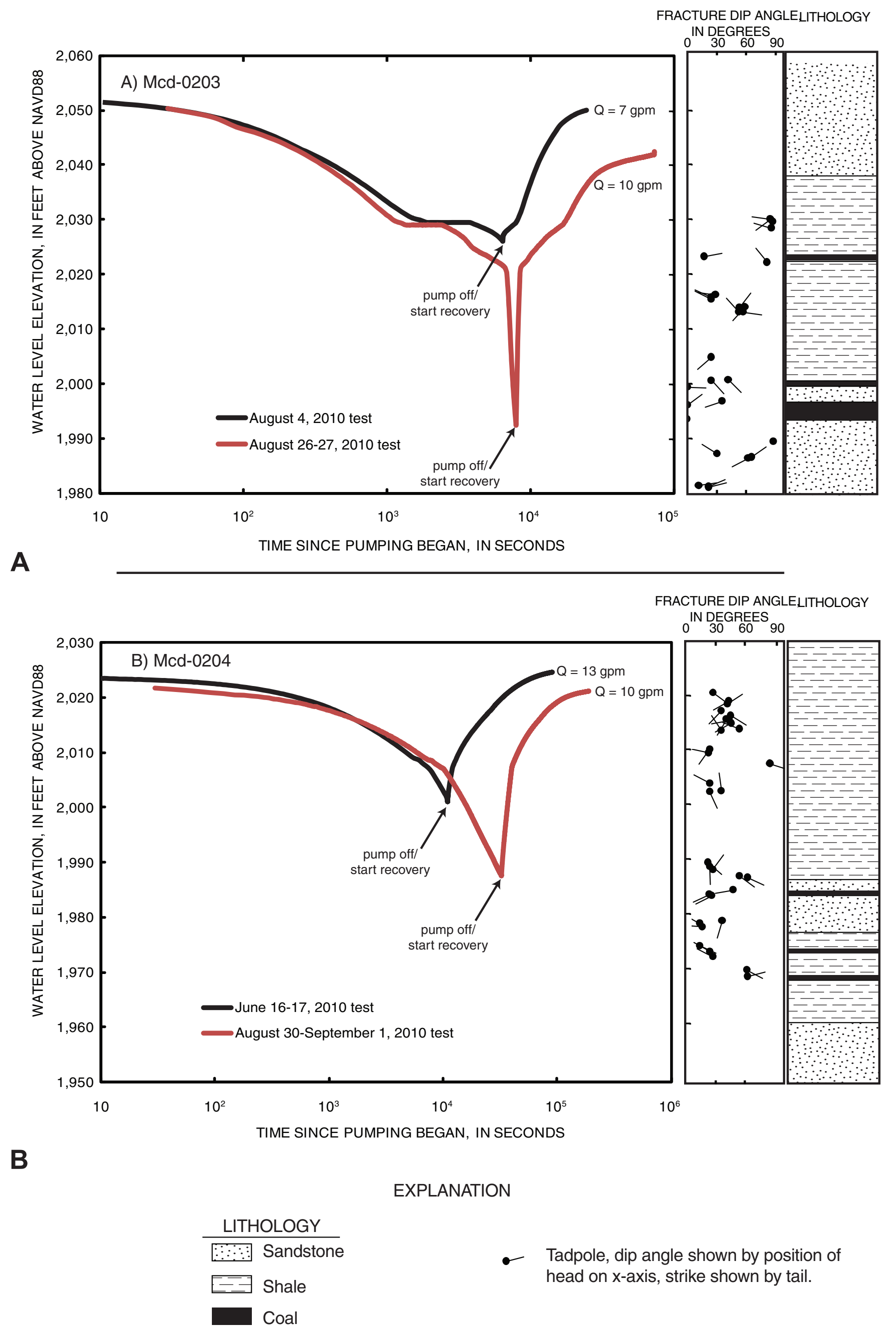


Figure 13A and B. Pumping test results and borehole logs from wells (A) Mcd-0203 and (B) Mcd-0204 in the Elkhorn area, McDowell County, West Virginia.

Aquifer Tests

A series of single-well aquifer tests were conducted in wells Mcd-0203 and Mcd-0204 (Figure 13) to assess the influence of individual strata on the overall shape of the drawdown curve and to estimate the hydraulic properties of aquifers in the Elkhorn area. The initial tests were conducted on June 16-17 (Mcd-0204) and August 4, 2010 (Mcd-0203) and were designed to measure drawdown for 100 minutes and subsequent water-level recovery until post-pumping static conditions were met. A second round of tests were conducted on August 30 - September 1 (Mcd-0204) and on August 26-27, 2010 (Mcd-0203) to evaluate the response of aquifers to longer periods of pumping than those of the initial tests. Water-level measurements made during the tests were recorded using pressure transducers lowered approximately 40-60 feet below the static water level.

Two pumping tests were conducted on well Mcd-0203 in August 2010 (Figure 13A). The initial test on August 4 was conducted at a pumping rate of 7 gallons per minute (gal/min) for a period of 100 min. A second test on August 26-27 was conducted at a pumping rate of 10 gal/min for a period of 130 min. Water levels during both pumping tests show nearly identical declines in early-time data. Water levels declined slightly faster at the higher pumping rate as storage in the well was depleted. Both pump-test plots flatten when the water level declined to 2,029 feet above sea level. Mcd-0203 is intersected by near vertical fractures in a massive sandstone at an elevation of 2,030 - 2,031 feet above sea level. The water level declined to a brief equilibrium level of 2,029 feet and stayed at that level for 32 min while being pumped at 7 gal/min (August 4 test), and 17 min while being pumped at 10 gal/min (August 26-27 test). Following the brief period of equilibrium, water levels during both tests continued to decline below 2,029 feet. Pumping was terminated during the August 4 test when the water level reached a minimum elevation of 2,027 feet above sea level. The August 26-27 test shows additional changes in the rate of water-level decline at 2,026 and 2,022 feet, respectively. At 2,022 feet, the drawdown curve has a sharp deflection coincident with the depth at which Mcd-0203 intersects a fracture dipping approximately 78 degrees to the northwest. The rate of water-level decline rapidly increased below this level until the test was terminated. Data following pump shut off show rapid recovery to 2,022 feet. Both the August 4 and August 26-27 test show changes in the rate of water-level recovery in Mcd-0203 coincident with elevation of the sub-vertical fractures at 2,030-2,031 feet.

At Mcd-0204, a series of two pumping tests show similar results to those of the Mcd-0203 tests. Pumping tests were conducted at Mcd-0204 on June 16-17 and August 30-September 1, 2010 (Figure 13B). The data from both tests show a deflection in the water-level drawdown curves at an elevation of 2,008 feet coincident with the level of a fracture in shale dipping 78 degrees to the southeast. An increase in the rate of water-level decline with time below 2,008 feet suggests that storage within the fracture had been depleted or that the fracture had simply dewatered. Following pumping, the water level in Mcd-0204 recovers rapidly to 2,008 feet, followed by a more gradual recovery to static conditions.

Dual-porosity and single-fracture analytic solutions were evaluated for their ability to provide hydraulic properties from the pumping-test data at Mcd-0203 and Mcd-0204. Risser (2010) showed the value of using such models in analysis of tests with distinct slope breaks associated with fracture desaturation. Model inputs were iteratively varied, yet solutions were unable to satisfactorily replicate the observed drawdowns from the Mcd-0203 and Mcd-0204 tests. Breaks in pumping-curve slope in the aquifer tests from Mcd-0203 and Mcd-0204 prohibited the use of conventional type-curve analysis for determining aquifer properties.

Advanced analysis, however, was conducted by evaluating the shape of the drawdown curves on various diagnostic plots. In all tests, early time data (4-5 min at Mcd-0203 and 7-8 min at Mcd-0204) display a unit slope on log-log plots indicative of drawdown due to depletion of wellbore storage.

Following the depletion of wellbore storage, flow to the wells is initially linear, perhaps through a single near-vertical fracture as indicated by a 0.5 slope on a log-log plot. Depending on the rate of pumping, linear flow conditions in the wells ranges from 19.5 min (August 4, 2010 test at Mcd-0203) to 129 min (August 30, 2010 test at Mcd-0204). Linear flow to wells ceases when water levels indicate the onset of fracture desaturation and influence of boundary conditions on the well response. Drawdown curves for Mcd-0203 and Mcd-0204 show deflections that are consistent with the depths at which both wells intersect fractures with 78 degree dips. In both wells, the steeply dipping fractures are oriented northeast-southwest or parallel to the respective adjacent valleys, suggesting a stress-relief origin. The pumping tests indicate that the rate of water-level decline in these two wells is dependent on the location and permeability of hydrologically active fractures and the variation in fracture characteristics associated with multiple stacked aquifers. The observations are, however, particularly illustrative of stacked, perched aquifer systems that are common in above-grade cyclothems of the Appalachian Plateaus. However, more complex numerical methods for evaluating these pumping tests are needed to estimate aquifer properties from the observations at Mcd-0203 and Mcd-0204.

In lieu of generating aquifer properties from the analytical or numerical methods of analysis for this complex system, specific capacity estimates were derived from late-time data and converted to aquifer transmissivity using relations outlined in Kozar and Mathes (2001). These estimates were computed to place maximum bounds on aquifer properties used in the MODFLOW simulation of the Elkhorn basin. Risser (2010) found large decreases in specific capacity when water levels were drawn below shallow, productive stress-relief fractures. Specific capacity computed at 60 min of pumping, prior to fracture desaturation, averaged 0.36 gpm/ft for Mcd-0203 and 1.1 gpm/ft for Mcd-0204. These values equate to transmissivities of 720 to 2,200 ft^2/d (Kozar and Mathes, 2001; equation 3). Specific capacity computed at 90 min of pumping, after onset of fracture desaturation, averaged 0.32 gpm/ft for Mcd-0203 and 0.80 gpm/ft for Mcd-0204, equating to transmissivities of 600 and 1,600 ft^2/d. Given an approximate saturated thickness for the interval tested of 150 feet, this equates to an estimated hydraulic conductivity indicative of rocks in stress-relief fractured portion of the aquifer, of 4 to 12 ft/d. Near horizontal areas on the drawdown curves for the aquifer tests correlate with high angle fractures from the acoustic televiewer logs, indicative of stress-relief fractures near the upper portion of the borehole (Figure 13).

Straddle-Packer Tests

Aquifers in the Appalachian Plateaus are highly heterogeneous and their hydraulic properties vary by orders of magnitude, which can be attributed to the diversity of fracture orientation, size, and connectivity. The ability of the aquifer to transmit water depends entirely upon the network of interconnecting fractures, as the surrounding rock mass is relatively impermeable. Aquifer hydraulic properties determined from aquifer response to extended periods of pumping incorporate many fractures over a large area. Results from these aquifer tests are indicative of a composite fracture network and interpretations require careful consideration of aquifer heterogeneity.

Table 3. Transmissivities computed from straddle-packer injection tests conducted in the Elkhorn area, McDowell County, West Virginia.

[Site locations shown on figure 1; ft bls, feet below land surface; ft^2/d, feet squared per day; BD, below detection; --, no analysis]

Well	Interval top (ft bls)	Interval bottom (ft bls)	Transmissivity (ft^2/d)	Analysis Method	Lithology of interval
Mcd-0203	58.2	63.7	BD	--	Shale
	64.2	69.7	1.1E-06	Steady-State Radial	Shale & coal
	107.2	112.7	2.1E-06	Steady-State Radial	Sandstone & coal
	116.2	121.7	1.8E-05	Transient Radial	Shale & coal
	127.2	132.7	BD	--	Shale
Mcd-0204	32.1	37.6	9.1E-04	Transient Radial	Shale & sandstone
	37.1	42.6	1.6E-05	Transient Radial	Sandstone
	50.7	56.2	5.9E-02	Steady-State Radial	Coal & sandstone
	62.2	67.7	4.0E-03	Transient Radial	Coal & shale
	69.2	74.7	3.7E-06	Steady-State Radial	Shale
	108.2	113.7	BD	--	Sandstone & coal
	131.9	137.4	BD	--	Shale

Using the BAT3 (Bedrock Aquifer Transportable Testing Tool) (Winston and Shapiro, 2007) system developed by the USGS, a series of straddle-packer tests were conducted in wells Mcd-0203 and Mcd-0204 (Figure 1 and Table 3) to determine a range of transmissivity for individual fractures intersecting the boreholes. A straddle-packer assembly is simply a pair of rubber bladders that are expanded against the side of the borehole to prevent leakage of water between the intervals above, below, and between the packers. The assembly used for these tests isolated an approximately 5.5-feet interval of the borehole and allowed individual fractures to be hydraulically tested. Three pressure transducers, one above the upper packer, one below the lower packer, and one in between the packers, were used to measure pressure (piezometric) head changes in those zones. A fluid injection port was installed in the interval between the packers to allow fluid injection into the individual fractures for aquifer test analyses.

Test intervals in Mcd-0203 and Mcd-0204 were determined from borehole log analyses. All intervals were in unmined strata below the base of the P3CMA. Test intervals were designed to bracket fractures within a single lithology if possible. In many cases, however, fractures were coincident with coal-sandstone contacts. Because undisturbed coal is the primary aquifer in unmined basins in the Appalachian Plateaus (Harlow and LeCain, 1993), coal-sandstone contacts were assumed to represent permeability within the coal.

Transmissivity calculated from the straddle-packer injection tests (Table 3) ranged over five orders of magnitude, from below the detection limit of (1 x 10-9 ft^2/d) to 5.9 x 10-2 ft^2/d, with a median of 1.7 x 10-5 ft^2/d, indicating a high variability in the hydraulic properties of individual fracture zones. Despite the number of fractures in these boreholes, it is thought that most are unproductive, discontinuous, and poorly interconnected. Supporting evidence from borehole logs indicates that the majority of groundwater flow occurs only through one or two of the fractures intersecting the borehole. Some of the more permeable fractures could not be tested, as the packers could not be inflated in portions of the borehole with erratic walls or near the edge of steel well casing.

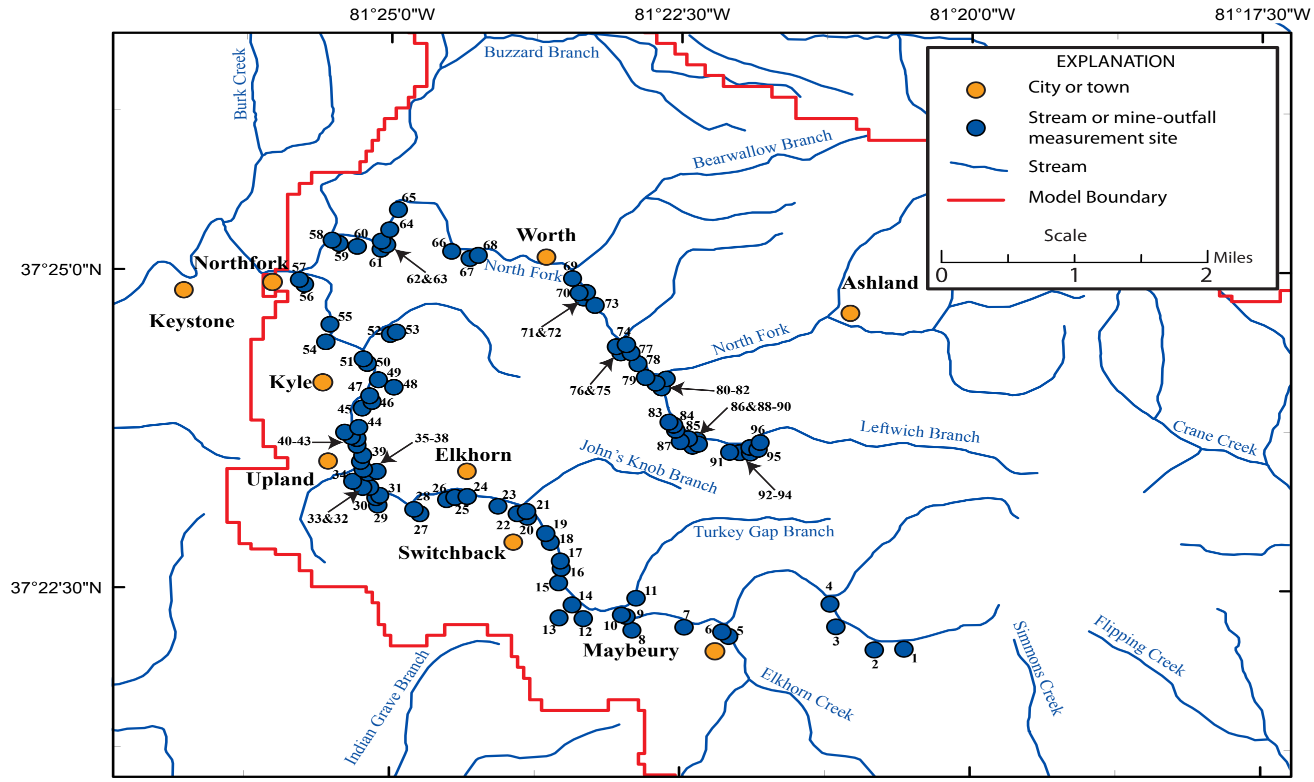


Figure 14. Locations of 96 sites where one or more measurements of base-flow or mine-outfall discharge were made in the Elkhorn area, McDowell County, West Virginia.

Base-Flow Surveys

Three separate base-flow surveys were conducted to estimate groundwater discharge, which could then be used to help calibrate the groundwater-flow model. Base-flow data collected for the study are presented in Appendix 3 and the locations of the 96 sites where one or more base-flow or mine-outfall discharge measurements were made are shown in Figure 14. A streamflow gaging station was constructed on Johns Knob Branch to continuously monitor discharge from the P3CMA. A precipitation gage was also installed at the gaging station. Data were collected between February, 2009 and September, 2010 (Figure 15). The first base-flow survey was conducted on April 27-28, 2009. Mean daily discharge at the Johns Knob Branch gaging station for each day was 6.7 and 5.8 ft^3/s respectively. Due to the large difference in base flows on the two days and the high flow condition, this data was not used in calibration of the groundwater-flow model. The second base-flow survey was conducted on October 20-22, 2009. Streamflow at Johns Knob Branch on each day was 4.0, 3.8, and 3.8 ft^3/s, respectively. Due to the late start on the first day, a near constant discharge of 3.8 ft^3/s was present during the entire base-flow survey, and adjustments of individual discharge measurements were not necessary. The third base-flow survey was conducted on September 8-9, 2010. Streamflow at the Johns Knob Branch gaging station on each day was 3.3 and 3.2 ft^3/s respectively. Due to near constant discharge during the course of the base-flow survey, no adjustments of individual discharge measurements were necessary.

Given the extreme range of discharge that was measured for the study (.001 – 44.0 ft^3/s) and the accuracy of the current meters used to measure base flow, the margin of error for the measurements varied over a wide range, from less than 5% for some of the larger tributary streams (flow> 1.0 ft^3/s)

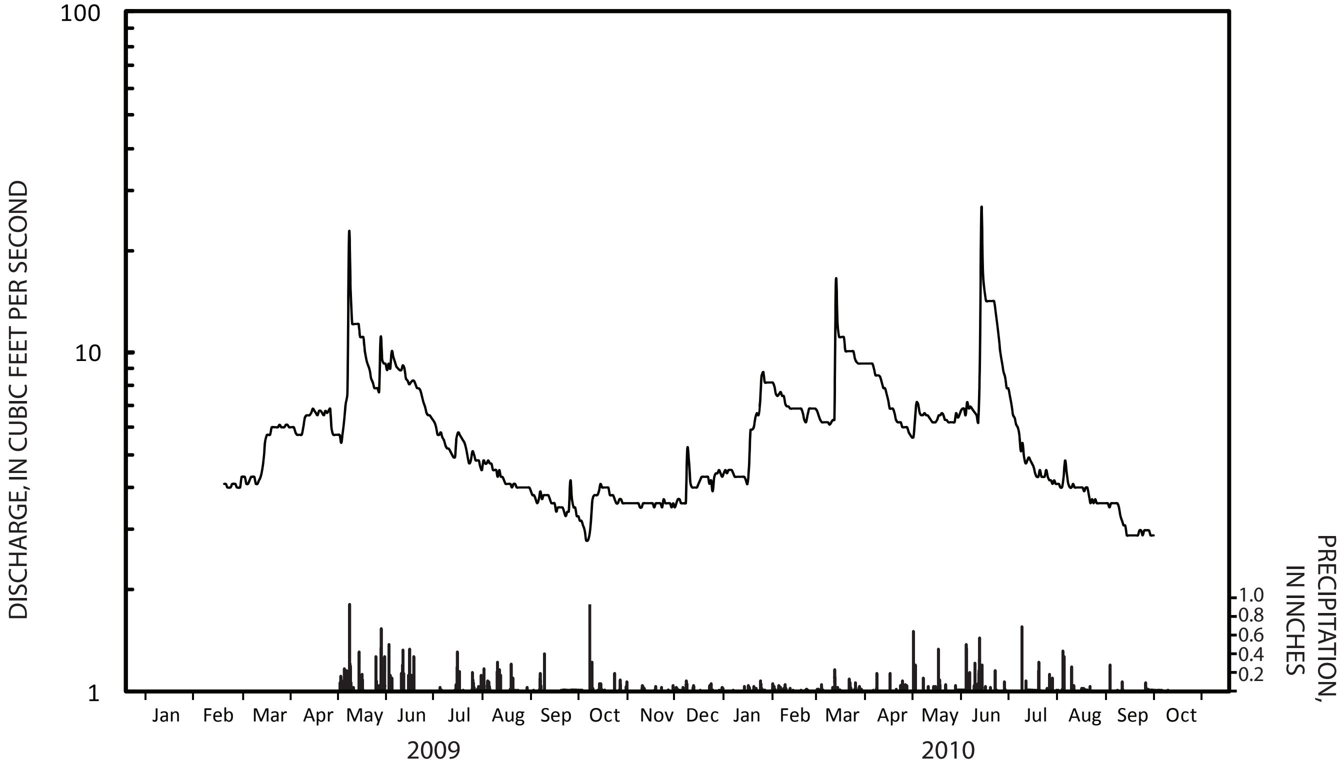


Figure 15. Streamflow and precipitation for February, 2009 through September 2010, for USGS gaging station 03212640 on Johns Knob Branch at Elkhorn, McDowell County, West Virginia.

to as much as 20% or more for some of the smaller measured flows (<0.01 ft^3/s). This variability in accuracy, especially for low-flow values, results in less confidence and greater variability in the low flow values used for calibration of simulated flux within the groundwater flow model.

Hydrologic Conditions

Streamflow during the study period was compared to long-term streamflow to characterize hydrologic conditions as average, below average (low flow), or above average (high flow). Long-term streamflow records for four USGS streamflow gaging stations were analyzed and the flow conditions for the respective two to three day periods during which base-flow surveys were conducted were compared to the long-term statistical data for each gage. Table 4 presents the flow-duration statistics (percentage of time flow is equaled or exceeded) as long-term percentiles of flow by month and annually for each gaging station. These values were compared to the mean daily discharge for the gages during each respective base-flow survey. Base flow was measured on three separate occasions (Appendix 3), on April 27 and 28, 2009, October 20 and 21, 2009, and again on September 8 and 9, 2010. Mean daily streamflow at the gages for these periods are also summarized in Table 4. Based on comparisons of base-flow measurements in Appendix 3 to flow-duration statistics for long-term gages in Table 4, the base-flow and mine-outfall discharge measurements made in April of 2009 represent fairly high flow conditions, approximately the 38th percentile of mean annual streamflow (discharge for the period was equaled or exceeded only 38% of the time). Base-flow measurements made in October of 2009 represent flow conditions below average, approximately the 70th percentile of mean annual streamflow (flow was equaled or exceeded 70% of the time). Base-flow measurements made in September of 2010 represent extremely low-flow conditions, at approximately the 87th percentile of mean annual streamflow (flow

Table 4. Hydrologic conditions during the study, as represented by flow-duration statistics for four long-term gaging stations in the Elkhorn Creek area, McDowell County, West Virginia.

[mi^2, square miles; ft^3/s, cubic feet per second; percentile of flow duration is the amount of time streamflow was equaled or exceeded for month specified or annually]

USGS Site ID	Station name	Drainage area (mi^2)	Date streamflow measured	Period of record of analyses	Number of years of record analyzed	Mean streamflow on dates specified: in ft^3/s	As percent of annual flow duration	As percent of monthly flow duration
03179000	Bluestone River at Pipestem, WV	395	4/27 - 4/28/09	1951-2011	60	302, 343	40%	78%
03213500	Panther Creek near Panther, WV	31	4/27 - 4/28/09	1947-2010	48	20, 25	35%	73%
03212750	Tug Fork at Welch, WV	174	4/27 - 4/28/09	1985-2011	24	217, 225	31%	74%
03185000	Piney Creek at Raliegh, WV	52.7	4/27 - 4/28/09	1952-2011	39	35, 38	48%	84%
						mean	39%	79%
						median	38%	78%
03179000	Bluestone River at Pipestem, WV	395	10/20 - 10/21/09	1951-2011	60	153, 172	56%	20%
03213500	Panther Creek near Panther, WV	31	10/20 - 10/21/09	1947-2010	48	4.0, 4.6	70%	33%
03212750	Tug Fork at Welch, WV	174	10/20 - 10/21/09	1985-2011	24	79, 81	70%	26%
03185000	Piney Creek at Raliegh, WV	52.7	10/20 - 10/21/09	1952-2011	39	2.12, 2.09	71%	32%
						mean	67%	28%
						median	70%	29%
03179000	Bluestone River at Pipestem, WV	395	9/8 to 9/9/2010	1951 - 2010	60	33, 35	92%	68%
03213500	Panther Creek near Panther, WV	31	9/8 to 9/9/2010	1946-2010	48	0.80, 0.87	95%	80%
03212750	Tug Fork at Welch, WV	174	9/8 to 9/9/2010	1985-2011	24	56, 57	81%	56%
03185000	Piney Creek at Raliegh, WV	52.7	9/8 to 9/9/2010	1952-2011	39	2.31, 2.30	80%	47%
						mean	87%	63%
						median	87%	62%

was equaled or exceeded approximately 87% of the time). The groundwater-flow model was calibrated against the October 2009 base-flow and water-level data, and is therefore representative of hydrologic conditions 20% below median annual streamflow.

Groundwater Withdrawals

There are no known or permitted large groundwater withdrawals from wells within the study area. The numerous mine outfalls in the study area have historically provided substantial quantities of groundwater for public and domestic supply, much of which is not metered. Any unknown well withdrawals in the study area would represent a small and negligible amount of water. The McDowell County Public Service District (PSD) is the only known permitted entity and withdraws water discharging from four mine outfalls (Figure 1). Two are on the north side of Elkhorn Creek (outfall 1 for the Upland plant and outfall 2 for the Elkhorn plant), a third is on the south side of Elkhorn Creek for the Upland plant (outfall 3), and the fourth (outfall 4) is in the headwaters of Elkhorn Creek near the Mercer and McDowell County line (Figure 1). These withdrawals are not groundwater withdrawals, but rather flow taken from mine-outfall discharge points, usually at the headwaters of small tributary streams. The total maximum measured withdrawals from the Elkhorn, Upland northern and southern, and the County Line outfalls were approximately 0.131, 0.351, 0.377, and 0.576 ft^3/s, respectively.

Dye Tracer Tests and Analyses

A dye tracer test was conducted during the period June 29 to July 1, 2010 to assess relative rates of groundwater flow within the P3CMA. Prior to injection of the dye, water samples were collected from seven mine outfalls and from Elkhorn Creek to establish background fluorescence in groundwater and surface water within the region. At 10:55 hrs on June 30, 1/2 pound of Fluorescein, a highly fluorescent

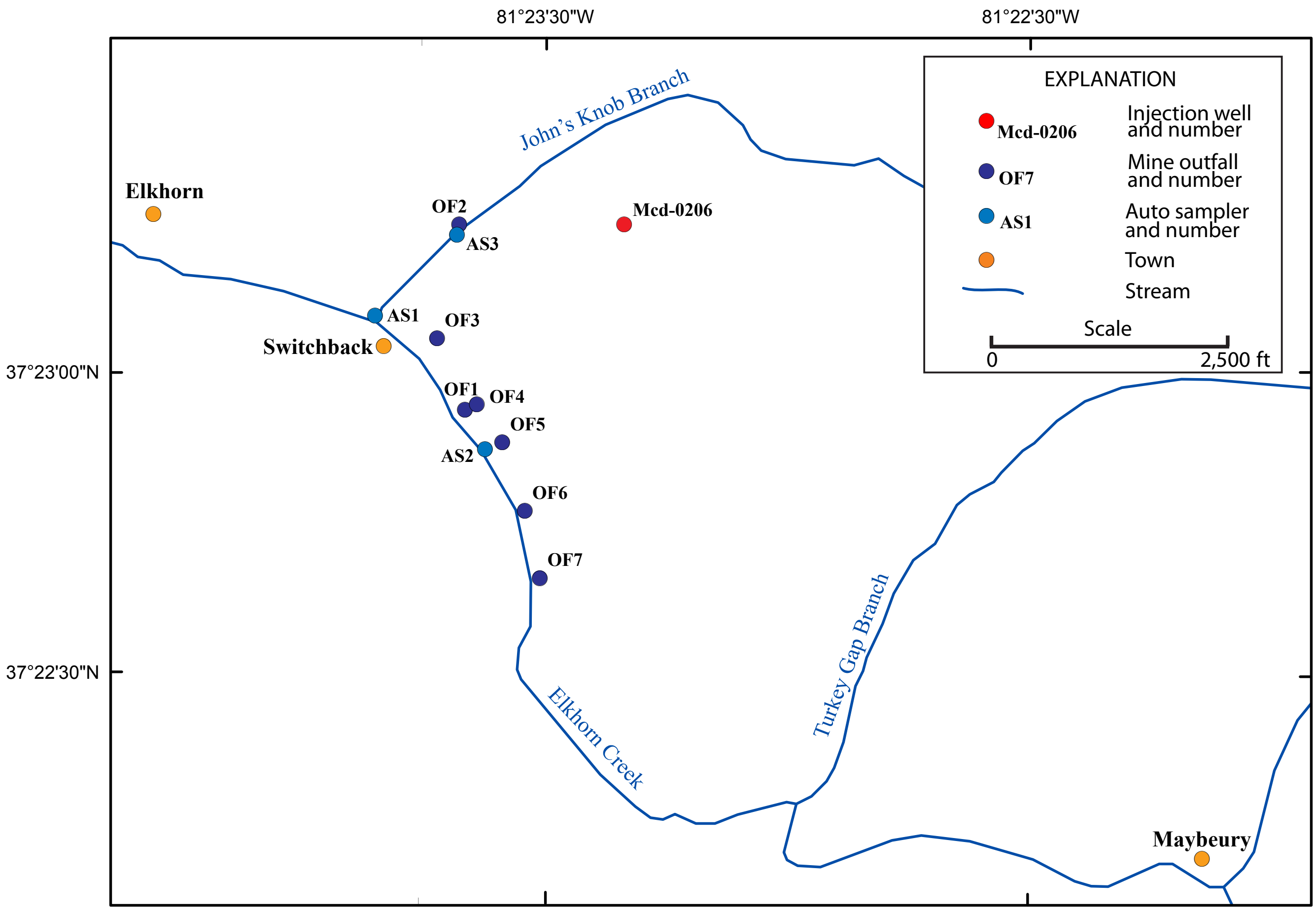


Figure 16. Map showing the location of the injection well and mine outfalls monitored for the fluorometric dye-tracer test of the Pocahontas No. 3 coal-mine aquifer in the Elkhorn area, McDowell County, West Virginia.

green colored dye was mixed with 1,500 gallons of clean water and injected into the P3CMA at well Mcd-0206. Water samples were collected at intervals ranging from 15 min to 3 hours during the course of the tracer test (data for the tracer test are presented in Appendix 4). The seven outfalls sampled encompassed a semi-circular area (Figure 16) down gradient of the injection well (Mcd-0206).

A Turner Model 111 fluorometer with a 546 nanometer (nm) primary and a 590 nm secondary filter was used to analyze samples collected from the seven outfalls. Water samples were collected manually at various intervals during the course of the test and analyzed on the fluorometer within an hour of collection. Additional samples were collected using automatic samplers at two locations, but instrument failures during the recovery period limited use of the data from the automated samplers to verification purposes only, especially with respect to the timing of dye recoveries.

Results of Tracer Tests

The fluorescent dye was detected at moderate concentrations in two of the seven outfalls, outfalls 1 and 2 (Figure16). At outfall 1 concentrations rose substantially above background and a peak concentration was detected at 00:11 hrs on July 1, with a secondary peak occurring at 13:26 hours on July 1. The straight line distance between the injection well (Mcd-0206) and outfall 1 is approximately 2,500 feet. Given the time from injection to recovery of dye at outfall 1 of 13 hours and 16 minutes

(.553 days) and the straight line distance of 2,500 feet, the estimated flow velocity within the P3CMA is approximately 4,520 ft/d.

At outfall 2 concentrations rose substantially above background and a peak concentration was detected at 23:47 hours on June 30. The straight line distance between the injection well (Mcd-0206) and outfall 1 is approximately 2,400 feet. Given the time from injection to recovery of dye at outfall 2 of 12 hours and 52 minutes (.536 days) and a straight line distance of 2,400 feet between the injection well and outfall 2, the estimated flow velocity within the P3CMA is approximately 4,480 ft/day.

Such rapid flow velocities seem contrary to the premise of long residence time of groundwater in abandoned underground coal mines assessed by analysis of chlorofluorocarbon (CFC) and isotopes in groundwater. However, as will be discussed in the conceptual models of groundwater-flow section of this report, several sources of water enter the mine. These include a slow component, which is basically the water that slowly infiltrates through overlying bedrock strata to the abandoned mine voids, and a much younger and faster component of flow derived from recharge through near surface stress-relief fractures near the periphery of hillsides. Since the tracer was injected into the most down gradient point of the potential flow path, it is believed that much of the water discharging from the mine outfall is near-surface, recent recharge through stress-relief fractures, rather than older water percolating downward through hundreds of feet of layered sedimentary rock. A further discussion of groundwater flow and residence and travel times of groundwater will be presented in the groundwater age and radionuclides (isotopes) and conceptual model of groundwater flow section of this report.

Groundwater Flow

Groundwater flow in the Elkhorn area is controlled by a complex interaction of both natural and human-induced factors. The natural factors that control groundwater flow are the hydraulic properties of the rock, topography, and geologic structure. The primary human-induced factor controlling groundwater flow is coal mining, primarily underground coal mining, but surface mining can also impact groundwater flow. The data collected during this project were used to develop a better understanding of the flow system and factors affecting groundwater flow. This conceptual understanding of the groundwater-flow system provides the foundation upon which numerical simulations of groundwater flow were made. Numerical simulations of groundwater flow serve several purposes, including but not limited to 1) testing the conceptual flow model to ascertain if it is mathematically feasible, 2) assessing groundwater-flow rates and directions under varying hydrologic conditions (high flow versus low flow), 3) assessing water availability for current and future demands, and 4) assessing the natural controls and human impacts on groundwater flow.

Conceptual Model of Groundwater Flow

Groundwater flow in the relatively flat-lying sedimentary rocks of the southern West Virginia coalfields has not previously been adequately described. During the drilling of the seven monitoring wells for this project, it was obvious that large proportions of the strata overlying the P3CMA were relatively devoid of water. During drilling of the monitoring wells, water was rarely encountered in any rock unit other than coal seams (especially seams of more than a foot in thickness). This is easily explained by the vertical or near-vertical subsidence fractures that are common above abandoned mines. Massive thicknesses of sandstone and shale separate the coal seams, which are the primary aquifers. While results of borehole geophysical logging showed numerous dominant high angle fractures with the capacity to convey large quantities of groundwater, logging of vertical boreholes may substantially underestimate the role of vertical or near vertical subsidence fractures.

In the study area, a series of perched coal-seam aquifers are separated by varying thicknesses of sandstone and shale confining or semi-confining units. Downward percolation of recharge to the underground coal-mine aquifers is limited by the relatively impermeable sandstone and shale bedrock, but may be enhanced by vertical subsidence fractures in the rock intervals immediately above abandoned coal-mine workings which comprise the P3CMA. The mechanism by which groundwater recharges deeper strata, including the prolific P3CMA is therefore not readily apparent or explained solely by the permeability of bedrock strata, and must take into account the role of vertical or near vertical subsidence fractures.

Wyrick and Borcher's (1981) expanded on Ferguson's (1967) theory of stress-relief fracturing and theorized that recharge occurs through numerous near-surface fractures that form in the bedrock as a result of stress relief when overlying strata is removed by erosion. This relief of stress, causes strata in valleys to arch upward, opening void space along bedding planes, and also forms vertical fractures at the periphery of valley walls, resulting in an interconnected network of near-surface, stress-relief fractures, and enhanced permeability along bedding planes (Figure 2). These stress-relief fractures are believed to be a dominant source of recharge to deeper aquifers. In addition, faults, joints, and other fractures can allow downward percolation of flow through otherwise low or impermeable strata. Coal miners have long noticed that the amount of water seeping into the mine from overlying strata is typically greatest near the mine portal or adit, which is indicative of stress-relief fracture recharge. Passing from mine portals (adits) further under the core of ridges, the percolation of water becomes less prevalent, unless a substantial vertical fault or fracture zone is encountered. In addition, subsidence of overlying strata due to collapse of coal pillars, especially prevalent when pillars are pulled during retreat room and pillar mining, or as a result of longwall mining, also have been shown to increase fracturing in overlying strata providing pathways for downward migration of groundwater (Shultz, 1988).

Geologic structures, especially the dip of bedrock strata, and synclinal troughs or anticlinal arches, are major controls on groundwater flow within the extensive P3CMA and similar areas within the Appalachian coalfields. In the study area, bedrock dips gradually to the west, at rates ranging from a minimum of 32 ft/mi to a maximum of 126 ft/mi and averaging 83 ft/mi. Although not apparent when examining the structural contours of the base of the No. 3 Pocahontas coal-mine aquifer (Figure 4), an elevation survey conducted using a surveying grade global positioning receiver (GPS) indicated local variations in the elevation of the bedrock surface (Figure 9). These local variations result in structurally high and low areas along the bedrock surface, potentially allowing local pools of groundwater to accumulate in the topographic lows between intervening structural highs within the P3CMA. In addition, synclinal troughs can aggregate water over a broad area, producing locally higher than average groundwater discharge from outfalls.

One such anomalous high groundwater discharge emanates from several mine outfalls that form in a synclinal trough near the headwaters of Johns Knob Branch (Figure 4). Median base flow per square mile for gaged streams in the southern coalfields (Table 1) is approximately 0.67 $ft^3/s/mi^2$, but Johns Knob Branch has a base flow per unit surface-water drainage area of 6.6 $ft^3/s/mi^2$. Thus the stream is capturing groundwater over a much broader area than can be explained by the 0.81 mi^2 surface-water drainage area. Given measured base flow for Johns Knob Branch of 5.35 ft^3/s, and the median base flow per unit surface-water drainage area of streams in the southern coalfields of 0.67 $ft^3/s/mi^2$, a minimum groundwater drainage basin area of approximately 8.0 mi^2 is necessary to produce the mean streamflow recorded at the Johns Knob Branch gaging station. Thus, the groundwater recharge source area is approximately ten times larger than the corresponding surface-water drainage area for Johns Knob Branch, and is due to interbasin capture and transfer of groundwater from the up-dip extent of the P3CMA within the Bluestone River watershed.

Analyses of well yield with respect to topographic setting was conducted by retrieving well yield and topographic position data from the USGS groundwater site inventory (GWSI) database for wells in similar bedrock settings in the 13 counties which comprise West Virginia's southern low-sulfur coal fields. The analysis indicates that well yields are typically lowest along ridges, highest in valley bottoms, and intermediate along hillsides (Figure 17). This agrees with the conceptual understanding of groundwater flow in the study area, as the low permeability of sandstone and shale bedrock in the core of ridges yields typically produces wells with very low yields. Enhanced fracturing of bedrock due to stress relief produces near vertical fractures in hillsides, resulting in intermediate well yield. Highest well yields are typically found in valley settings, where isostatic rebound and subsequent arching of bedrock due to stress relief, results in enhanced permeability along bedding.

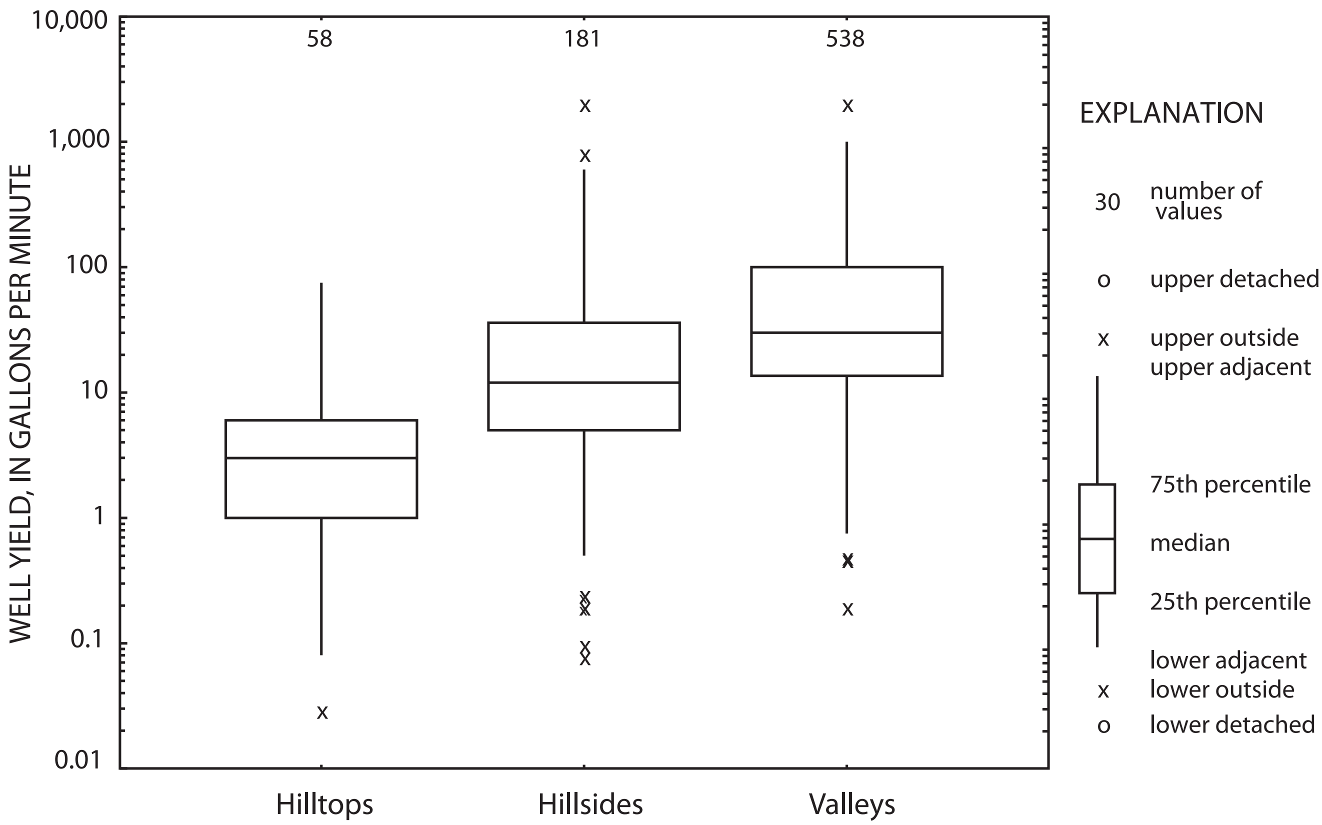


Figure 17. Box plot showing distribution of well yields with respect to topographic setting, based on analyses of USGS data for similar hydrogeologic strata in the southern West Virginia coal province.

The age of groundwater in the southern coalfields of West Virginia (Sheets and Kozar, 2000) also has been shown to vary with respect to topographic setting (Figure 2) with groundwater near hilltops being youngest (apparent average age of 13 years), water in valley settings being oldest (apparent average age of 42 years), and water from hillsides being intermediate in age (apparent average age of 29 years). This age data fits well with the conceptual model of groundwater flow, as precipitation falling on ridge tops would show the youngest apparent age, progressively becoming older, as groundwater percolates either along stress-relief fractures or through the ridge-core flow system, ultimately reaching the valley floor. Valleys can also receive groundwater recharge from deeper sub-regional or regional aquifers (10's to 100's of years; Figure 2). The time for groundwater to percolate through massive sequences of sandstone and shale can be long, especially in undisturbed strata. Coal mining, especially over broad areas such as for the P3CMA, can short circuit these pathways, resulting in much quicker recharge to deeper strata than is typical of unmined strata.

Numerical Model of Groundwater Flow

Groundwater flow in the Elkhorn area, McDowell County, West Virginia, was simulated using the U.S. Geological Survey modular three-dimensional finite-difference groundwater-flow model, MODFLOW-2000 (Harbaugh and others, 2000). MODFLOW-2000 uses packages (modules) to simulate groundwater-flow-system processes, such as recharge, flow, matrix permeability, discharge, and interactions between the aquifer and surface-water bodies. The model described in this report was developed to simulate long-term steady-state conditions for near average and below average water-level conditions. Steady-state conditions exist when the volume of water flowing into the system is equal to the volume flowing out.

Design and Assumptions

It is important to consider how the conceptual flow model was represented in the numerical simulation of groundwater flow. Also, limitations of available data, and the purpose of developing the simulation were important factors that were considered prior to developing the numerical model. The primary purposes of developing the model were to 1) test the conceptual model of groundwater flow to determine if it is mathematically feasible, and 2) to provide water managers, mine operators, and groundwater scientists with accurate estimates of recharge to and flux of groundwater within the extensive abandoned P3CMA.

Early in the design phases of the project, there was considerable concern that the complex hydrogeologic setting, coupled with a general lack of water-level data, a lack of understanding of the conceptual groundwater-flow system, and unavailability of accurate mine maps for the area, would make it difficult, and perhaps impractical, to develop a groundwater-flow model for the study area. After reviewing the available data, it was deemed that even though there was a paucity of water-level data, intensive collection of base-flow (groundwater discharge to streams or from mine adits) data could be used to calibrate the model. Limited water-level data for the seven wells completed for the study would be used to test the assumption that the majority of groundwater drains to abandoned mine workings in the P3CMA. Thus local heads in the groundwater table are governed by the elevation and extent of mining within the Pocahontas No. 3 coal seam. As such, the representation of water levels within the model should be regarded as an estimate only and used with caution, but water budgets derived by the model are considered accurate representations of the flux of water into and out of the groundwater-flow system, especially within the P3CMA, which is relied on for numerous public water supplies within the study area.

Spatial Discretization

The model was subdivided, horizontally and vertically, into rectilinear blocks called cells. The hydraulic properties of the material in each cell are assumed to be homogeneous. A model grid of 139 rows and 173 columns was used to represent the groundwater-flow system (Figure 18). A finer grid mesh was used in the primary emphasis area of the model, the area near Elkhorn between Northfork and Maybeury, West Virginia. As a result, cell area dimensions vary within the model and are 500 x 500 feet, 500 x 1,000 feet, or 1,000 x 1,000 feet. The model is comprised of approximately 24,000 cells in each of four layers of the model, but only approximately 60% of the cells represent active flow cells

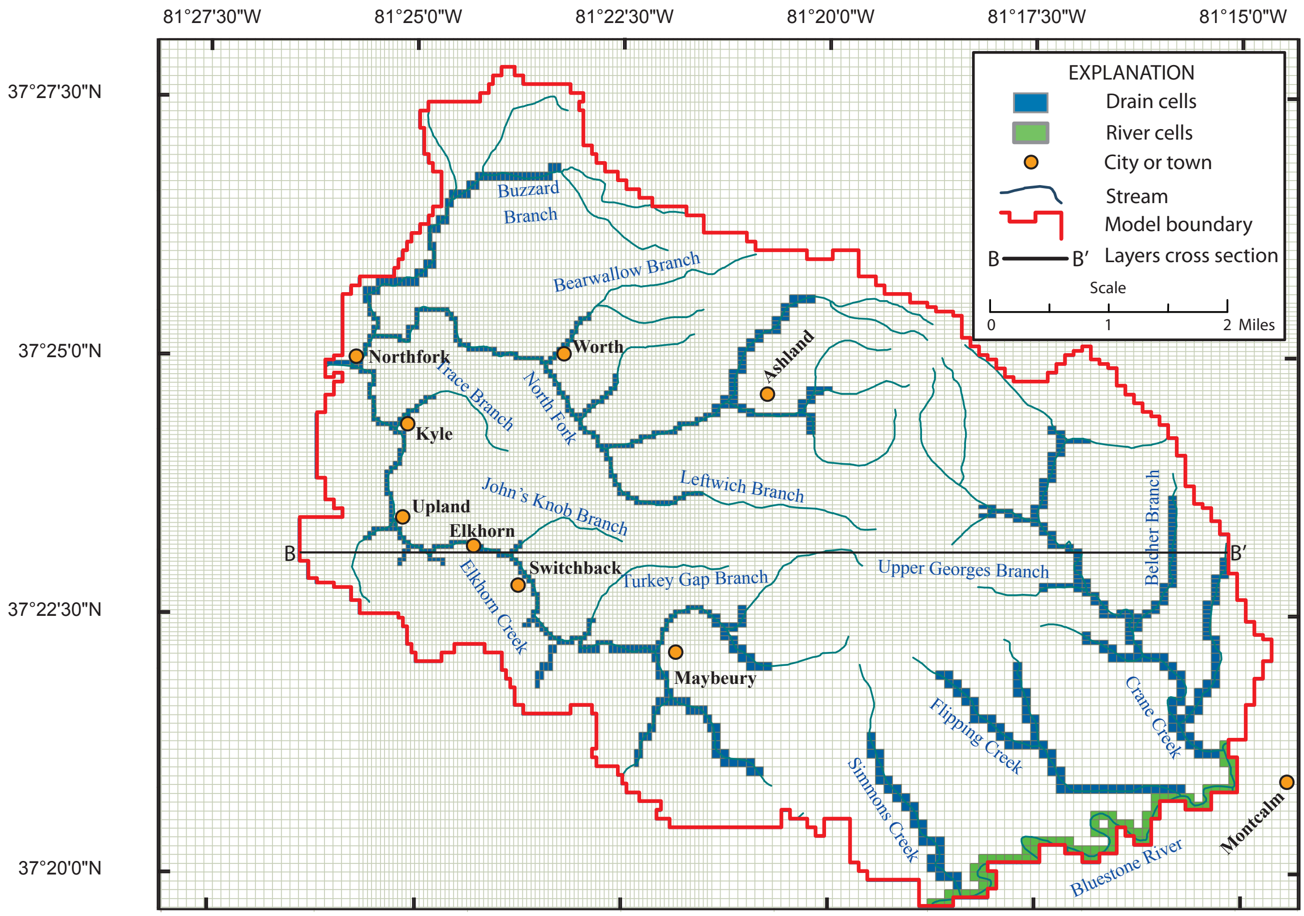


Figure 18. Map showing the model boundary, drain cells simulating streams, river cells, and the finite-difference grid, for the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

within the model domain. The model simulates groundwater flow in two primary drainage basins, the Elkhorn Creek and North Fork watersheds. To balance water budgets, it was determined that the Elkhorn Creek watershed captures water from the adjacent Bluestone River watershed to the east. A portion of that basin was included within the model, but is not an emphasis area within the model. The process by which water is captured from the Bluestone River watershed is primarily a function of the dip of the Pocahontas No. 3 abandoned coal mine, which crosses well beneath topographic divides far into the Bluestone River watershed area, and transports captured groundwater down dip to the west. The area for which the entire model was developed covers approximately 58.4 mi^2, with 17.5, 19.2, and 21.7 mi^2 within the Elkhorn Creek, North Fork, and Bluestone River watershed areas, respectively.

The model was constructed on the premise that recharge falling on the surface eventually drains vertically to the underlying P3CMA. During drilling of the seven monitoring wells for the project, very little water was encountered in bedrock strata overlying the P3CMA. Monthly water-level measurements made in seven monitoring wells confirmed this observation. Except for periods after heavy snow melt and periods of intense rainfall in winter months, percolation of water from overlying strata was negligible. Obviously there is water in some of the overlying perched zones, especially the coal-mine aquifers such as the Pocahontas No. 4 and No. 6 seams, but subsidence fractures in strata above the P3CMA allow water to easily percolate downward. Once water percolates downward to the P3CMA, groundwater flow is primarily horizontal along the base of the coal seam within the abandoned mine workings. Stress-relief fracturing in valleys and along valley walls also appears to be a dominant source of recharge to the coal-mine aquifer and underlying strata.

To simulate the conceptual flow system, a 4-layer model was developed (Figure 19). The upper layer is comprised of moderately permeable fractured bedrock and coal seams, mostly devoid of water, overlying the P3CMA. The second layer in the model represents the extensive P3CMA. Layers 3 and 4 represent bedrock aquifers underlying the P3CMA.

The thickness of model layers varies throughout the model area, with the upper layer of the model (layer one) representing a maximum thickness of approximately 835 feet, layer two representing the P3CMA with a uniform 6 feet thickness, layer three being a uniform 300 feet in thickness, and layer four having a maximum thickness of approximately 1,200 feet. The bottom of the model is an implicit no-flow boundary and coincides with deeper relatively impermeable bedrock layers. The Layer Property Flow (LPF) package was used to assign hydraulic properties to model cells in all four layers of the model.

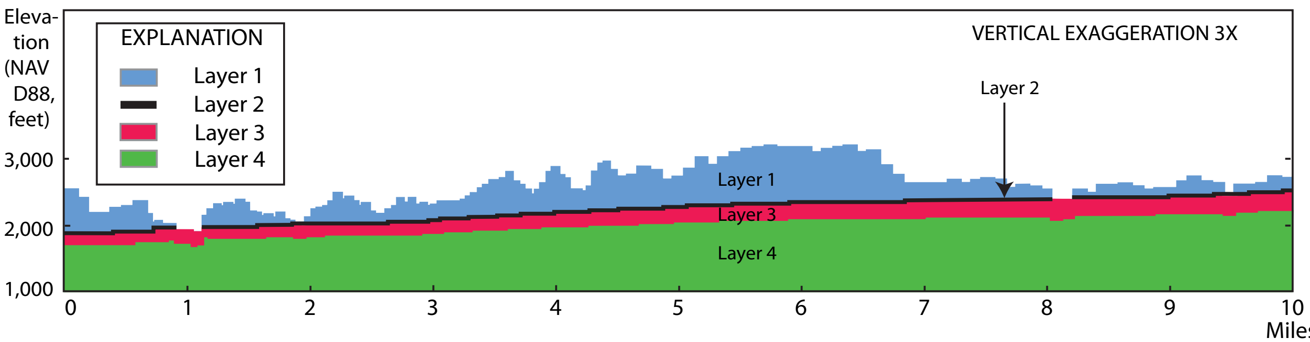


Figure 19. Cross section showing layers of the numerical groundwater-flow model developed for the Elkhorn Area, McDowell County, West Virginia.

Representation of the second layer of the model, the layer representing the P3CMA, required an innovative approach. Initially, the coal-mine aquifer was represented simply as a zone of high hydraulic conductivity within the model domain. However, this method failed to produce accurate estimates of discharges from the numerous mine adits which discharge large volumes of water to tributary streams in the study area, and failed to represent the interbasin transfer of water from the Bluestone River and North Fork Watersheds. The second approach was to simulate the mine entries typical of room and pillar operations as zones of higher hydraulic conductivity within a matrix of lower permeability bedrock. This approach also failed to produce accurate estimates of groundwater discharge to mine adits, and was incapable of simulating interbasin transfer of water. Both approaches were limited by one key factor. Neither approach allowed for water to be conveyed efficiently across topographic divides, and could therefore never yield accurate estimates of groundwater flow within the study area. The solution to this inherent inability of high hydraulic conductivity zones to effectively convey water was solved by the use of drain cells (Figure 20).

The model was initially developed with only three layers, but later it was deemed necessary to split the lowermost layer into two parts for computational reasons. Splitting the lowermost layer allowed more accurate simulation of streams and stress-relief fracturing in the valleys, thus resulting in the final 4-layer configuration of the model. As a result, layers 3 and 4 have essentially the same hydraulic properties, and a single uniform hydraulic conductivity was applied to bedrock aquifers in both layers underlying the P3CMA. During model development and calibration, it was also determined

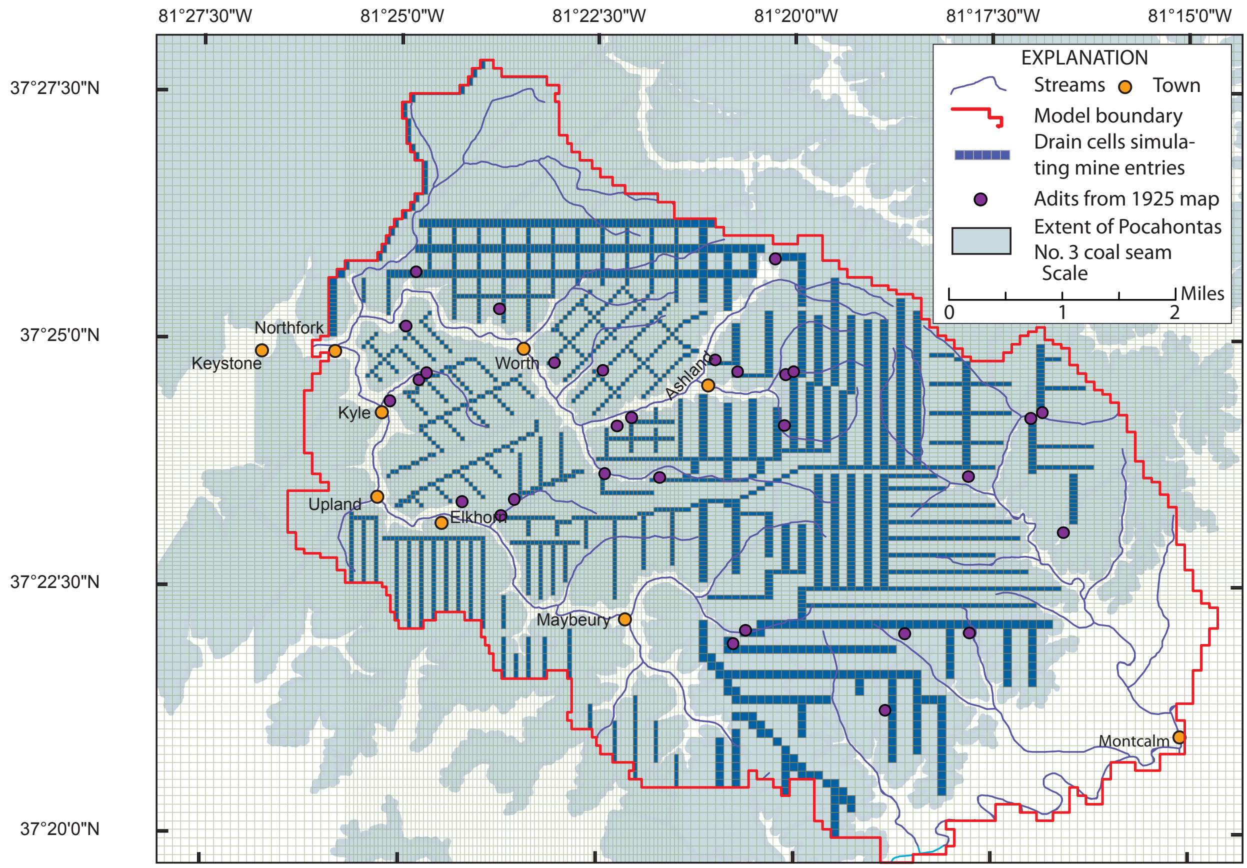


Figure 20. Locations of drain cells used in the numerical groundwater-flow model to simulate the free-flowing mine entries and outfalls from the Pocahontas No. 3 coal-mine aquifer in the Elkhorn area, McDowell County, West Virginia.

that representation of the stress-relief fracturing in valleys was essential to accurate simulation of groundwater flow. Stress-relief fracturing was simulated as higher hydraulic conductivity within layers 2 and 3 of the model along stream valleys and hillsides.

Boundary Conditions

Three different boundary conditions were used to represent the groundwater-flow system within the domain of the groundwater model (Figures 18 and 20). No-flow cells were used to represent the bedrock ridges that bound the model to the north, south, and west. Surface-water divides were used to set the limits of no-flow cells within the groundwater-flow model. Since structural contours crossed the study area at right angles to the ridges, it was initially assumed that the majority of groundwater would flow down dip to respective watersheds on either side of topographic divides. Much later, at a point when the development and calibration of the model was nearly completed, it was realized that this assumption is not valid in all cases. For areas to the north, the actual dip of bedrock is to the north and away from the North Fork watershed, and the assumption that surface-water drainage divides closely approximate groundwater divides is valid. In areas to the south however, the bedrock dips towards Elkhorn Creek. As a result, some of the estimated flows to the tributaries entering Elkhorn Creek from the south are slightly under-represented, as they likely capture water from adjacent watersheds to the south. Fortunately, this area is not an area of emphasis within the model, but development of future groundwater-flow models for above-grade coal-mine aquifers in the study area and similar settings should extend model limits to adjacent streams to assure that all water is accounted for.

The streamflow at the Johns Knob Branch gaging station is also much larger than would be expected for a surface watershed of its size. As such, significant interbasin transfer of groundwater from the Bluestone River watershed to the adjacent North Fork and especially the Elkhorn Creek watersheds was suspected. As a result, the model domain was extended to the Bluestone River (Figures 18 and 20), well beyond the topographic watershed divide. The Bluestone River, which is characterized by long stretches of deep pools and riffles, was simulated as a head-dependent flow boundary condition using the river package within MODFLOW-2000. The Bluestone River watershed was not an emphasis area within the model, and the model was only extended to these limits to simulate the interbasin capture of groundwater.

Other than the Bluestone River which was simulated as river cells, all streams within the model were simulated using the MODFLOW-2000 drain package (Figure 18). Except for one stream in the upper layer of the northwest corner of the model, all stream drain cells were located within layer three of the model, which includes the valley floor and the major tributary streams North Fork, Elkhorn Creek, and the Bluestone River.

Layer two lies approximately 80 feet above the valley floor and major tributary streams, and represents abandoned coal-mine workings in the P3CMA. Drains were used to aggregate water across the mine voids and direct the water to a corresponding mine adit or discharge point (Figure 20). Mine maps could not be located for the study area, as most of the mines were abandoned more than 80 years ago. The problem then became how to represent the intricate network of abandoned room and pillar mines within the P3CMA. The approach taken was simple, locate all known outfalls from mine adits (portals) or other groundwater-discharge points, and work backwards from each point based on structure contours and elevations for the base of the Pocahontas No. 3 coal seam. Locations of mine adits were determined from field surveys and from adits shown on the 1925 15-minute Bramwell, W.Va-Va. USGS topographic quadrangle (Figure 20). For each adit or discharge point, a series of drain cells were input into the model, the elevations of which were determined from elevations extrapolated from the structural contour map. The lowest elevation was at the mine adit and extended up gradient to the highest elevation. This approach worked well, by lowering the heads within the overlying bedrock to either within or just above the P3CMA. It was not critical to pattern the network of drain cells in any specific arrangement, only to insert sufficient numbers of drain cells to dewater the mine voids, and extend them to their logical end points at the highest and lowest structural elevations respective to known mine outfalls. This approach in essence establishes a groundwater recharge source zone for each mine adit or groundwater-discharge point.

The flows of groundwater exiting the P3CMA to the west and leaving the model domain were also simulated as drain nodes in layer two of the model (Figure 20). This flux of water could not be measured directly and is therefore unknown. However since Buzzard Branch is a major drain for groundwater from the east, and since areas to the north and south of the main Buzzard Branch outfalls are in areas where the P3CMA is suspected to be flooded, the flux across this drainage face is probably minimal.

As no well withdrawals were known in the study area, none were simulated within the numerical model. Finally, there is obviously turbulent flow within the abandoned underground mine workings in the P3CMA and this presents a unique challenge for simulating groundwater flow for mined settings. Use of the MODFLOW Drain package to simulate the accumulation and movement of water within and through the abandoned mine workings provides a novel approach for dealing with potential turbulent flow within the groundwater flow model, effectively treating the issue as a boundary condition rather than an internal flow regime. Although the approach works well for mined settings comprised of large sequences of more or less dewatered overburden strata overlying abandoned mine workings, it is not known whether the approach would be applicable if sequences of overlying bedrock strata were saturated with water or if perched aquifers were present above the abandoned mine aquifer.

Model Calibration

Model calibration is the adjustment of model parameters so that the differences (residuals) between measured and simulated observations (groundwater levels and base flows in this case) are minimized with respect to an objective function. This section of the report describes the method used for calibration, the calibration data, and the calibration results. The calibration is assessed by examining how well the simulated groundwater levels and base flows fit the measured values. Values of horizontal and vertical hydraulic conductivity and values for the drain conductance (representing tributary streams and mine outfalls), were estimated through steady-state calibration.

Calibration Procedure

The model was calibrated to hydraulic heads and measured streamflow in a multiple step procedure. First, initial estimates of hydraulic properties were obtained from previously published reports in and adjacent to the model area (Kozar and Mathes, 2001), and from published values in other work conducted in the Appalachian region as summarized by McCoy and others (2006), and from straddle packer and aquifer tests described in this report. Initial estimates of recharge were obtained by analysis of base-flow data for streams in the region using hydrograph analysis methods, as previously described. These initial hydraulic property and recharge estimates were used in construction of the model. The model was then manually calibrated to heads and flows through a rigorous process which involved more than 35 trial and error manual variations of input parameters until residuals were minimized and the model was considered stable and initially calibrated. However, uncertainty remained as to whether additional manipulation of input parameters could significantly improve the model.

The second phase of the calibration procedure was based on estimating parameters using the parameter estimation program PEST (Doherty, 2010a and 2010b). PEST automatically minimizes the residuals based on a non-linear weighted least squares regression. PEST was used even though MODFLOW-2000 has built in parameter estimation capabilities. Parameter estimation was conducted for two principal reasons, 1) to determine which parameters within the model were most sensitive to variation and 2) to further refine the initial manually calibrated model. Two separate PEST parameter estimation runs were made, one to assess parameter sensitivity and a second to produce final calibrated parameters for the model. The initial PEST run indicated that parameter estimates of horizontal hydraulic conductivity (Kxy), vertical hydraulic conductivity (Kz), and recharge were sensitive parameters, and thus were retained in the final PEST simulation. Recharge and vertical hydraulic conductivity (Kz) for certain hydrogeologic units within the model were found to be the most sensitive model parameters. The initial PEST run also indicated that conductance values assigned to drains representing streams or the simulated mine entries within the model were insensitive parameters. As a result, drain conductance was not included in the subsequent final PEST run and were set at the values determined by manual calibration. The second PEST parameter estimation routine was conducted with the parameters deemed to be sensitive from the first PEST run; horizontal (Kxy) and vertical (Kz) hydraulic conductivity and recharge. Detailed discussion of final calibrated parameters follows in subsequent sections of this report.

PEST automatically adjusted the Kxy and Kz and recharge either upward or downward within a range of specified plausible values through a series of model runs. After each run, simulated groundwater levels and streamflow were compared to measured values and model runs continued until the residuals were minimized. PEST implements a nonlinear least-squares regression method (Gauss-Marquardt-Levenberg) to estimate model parameters by minimizing the sum of squared weighted residuals (objective function). Details of this method are given in the PEST user's manual (Doherty, 2010a and 2010b). The aquifer properties were allowed to vary during model calibration within one order of magnitude, except for estimates of vertical hydraulic conductivity which were allowed to vary as much as two orders of magnitude of initial specified values.

Calibration Data

The model used both the measured water levels from monitoring wells, as well as the base-flow measurements as calibration targets, and was calibrated for steady-state conditions only. The steady-state calibration used water levels measured in seven wells during a period characteristic of slightly below average hydrologic conditions in September of 2009 (Appendix 1), and on base-flow measurements during the same period (Appendix 3). Water levels and base flow measurements were measured specifically for model calibration and were not weighted, thus equal importance was given to both base flow and water level measurements for model calibration.

Groundwater levels, as depth below land surface, were converted to water-level altitudes, according to the North American Vertical Datum of 1988, based on altitude data collected using a high accuracy surveying-grade GPS receiver (Trimble 5800). On average, approximately 1 to 2 hours of positional data were collected at each well and the elevations were post processed using the National Oceanic and Atmospheric Administration's OPUS website (http://www.ngs.noaa.gov/OPUS/). Wells used to measure water levels were located within a model cell at a location given by the measured latitude and longitude of the well. The reported depth of the well and water levels measured for each

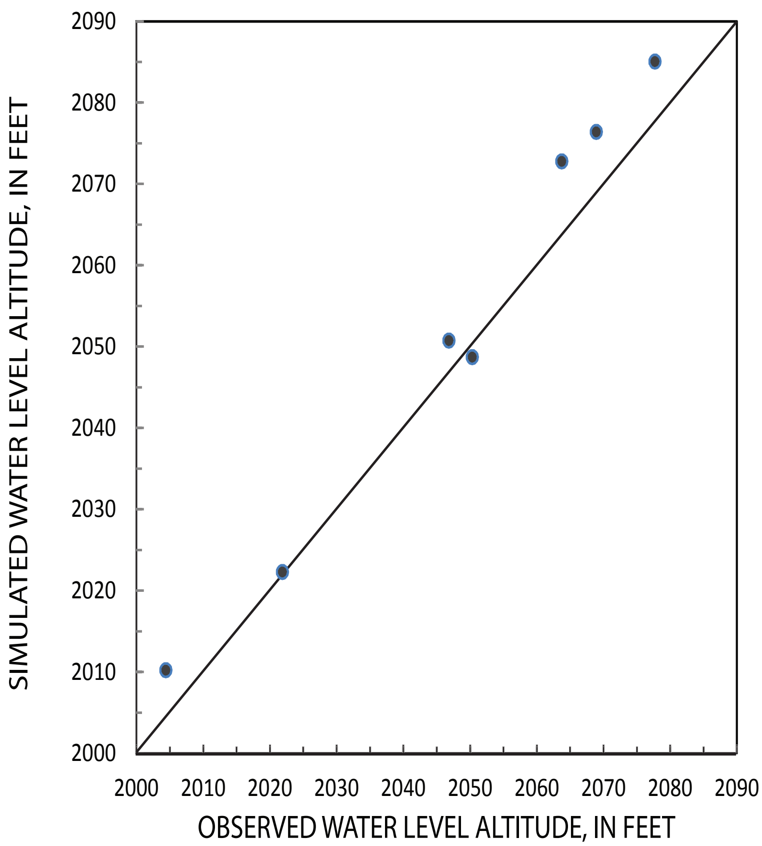


Figure 21. Plot of measured versus simulated water levels within the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

well were assessed to determine the model layer that represented the hydrogeologic unit tapped by the well.

There was excellent agreement between simulated and measured water levels for the final calibrated numerical model, with a root mean square error (RMSE) of 5.85 feet (Figure 21). There is slight bias for simulated heads within the model which was intentional. Simulated water levels for the P3CMA are biased slightly high, as drain node elevations within layer 2 of the model simulating abandoned mine workings were arbitrarily set 1 foot from the top of layer 2 as opposed to near the base of layer 2 as was the case for most of the measured water levels. The drain elevations were set arbitrarily high to avoid dewatering of layer 2 and associated instability within the model; the bias however is minimal.

The base-flow measurements collected in October of 2009 used for calibration of the steady-state groundwater-flow model are respective of conditions at the 70th percentile flow duration for streams in the region. The data for the high base-flow period (April 2009) were not used in model simulations, and the data for the low base-flow period (October 2010) were used in a scenario to assess the accuracy of base-flow simulations for low-flow conditions, respective of the 87th percentile flow duration for streams in the region. There was also a very good fit (RMSE of just 0.20 ft^3/s) between simulated and measured mine-outfall discharges and tributary base flows for the final calibrated numerical model (Fgure 22).

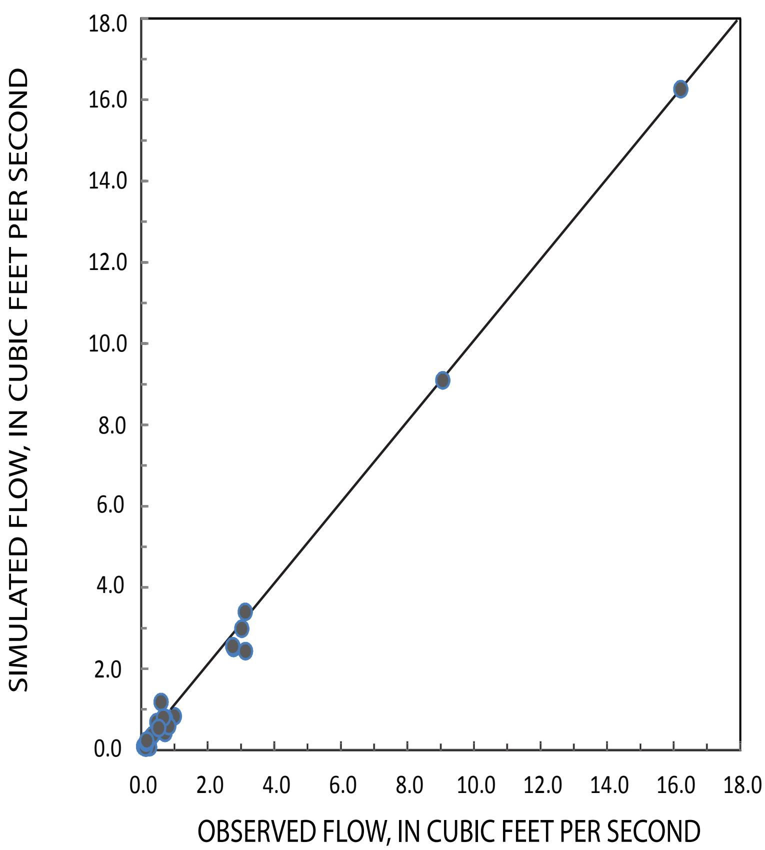


Figure 22. Plot of measured versus simulated mine-outfall discharge and base flow within the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

Parameter Sensitivity

Sensitivity is the relative effect that changes to an individual parameter value has on the overall objective function. Sensitivity analysis assesses the effects of variations in parameter values on the simulated heads and discharges within a model, and is commonly used to aid in development and calibration of numerical groundwater flow models (Hill, 1998; Hill and Tiedeman, 2003). The ability to estimate a parameter value using nonlinear regression is a function of the sensitivity of simulated values to changes in the parameter value. For this model, the sensitivity analysis was conducted by varying input parameters over a magnitude (+ or -) change in manually calibrated values, except for Kz which was assessed over two orders of magnitude. Generally speaking, if a parameter has a high sensitivity, variation of calibrated parameters will have significant effect on the model sum of squared errors. Conversely, if a parameter has low sensitivity, changing the parameter value will have little effect on the sum of squared errors. As only minor variation in parameters was produced between the initial and final parameter estimation runs, the results of the second parameter estimation run were considered as final calibrated parameters (Table 5) for the model.

The composite scaled sensitivities of the parameters to the overall objective function including head (water level) and stream base-flow values are shown in Figure 23. Because the objective function

Table 5. Final calibrated parameter values used in the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia. [Kxy, horizontal hydraulic conductivity; Kz, vertical hydraulic conductivity; ft/d, feet per day; in/yr, inches per year].

Parameter	Parameter Name	Value
	Horizontal hydraulic conductivity (ft/d)	
Kxy1	Layer 1 K xy Pennsylvanian age rocks	0.350
Kxy2	Layer 2 K xy stress relief fracturing	0.716
Kxy3	Layer 2 K xy Pocahontas No. 3 abandoned mines	7.27
Kxy4	Layer 2 K xy Pocahontas No. 3 seam barriers	0.028
Kxy5	Layer 3 K xy stress relief fracturing	0.716
Kxy6	Layer 3 K xy Pennsylvanian age rocks	0.040
Kxy7	Layer 3 K xy Mississippian age rocks	0.031
Kxy8	Layer 4 K xy Pennsylvanian age rocks	0.040
Kxy9	Layer 4 K xy Mississippian age rocks	0.031
	Vertical hydraulic conductivity (ft/d)	
Kz1	Layer 1 Kz Pennsylvanian age rocks	0.035
Kz2	Layer 2 Kz stress relief fracturing	0.042
Kz3	Layer 2 Kz Pocahontas No. 3 seam abandoned mines	0.002
Kz4	Layer 2 Kz Pocahontas No. 3 seam barriers	0.005
Kz5	Layer 3 Kz stress relief fracturing	0.042
Kz6	Layer 3 Kz Pennsylvanian age rocks	0.027
Kz7	Layer 3 Kz Mississippian age rocks	0.035
Kz8	Layer 4 Kz Pennsylvanian age rocks	0.027
Kz9	Layer 4 Kz Mississippian age rocks	0.035
	Drain Conductance (ft/d)	
Dr1	Median drain conductance for simulated mines	500
Dr1	Maximum drain conductance for simulated mines	1,000
Dr1	Minimum drain conductance for simulated mines	375
Dr2	Median drain conductance for streams	750
Dr2	Maximum drain conductance for streams	150,000
Dr2	Minimum drain conductance for streams	375
	Recharge (in/yr)	
R1	Steep upland areas	7.56
R2	Flat upland areas	9.09
R3	Flooded mine complex	6.64

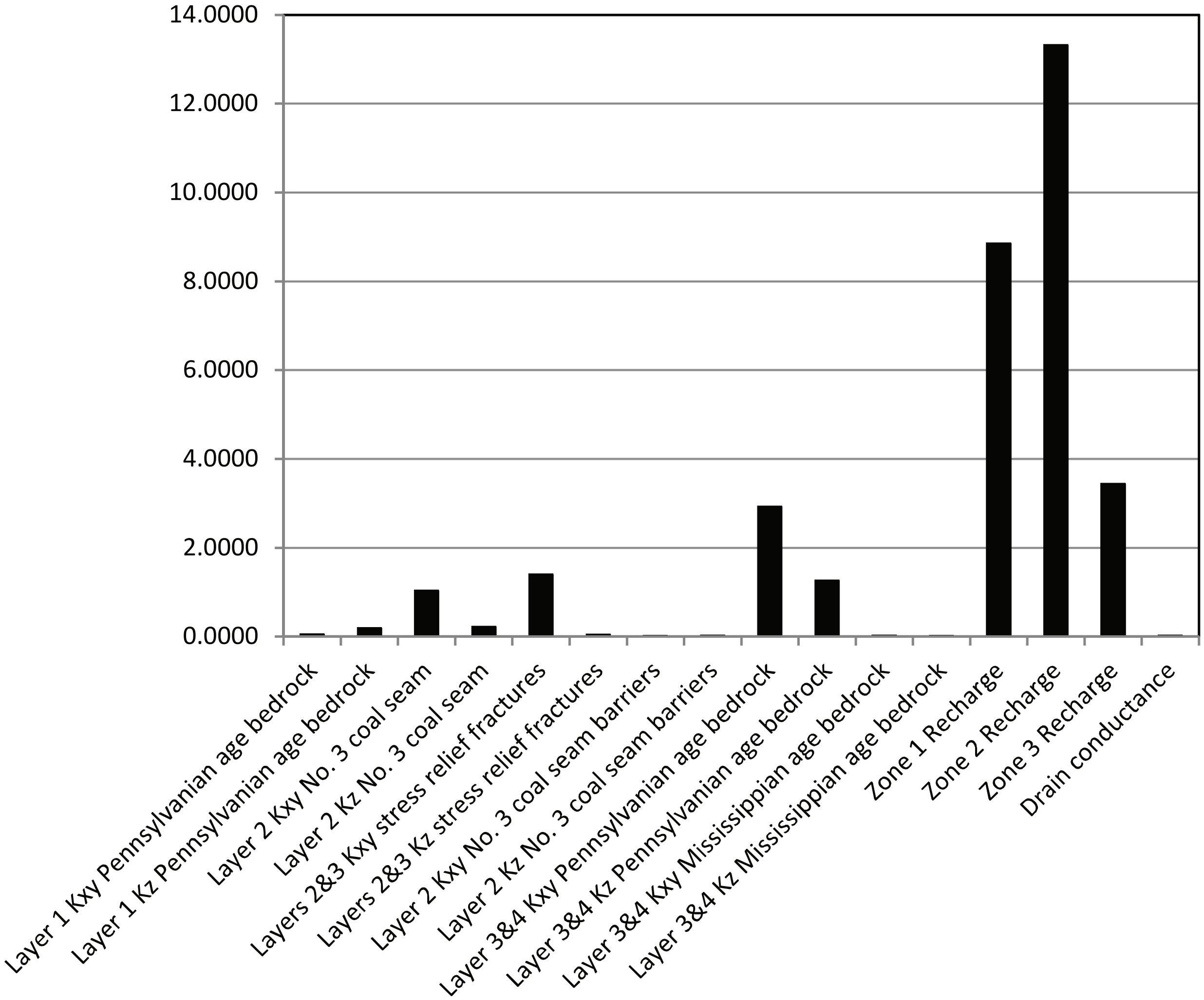


Figure 23. Normalized composite scaled sensitivities of final calibrated parameters to hydraulic head observations and stream base flow and mine-outfall discharges within the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

is nominally scaled by the weighting factors (as inverse standard deviations), the sensitivity can be considered non-dimensional. As water level and flow data were specifically collected for this project, all parameters in the sensitivity analysis were given equal weight. The values of insensitive parameters, such as 1) drain conductance, 2) Kxy of a) the Pennsylvanian-age bedrock hydrogeologic unit in layer 1, b) coal seam barriers in layer 2, c) Mississippian-age bedrock hydrogeologic units in layers 3 and 4 of the model, and 3) Kz of a) the Pennsylvanian-age bedrock hydrogeologic unit in layer 1, b) the Pocahontas No. 3 coal seam and coal barriers in layer 2, c) stress-relief fractures in layers 2 and 3, and d) the Mississippian-age bedrock hydrogeologic units in layers 3 and 4 of the model remained largely unchanged during the PEST calibration process. Therefore, the insensitivity of these parameters places greater importance on the initial values assigned to them. The model was also insensitive to values of drain conductance, and initial manually calibrated values of drain conductance for streams and simulated mine entries within the model were therefore not adjusted by parameter estimation.

Results from the steady-state sensitivity analysis (Figure 23) indicate that the model is most sensitive to 1) recharge for all three recharge zones within the model, 2) Kxy of a) the Pocahontas No. 3 coal seam in layer 2, b) stress-relief fractures in layers 2 and 3, c) the Pennsylvanian-age bedrock hydrogeologic units in layers 3 and 4 of the model, and 3) Kz of the Pennsylvanian-age bedrock in layers 3 and 4 of the model.

Model Calibrated Parameters

Once manual calibration and parameter estimation had been completed, final values for parameters (Table 5) were used in the final calibrated groundwater-flow model. As few data exist for hydraulic properties for the study area, especially with respect to Kz, detailed discussions of the parameters used in the final calibrated groundwater-flow model are presented.

Nine specific hydrogeologic units were simulated within the final calibrated model (Table 5). These hydrogeologic units include Mississippian and Pennsylvanian-age bedrock in layers 3 and 4 of the model. Mississippian-age bedrock is not present above the P3CMA and therefore was not simulated in layers 1 and 2 of the model. Stress-relief fracturing was simulated in layers 2 and 3 of the model along the margins of stream valleys and hillsides. Simulation of stress-relief fractures, especially for layer 3 of the model, was critical for accurate simulation of water levels in stream valleys. The abandoned mine workings in the Pocahontas No. 3 coal seam represent the principal aquifer unit within the model. Mine barriers or areas of unmined coal comprise an additional hydrogeologic unit. Each hydrogeologic unit likely exhibits a range in the spatial distribution of the values of hydraulic properties that is not well understood. Even though it would have been possible to aggregate horizontal and vertical hydraulic conductivity for those hydrogeologic units with similar hydraulic properties, each hydrogeologic unit was simulated as a separate entity within the model to better match the conceptual model and aid in assessing parameters as part of model calibration using PEST.

Recharge

Because precipitation is the dominant source of water that recharges groundwater in the model area, it is reasonable to expect the rate of recharge to vary with the rate of precipitation. However, other factors, such as the permeability of surficial hydrogeologic units, land-cover, topography, slope, and climate also determine the rate of recharge. The distribution of recharge from precipitation in the model area was estimated by hydrograph analysis of streamflow. Specifically, the computer software package PART was used to analyze streamflow hydrographs for streamflow gaging stations in the Tug Fork watershed to determine base flow groundwater discharge to streams, which also can provide approximate initial estimates of groundwater recharge (Table 1). The median base flow of 9.1 in/yr for those gages served as the baseline for recharge in the calibrated steady-state groundwater-flow model. The model was calibrated with data for a period of precipitation and recharge corresponding to the 70th percentile flow duration (Table 4) for streams in the region, which is approximately 20% below long-term average hydrologic conditions. Since hydrologic conditions on which the model is calibrated are slightly below average, the recharge applied to the calibrated model was adjusted downward slightly during initial manual model calibration.

Recharge was also adjusted either upward or downward only slightly to accommodate for differences in topographic slope. Based on topographic analysis of basin slope, areas with less relief were given slightly higher recharge rates than more characteristically steep areas of the Appalachian Plateaus in the region. The study area sits near the transition between the Appalachian Plateaus and Valley and Ridge Physiographic Provinces, and thus there is a transition in the surface topography and relief which is clearly visible on hill-shaded digital elevation imagery (Figure 24). A three-dimensional representation of the slope of the P3CMA also shows similar flat uplands for the P3CMA in the study area (Figure 25).

In most areas the P3CMA occurs at an elevation approximately 80 feet above local tributary streams, but in the northwest portion of the study area the P3CMA dips below local tributary streams and there is no readily apparent point of discharge for the abandoned coal mines. The mines in these

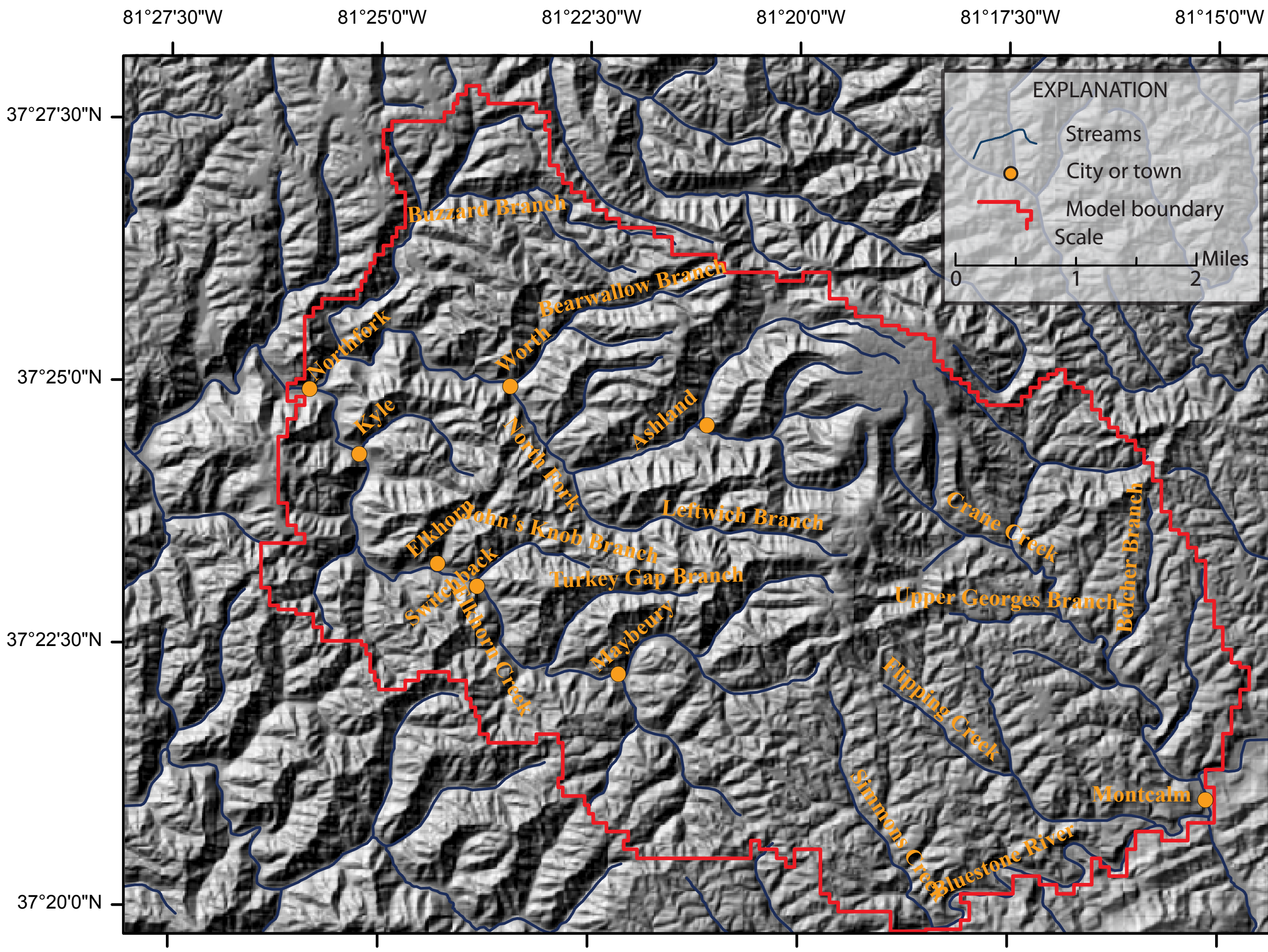


Figure 24. Shaded relief topographic imagery, based on digital elevation models, showing distinct differences in geomorphic and topographic features in the Elkhorn area, McDowell County, West Virginia.

areas are not free-flowing as they are in the majority of the model domain, and only so much water can infiltrate into and accumulate in the abandoned mine workings. Recharge is limited in this area of the model and represents the only area within the model where substantial proportions of bedrock overlying the P3CMA have the capacity to become saturated with groundwater. As such, the permeability of the rock overlying the P3CMA in layer 1 becomes the limiting factor affecting recharge in this portion of the model, as opposed to the much more permeable and porous P3CMA in the remainder of the model domain.

Model-calibrated recharge for the three areas shown on Figure 26, which is based on manual calibration and results of the final parameter estimation run using PEST, varies from a minimum of 6.64 in/yr for the areas of flooded abandoned mines to 9.09 in/yr for the more flat lying terrain in the upland transition area between the Appalachian Plateaus and the Valley and Ridge provinces (Table 5). The area more characteristic of the Tug Fork Basin has an estimated recharge rate of 7.56 in/yr based on results of hydrograph analyses and parameter estimation. These model calibrated values are slightly lower than the initial 9.1 in/yr estimate of recharge based on analysis of streamflow hydrographs, which is expected as the hydrologic conditions for which the model was calibrated are respective of the 70th percentile flow duration, which is 20 percent below long-term average conditions.

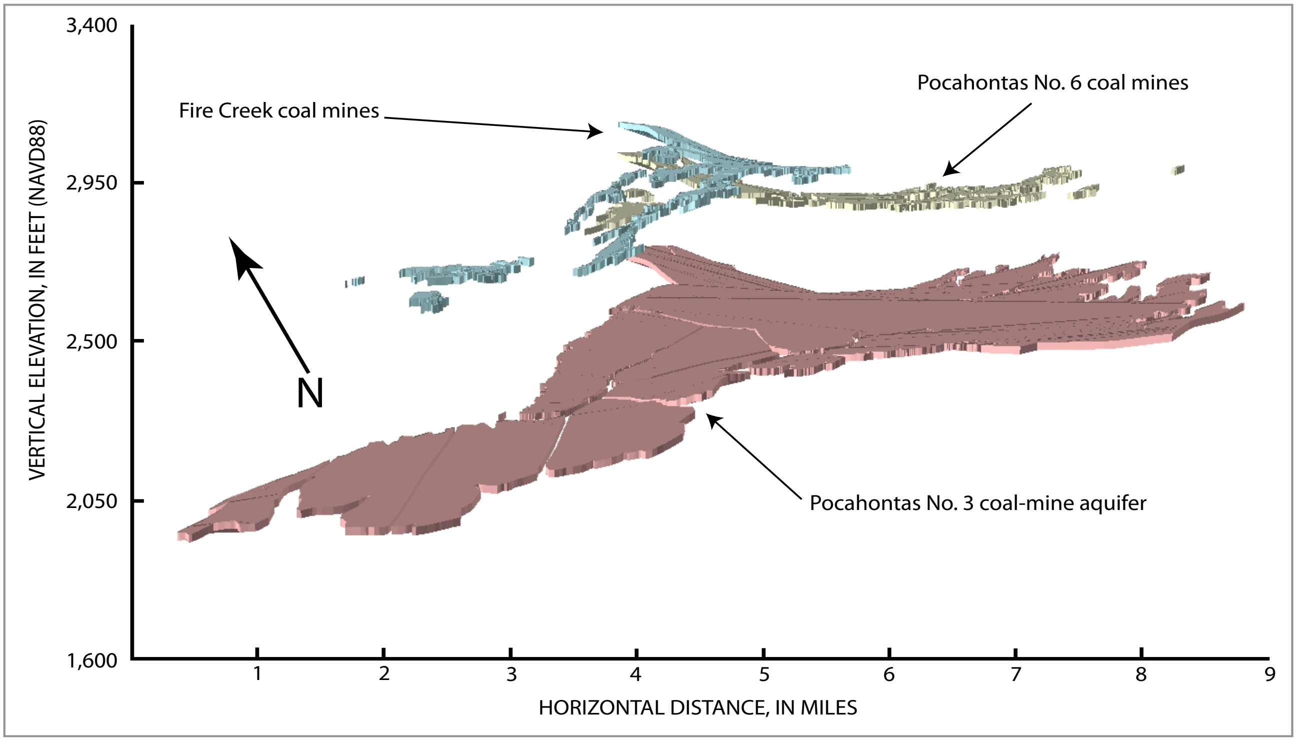


Figure 25. Three-dimensional image of the slope of a portion of the P3CMA and overlying coal seams in the Elkhorn area, McDowell County, West Virginia.

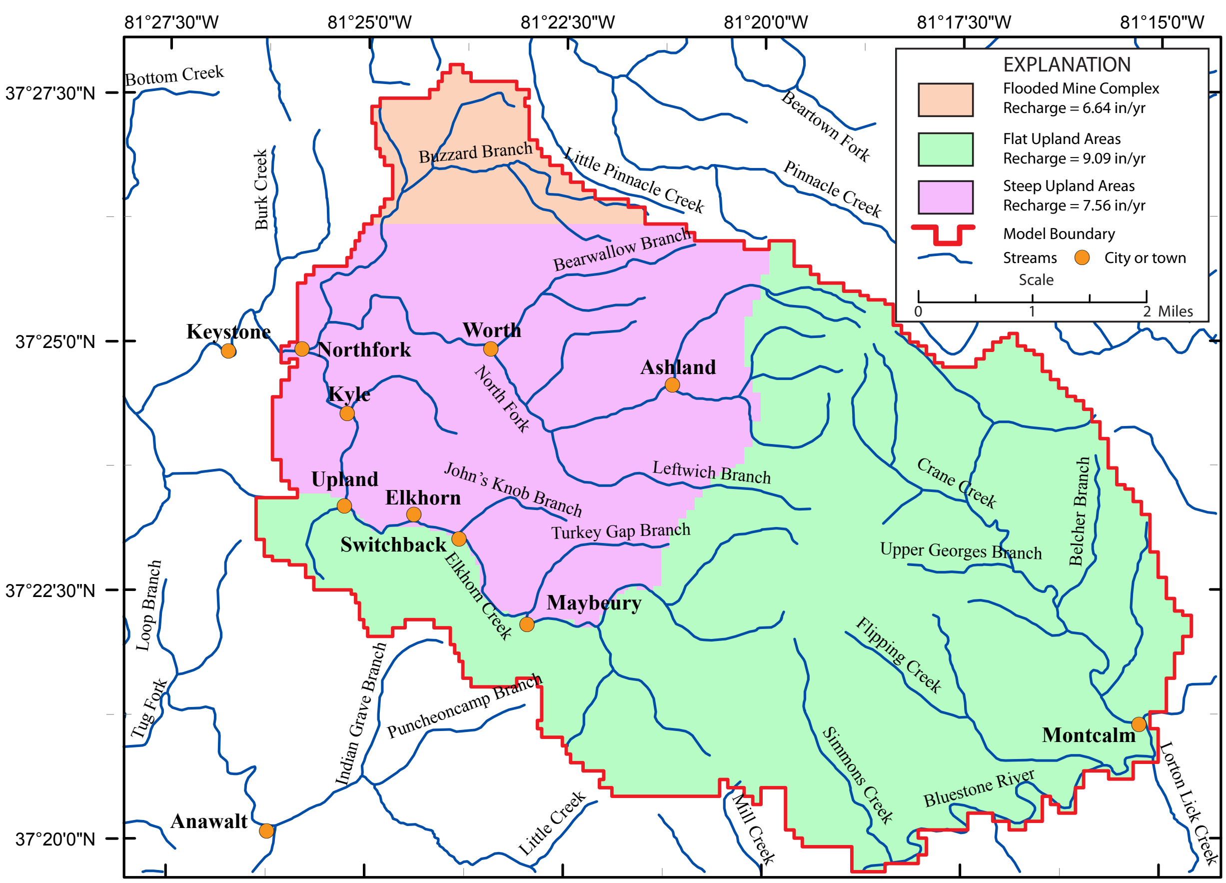


Figure 26. Recharge for three distinct regions within the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

Horizontal Hydraulic Conductivity

Initial values of horizontal hydraulic conductivity (Kxy) for the hydrogeologic units (Table 2) were based on analyses of specific-capacity data, results of aquifer tests, and previously developed groundwater-flow models (Kozar and Mathes 2001; McCoy and others, 2006). A uniform distribution of hydraulic parameter values was initially specified for each hydrogeologic unit in the numerical model. These estimates were modified based on results of straddle-packer hydraulic tests (Table 3) and finally, as a result of parameter estimation using PEST. Because there is no evidence to suggest that Kxy varies significantly with direction (no preferential flow in one direction versus another), horizontal isotropy (Kx=Ky) was assumed. Calibrated values of Kxy in aquifer units ranged from a minimum of 0.028 ft/d for barriers within the P3CMA, to a maximum of 7.27 ft/d for mined-out areas within the P3CMA. Locations of coal-seam barriers within the model were inferred based on a relative absence of known mine portals, or where the limited water-level data showed a distinct difference in head up gradient and down gradient of the suspected location of the barrier. It was not uncommon in the 1920's and 1930's to leave such barriers, which were then later partially removed by strip mining along the contour of the Pocahontas No. 3 coal seam outcrop.

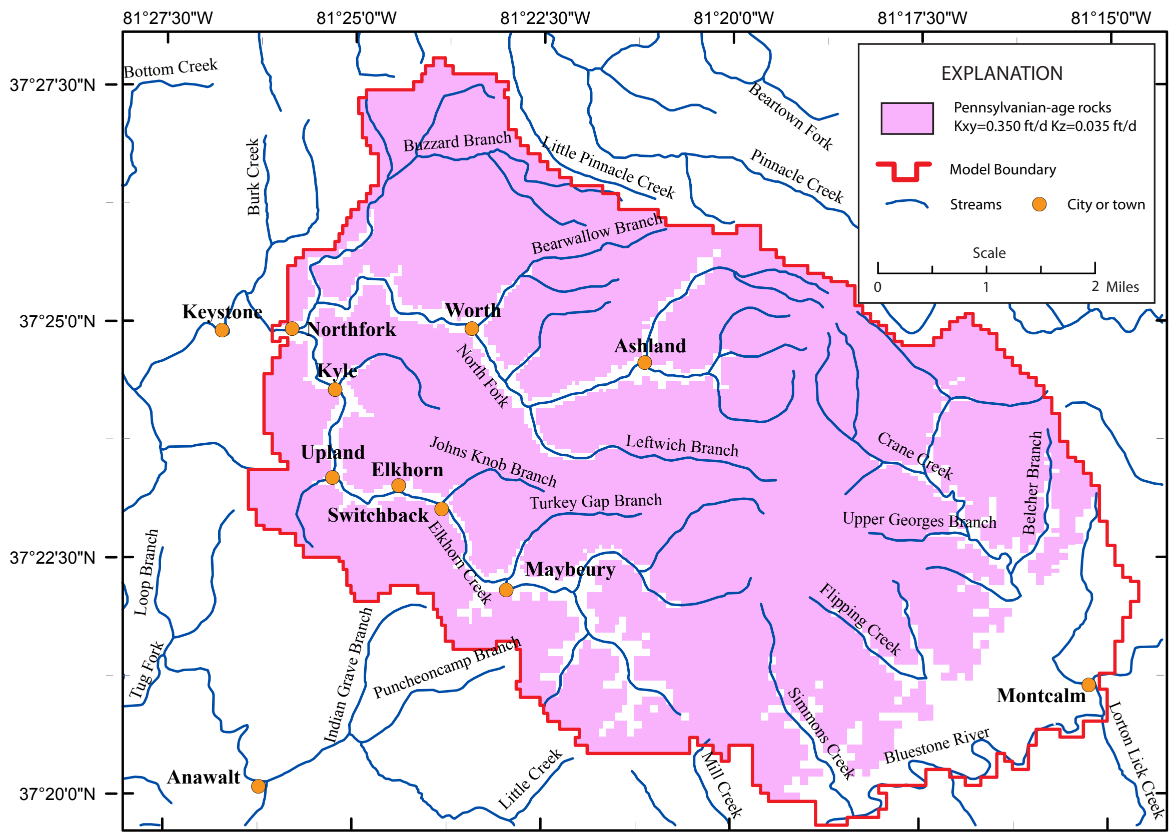


Figure 27. Distribution of hydraulic conductivity in the upper layer (layer 1) of the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

For the upper layer of the model, a calibrated uniform Kxy of 0.350 ft/d was used to simulate the hydraulic properties of Pennsylvania-age bedrock overlying the P3CMA (Figure 27). This moderately high hydraulic conductivity represents fracturing of overburden strata due to subsidence caused by the near complete extraction of coal from the underlying P3CMA.

For layer 2 of the model, the layer which represents the P3CMA, calibrated Kxy of 7.27 ft/d was used to represent the P3CMA, and a value of 0.028 ft/d was used to represent coal-seam barriers or unmined sections of the Pocahontas No. 3 coal seam (Figure 28). Barriers were placed in the model where measured water levels indicated a head difference above and below known mine boundaries, or where unmined areas of coal seams near out crops were suspected based on an absence of mapped mine portals.

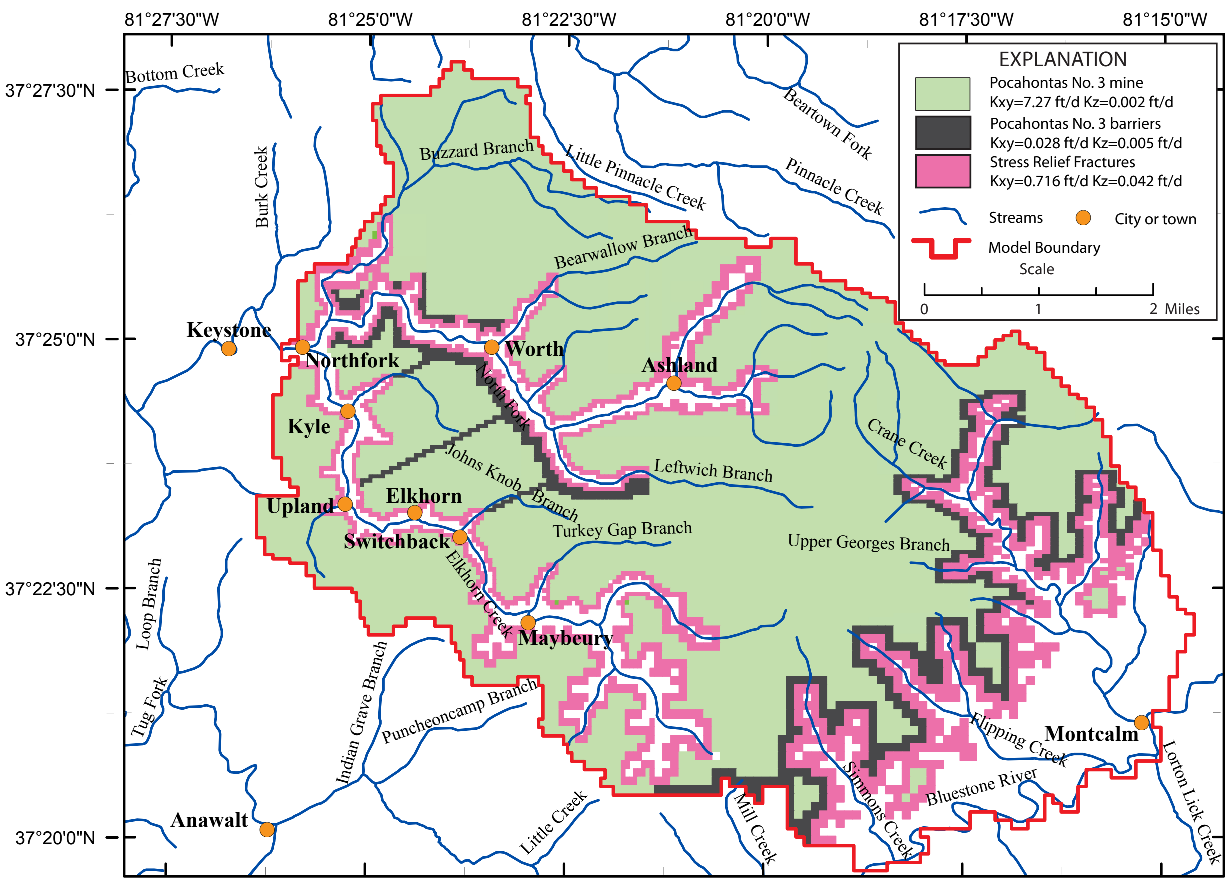


Figure 28. Distribution of hydraulic conductivity in layer 2 of the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

For layer 3 of the model, the layer which represents shallow bedrock in which the tributary streams are located, and which includes the interval of substantial stress-relief fracturing, calibrated Kxy of 0.040 ft/d was used to represent the Pennsylvanian-age bedrock and a value of 0.716 ft/d was used to represent areas near the center of the valley and along valley walls where stress-relief fracturing dominates (Figure 29). Calibrated Kxy for the Mississippian-age strata, which includes some limestone bedrock, was 0.031 ft/ d.

Initially the model was developed as a 3 layer model, but the lower layer was later split into two layers (layers 3 and 4). This was done to separate streams in layer 3 from deeper bedrock in layer 4, and to allow for simulation of stress-relief fracturing within the model along valley bottoms coincident with stream channels. As a result, layer 4 of the model, the layer which represents the deeper, less permeable bedrock below the local tributary streams, has hydraulic conductivity identical to that for layer 3, but lacks the stress-relief fracturing and drains that are present in layer 3 of the model. Calibrated Kxy for Pennsylvanian-age bedrock is 0.040 ft/d (Figure 30), and calibrated Kxy for the Mississippian-age bedrock, which includes some limestone, was 0.031 ft/ d.

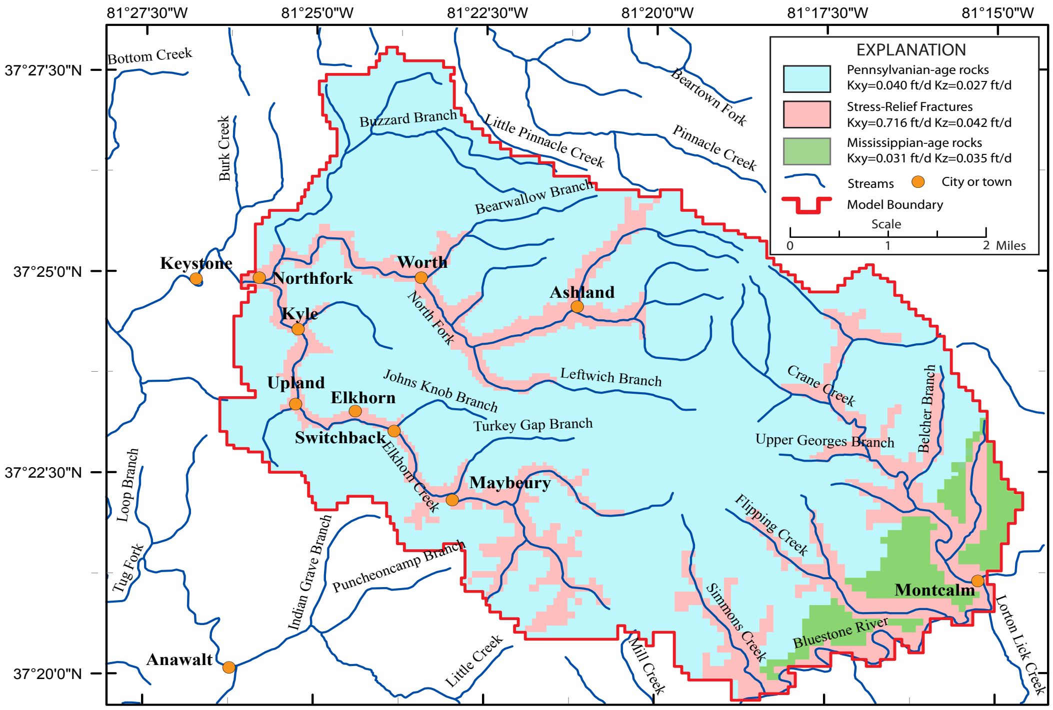


Figure 29. Distribution of hydraulic conductivity in layer 3 of the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

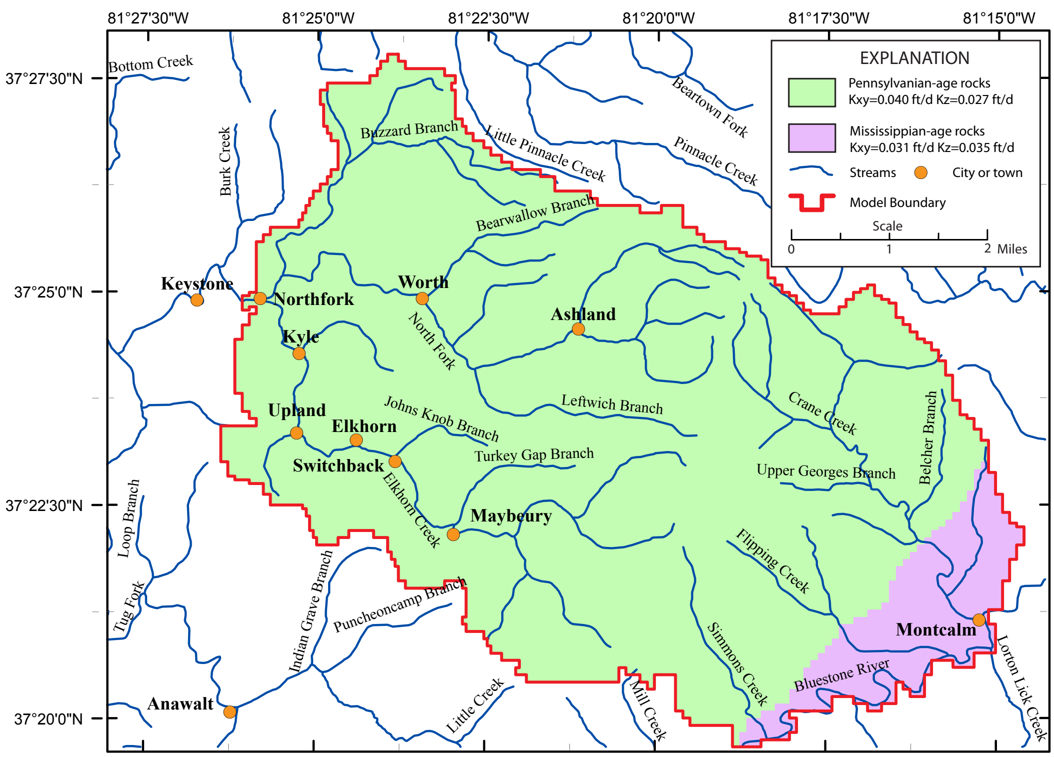


Figure 30. Distribution of hydraulic conductivity in layer 4 of the numerical groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

Vertical Hydraulic Conductivity

Few studies have evaluated the contrast in vertical (Kz) and horizontal hydraulic conductivity (Kxy) for layered sequences of sandstone, shale, coal, limestone and other sedimentary rocks in the Appalachian coalfields. Abate (1993) suggested a Kz/Kxy ratio of 0.25 for massive units and a much higher, orders of magnitude contrast of Kz/Kxy for coal underclays. The Kz of coal underclays was also conceptualized to be much lower than that in massive units (Abate, 1993). Peffer (1991) focused a series of aquifer tests data in aquitards of the Appalachians and found Kz of a thick shale unit to be 0.0004 ft/day.

Values of Kz in the Elkhorn model were initially assigned to each hydrogeologic unit based on a global vertical anisotropy ratio (Kz/Kxy) of 0.1. The parameter estimation software PEST (Doherty, 2010a and 2010b) was used to adjust initial Kz values either upward or downward to match measured values of head (water levels) and water flux (discharge from mine outfalls and base flow discharge to tributary streams) to model simulated values.

Calibrated Kz for all 10 hydrogeologic units was rather uniform, with mean and median values of 0.028 and 0.035 ft/d respectively, and ranged from 0.002 ft/d for layer 2 which simulates relatively impermeable underclays (fireclay) beneath the Pocahontas No. 3 coal seam, to 0.042 ft/d in parts of layers 2 and 3 that represent stress-relief fractures (Table 5). Model-derived estimates of vertical to horizontal anisotropy (Kz/Kxy) varied over a wide range; 0.001 (1:1,000) for impermeable underclays beneath coal seams, 0.1 (1:10) for fractured overburden strata above the P3CMA, and approximately 1 (1:1) for deeper strata indicative of regional bedrock aquifers. For this model, only one layer was used to represent both the coal seam and the underlying fire clay (layer 2 of the model). For practical applications in unmined strata, it is likely that the horizontal and vertical hydraulic conductivity of the coal seams themselves more approximate a 1:1 value. Lumping underclays with coal seams clearly has an effect on the bulk aquifer properties determined using PEST. Adjusted model-calibrated values of Kz provide a reasonable fit between measured and simulated heads and flux, and are consistent with the findings of Abate (1993) and Peffer (1991). It was therefore critically important to include estimates of the vertical hydraulic conductivity of underclays when assigning Kz to simulated coal seams within the model.

Drain and Riverbed Conductance

River cells were used to represent the deep pools common for the Bluestone River in the study area. The Bluestone River was not considered an important emphasis for the model, and was only considered as a sink for local discharge of groundwater. Thus the river cells were not part of the parameter estimation process. A constant value of 380 ft/d was selected as the final value for riverbed conductance.

The conductance of drain cells, however, varied in the original manually calibrated model based on base-flow measurements. Reaches of streams with higher base flow were assigned higher values of drain conductance than reaches with little or no base flow. Three ranges of hydraulic conductivity (10.0, 1.0, and 0.1 ft/d) were used to estimate drain conductance for streams within the model, representing sections of stream with high, moderate, or low base flow discharge. Parameter estimation indicated that the model was not sensitive to drain conductance, and as such drain conductance values were not altered from the initial manually calibrated estimates. Drain conductance was also a function of the size of individual cells in the model. Small 500 x 500 ft^2 cells have lower drain conductance than the larger 500 x 1,000 ft^2 or 1,000 x 1,000 ft^2 cells. Thus, based on cell size and whether the drain receives substantial or insubstantial amounts of base flow, drain conductance for streams simulated within the model varied over a large range, from a minimum of 375 ft/d to a maximum of 150,000 ft/d, but with a median value of 750 ft/d.

For conductance assigned to drains simulating mine entries within the model, a uniform hydraulic conductivity of 0.1 ft/d was used to compute drain conductance for the simulated abandoned mine workings. Given similar cell sizes as for streams simulated within the model, drain conductance for simulated mine entries also varied, but over a much narrower range, from a minimum of 375 to a maximum of 1,000 ft/ d, and a median of 500 ft/d. As mentioned previously, drain conductance was an insensitive parameter within the model, and therefore was not adjusted as part of parameter estimation using PEST.

Within the model, the primary factor affecting fluxes of water to and from the P3CMA are the elevations assigned to individual drain nodes within layer 2 of the model. As stated previously, the elevations of individual drain nodes were extrapolated from a structural contour map developed by the West Virginia Geological and Economic Survey for the base of the Pocahontas No. 3 coal seam. The structural contour map was modified based on additional structural elevation data for the seven wells completed for the study. The drain nodes were used to simulate flow of groundwater through the simulated abandoned mine workings in the P3CMA and were effective at simulating interbasin transfer of groundwater. Detailed discussions of interbasin transfer of groundwater and applications of the MODFLOW Drain Package for simulating interbasin transfer are presented in a subsequent section of this report.

Simulated Flow for the 70th Percentile Flow Duration

In order to simulate flow approximating base hydrologic conditions slightly below normal, the model was calibrated against the base-flow and mine-outfall discharges measured in October 2009. Flow-duration statistics (Table 4) indicate this period was representative of the 70 percentile flow duration (streamflow is equal to or greater than that measured 70% of the time). Thus, on an annual basis, the model was calibrated against a data set which represents hydrologic conditions about 20% below median annual streamflow conditions. The model was used to generate both simulations of the water levels in the aquifer, and the flux of groundwater discharge from mines and to streams under similar hydrologic conditions. Figures 21 and 22 show a reasonable fit between the observed and simulated water levels and base flow for the calibrated model. Within the model all inputs are from recharge and all flow out of the model is from drain or river cells.

Water Budgets

Overall, the model simulated 16.4 ft^3/s of base flow from the Elkhorn Creek watershed versus 9.1 ft^3/s of base flow from the North Fork watershed, which compare favorably to the 16.5 ft^3/s and 9.1 ft^3/s of water measured in the respective watersheds at the 70th percentile flow duration (Table 6). Given the complexity of the hydrologic system and the lack of gaging station and precipitation data for the North Fork and Elkhorn Creek watersheds, development of complete water budgets with precipitation, groundwater recharge, surface runoff, and evapotranspiration was not practical. Therefore, measurements of base-flow and mine-outfall discharge to streams were used to estimate groundwater availability (in terms of expected "yield" or discharge per unit contributing area) in the study area. Flow-duration statistics for nearby, long-term gaging stations, were used to provide context as to the potential amount of groundwater that might be available during differing hydrologic conditions.

Table 6. Measured and simulated base flow for four index stations, two each in the Elkhorn Creek and North Fork watersheds, in the Elkhorn area, McDowell County, West Virginia.

[mi^2, square miles; ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per square mile; n/d, no data available]

	Watershed			
	North Fork	Elkhorn Creek	Johns Knob Branch	Buzzard Branch
Drainage area (mi^2)				
Surface drainage area	19.6	17.4	0.86	5.19
Groundwater recharge area	17.8	29.6	7.62	7.96
Hydrologic conditons respective of the 87th percentile flow duration				
Simulated base flow (ft^3/s)	7.61	13.3	2.69	1.93
Measured base flow (ft^3/s)	6.52	13.5	2.82	2.95
Unit flow for surface drainage area ($ft^3/s/mi^2$)	0.33	0.78	3.30	0.57
Unit flow for groundwater recharge area ($ft^3/s/mi^2$)	0.37	0.46	0.37	0.37
Hydrologic conditions respective of the 70th percentile flow duration				
Simulated base flow (ft^3/s)	9.09	16.4	3.39	2.43
Measured base flow (ft^3/s)	9.07	16.5	3.13	3.14
Unit flow for surface drainage area ($ft^3/s/mi^2$)	0.46	0.95	3.66	0.61
Unit flow for groundwater recharge area ($ft^3/s/mi^2$)	0.51	0.56	0.41	0.39
Hydrologic conditions respective of the 38th percentile flow duration				
Measured base flow (ft^3/s)	28.8	44.0	6.00	n/d
Unit flow for surface drainage area ($ft^3/s/mi^2$)	1.47	2.53	7.02	n/d
Unit flow for groundwater recharge area ($ft^3/s/mi^2$)	1.62	1.49	0.79	n/d

Table 6 contains estimates of observed and simulated base flow of streams, derived primarily from mine-outfall discharge to tributary streams, over various hydrologic conditions. For the 70th percentile flow duration, observed base flow for the four watersheds, based on the contributing groundwater drainage areas, ranged from 0.39 to 0.56 $feet^3/s/mi^2$, with a mean of 0.47 and a median of 0.46 $feet^3/s/mi^2$. Unit discharges based on surface-water drainage areas are also provided in table 6, but do not reflect the true unit flow for the streams, as they do not account for the larger recharge source areas resulting from interbasin transfer of groundwater from adjacent watersheds.

Finally, even though the model was not used to simulate flow for the 38th percentile flow duration, estimates of groundwater availability based on measured base flow range from 0.79 to 1.62 $feet^3/s/mi^2$, with a mean of 1.30 and a median of 1.49 $feet^3/s/mi^2$ (Table 6). These measurements are presented to provide an estimate of water availability for higher base-flow conditions, as might be anticipated in late winter or early spring.

Groundwater-Flow Directions

Water levels simulated for the 70th percentile flow duration for layers 2 and 3 of the numerical groundwater-flow model are shown in Figures 31 and 32, respectively. Groundwater-flow directions are controlled mostly by the dip of the Pocahontas No. 3 coal seam and the abandoned mine workings within that seam. As a result, groundwater-flow direction can be inferred from the simulated water levels for the P3CMA (Figures 31 and 32). In addition, the network of drains developed within the model to simulate abandoned mine workings in the P3CMA can serve as delineations of the recharge source area for specific mine outfalls (Figure 20). The effect of the drains on simulated water-level

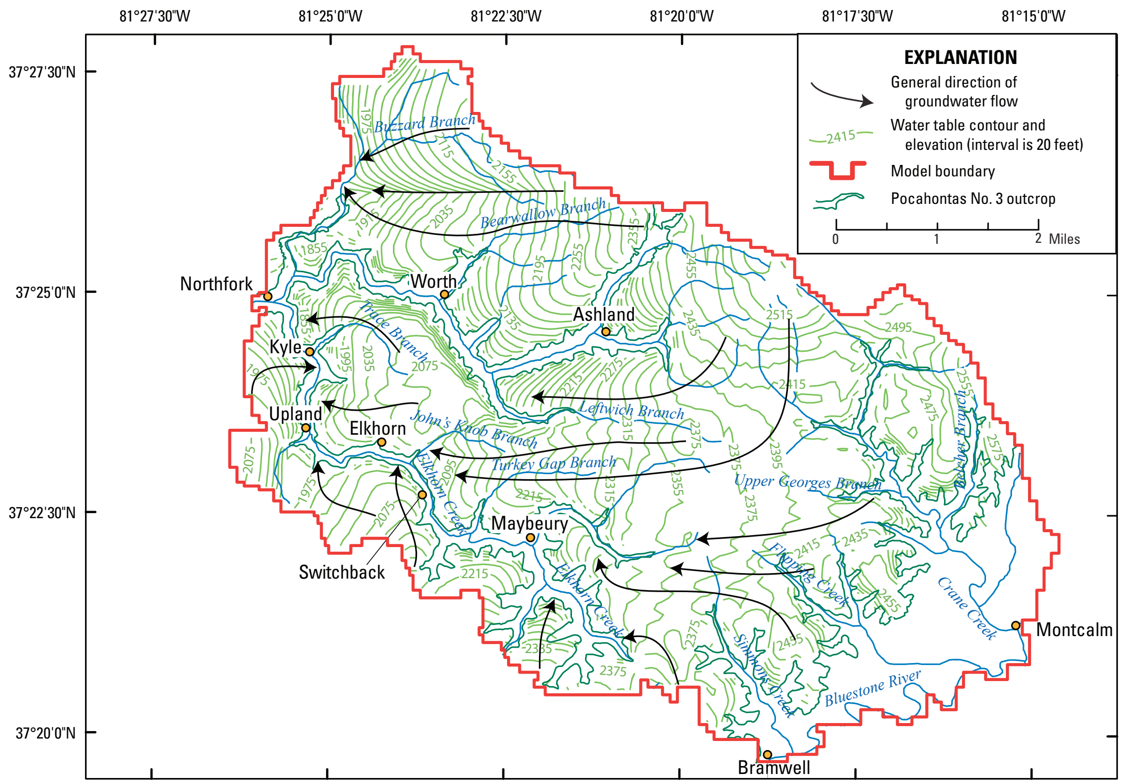


Figure 31. Simulated water levels for hydrologic conditions respective of the 70th percentile flow duration, in layer 2 of the groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

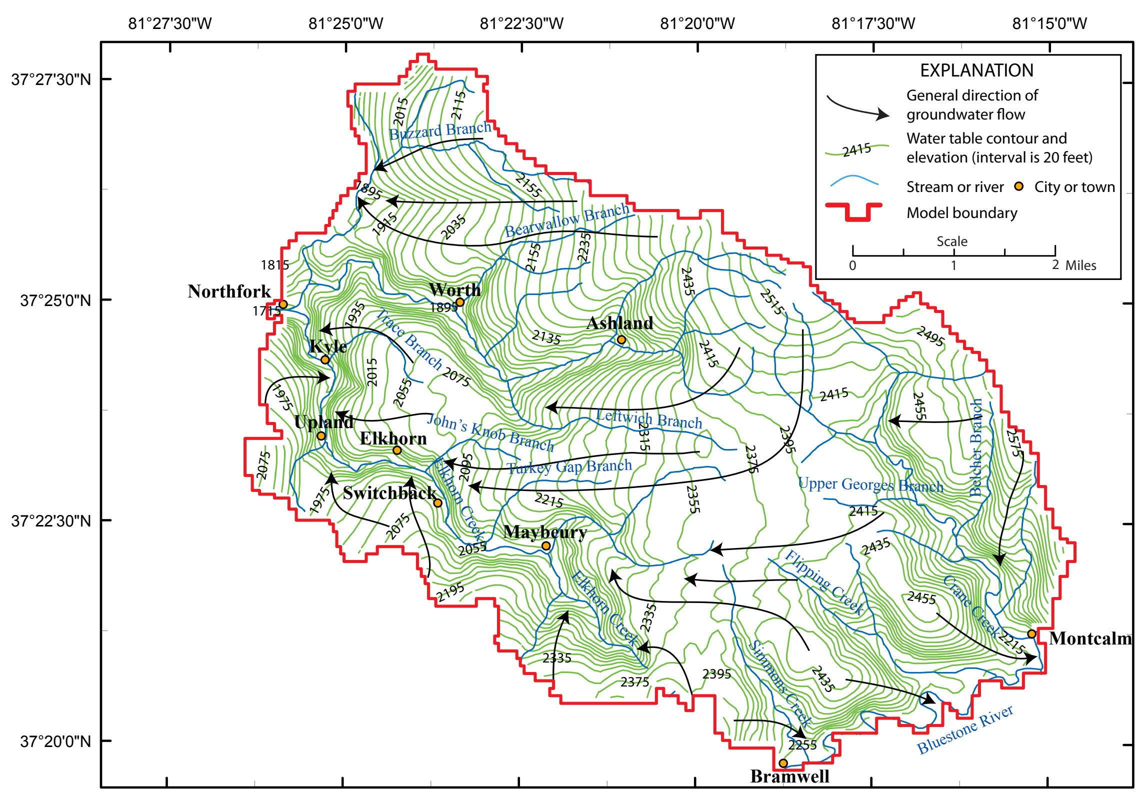


Figure 32. Simulated water levels for hydrologic conditions respective of the 70th percentile flow duration, in layer 3 of the groundwater-flow model developed for the Elkhorn area, McDowell County, West Virginia.

contours is clearly visible for layer 2 of the model (Figure 31), resulting in the irregularly-shaped contour lines corresponding to location of simulated mine entries (Figure 20), as compared to the more uniform contour lines for layer 3 of the model (Figure 32).

Simulated Flow for the 87th Percentile Flow Duration

In order to simulate flow for low-flow hydrologic conditions, recharge in the calibrated model was reduced by 17 percent to produce base flow similar to that of September 2010. Flow-duration statistics indicate that the conditions were representative of approximately the 87th percentile flow duration (Table 3). The low-flow simulation represents conditions similar to what would be expected for a moderate drought, and presents both simulations of the water levels in the aquifer and the flux or changes in base-flow discharge to streams. Recharge of 6.27 in/yr was used in the model to represent steep upland areas, 7.54 in/yr was used to represent the flat upland area, and 5.52 in/yr was used to represent the area above the flooded portion of the P3CMA.

Water Budgets

For the 87th percentile flow duration, measured unit base flow, resulting primarily from groundwater discharge from mine outfalls to tributary streams, for the four watersheds analyzed, ranged from 0.37 to 0.46 $ft^3/s/mi^2$ (Table 6), with a mean of 0.39 and a median of 0.37 $ft^3/s/mi^2$. Unit base flow discharge based on surface-water drainage areas are also provided in table 6, but do not reflect the true unit base flow for the streams, as they do not account for the larger recharge source areas resulting from interbasin transfer of groundwater from adjacent watersheds.

Overall, the model simulated 13.3 ft^3/s of water in the Elkhorn Creek watershed and 7.6 ft^3/s of water in the North Fork watershed, which compares favorably to the 13.5 ft^3/s and 6.5 ft^3/s of water measured in the respective watersheds during the September 2010 base-flow survey (Table 6). Given the model was calibrated against the data for the 70th percentile flow duration, it is not surprising that the model fit is not as accurate for the simulated 87th percentile flow duration period. Other factors, such as shifting zones of contribution and water-table divides can also impact the distribution of water between the various watersheds within the model under different flow conditions. Overall, the model represents flow in the Elkhorn Creek very well, but over-represents flow in the North Fork watershed by about 1.1 ft^3/s.

Interbasin Transfer

The groundwater-flow model provides substantial insight into processes of interbasin transfer of groundwater within the Elkhorn Creek, North Fork, and Bluestone River watersheds (Figure 33). Based on groundwater divides extrapolated from elevations of the surface of the P3CMA and drain cells in layer 2 used to simulate the mine elevations, and on water budgets computed by the model, Elkhorn Creek (Area I on Figure 33) captures a small proportion of groundwater from the adjacent North Fork watershed (Area III on Figure 33) and a much larger proportion of water from the adjacent Bluestone River watershed (Area IV on Figure 33). This is due to groundwater capture from up-dip areas within the P3CMA, which extend to the outcrop terminus of the Pocahontas No. 3 coal seam more than three miles beyond the topographic watershed divide between the Elkhorn Creek/North Fork watersheds and the Bluestone River watershed (Figure 3 and 20). The surface drainage areas of the North Fork (Areas II

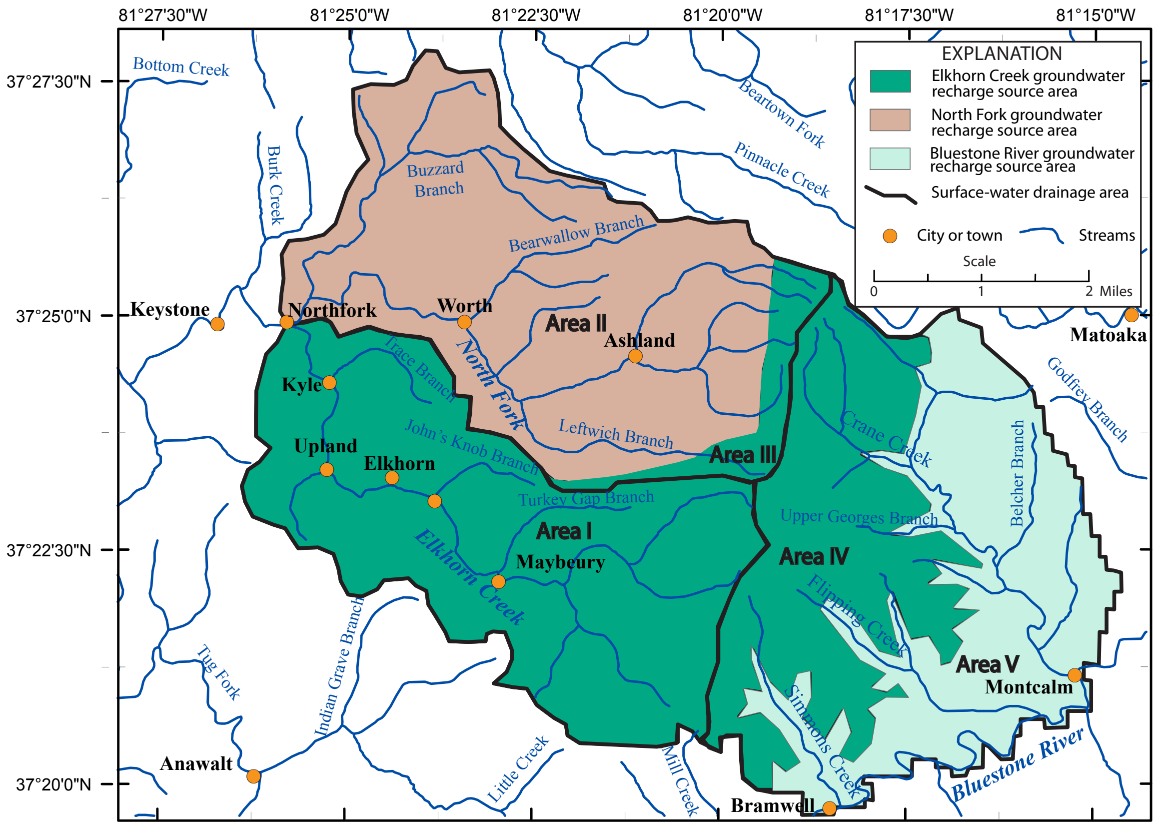


Figure 33. Surface-water drainage areas and groundwater recharge source areas for Elkhorn Creek, North Fork, and a portion of the Bluestone River, in the Elkhorn area, McDowell County, West Virginia.

and III on Figure 33) and Bluestone River watersheds (Areas IV and V on Figure 33) are therefore larger than their corresponding groundwater recharge source areas.

Two streams, Johns Knob Branch and Buzzard Branch, have anomalously large discharge when compared to their respective surface-water drainage areas (Table 6). The anomalously large discharge of these two streams is due to interbasin capture of groundwater from adjacent watersheds (Figure 34). Earlier in this report, it was determined that although Johns Knob Branch has a surface watershed of only 0.86 mi^2, an approximate surface drainage area of 8.0 mi^2 is necessary to produce the mean stream flow recorded at the Johns Knob Branch gaging station, based on average mean streamflow in the region. Based on groundwater divides extrapolated from elevations of drain cells in layer 2 of the model, it was determined that Johns Knob Branch has a groundwater recharge source area of 7.62 mi^2. Thus the groundwater recharge source area of 7.62 mi^2 estimated as part of the groundwater model is in very close agreement to the 8.0 mi^2 groundwater capture area postulated earlier in the report.

Results of the groundwater modeling indicate that Johns Knob Branch has a surface-water drainage area of only 0.86 mi^2, but a groundwater recharge source area of 7.62 mi^2, about 8.9 times larger than the surface-drainage area. Likewise, Buzzard Branch has a surface-drainage area of 5.19 mi^2, and a groundwater recharge source area about 1.5 times larger (7.96 mi^2). Interbasin transfer is common in areas of active and abandoned mining, and must be accounted for to obtain realistic estimates of surface-water and groundwater flow for a given watershed.

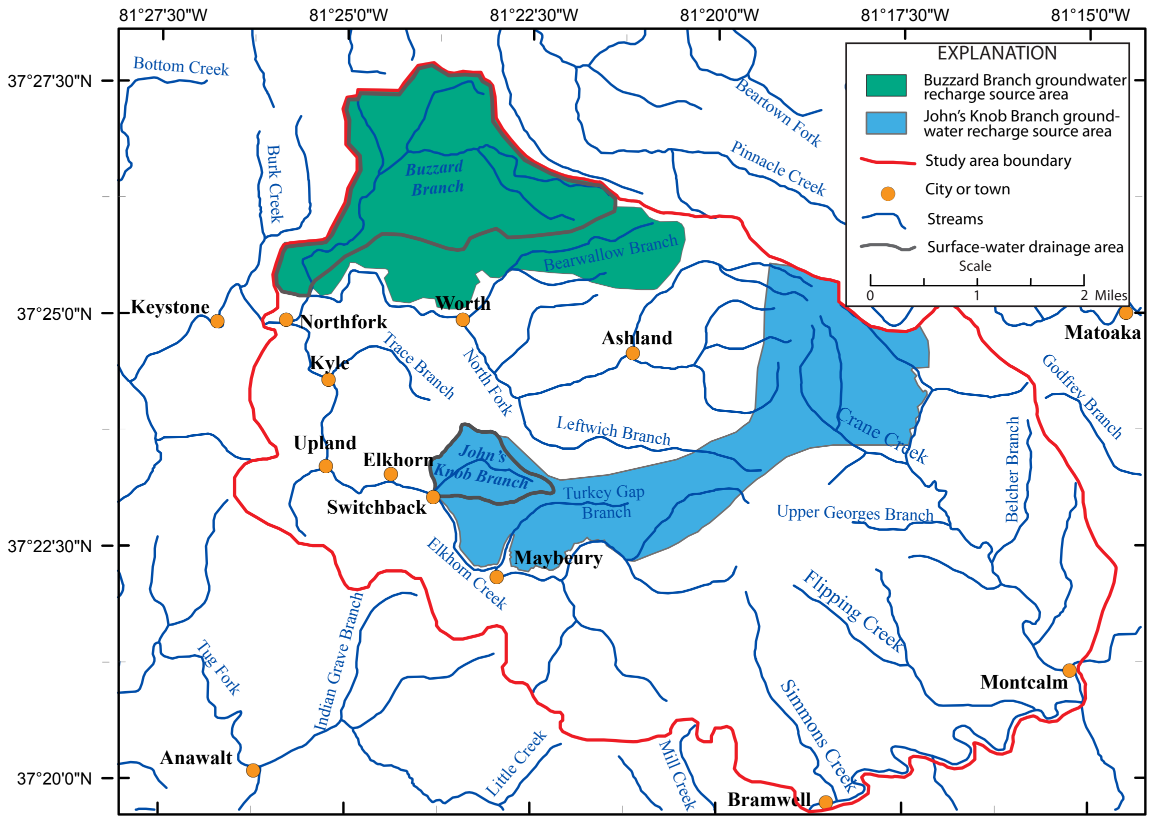


Figure 34. Surface-water drainage areas and estimated groundwater recharge source areas required to produce measured flows for Johns Knob Branch and Buzzard Branch, in the Elkhorn area, McDowell County, West Virginia.

Limitations of the Simulations

There are no known previous simulations of groundwater flow for above-grade (above local tributary streams) underground coal-mine aquifers in the Appalachian coal-mining province. As such, this study presents a preliminary effort to develop an approach for simulating such systems, and discussion of the limitations of the model and approach are important. A primary limitation of the simulation was a lack of data for water-levels and hydraulic properties, especially vertical hydraulic conductivity of the hydrogeologic units within the study area. Due to budget limitations and the steep inaccessible topography within the study area, only seven wells were installed for the study and no other wells were identified during field reconnaissance. Fortunately, for all seven wells, water levels were within or very near the elevation of the P3CMA. Thus the simplifying assumption that most water levels within the model domain were controlled by the elevation of the P3CMA seems valid. For the seven wells, two wells had water levels in layer 1 just a few feet above the coal-mine aquifer, 3 wells had water levels within the P3CMA, and two additional wells had water levels just below the elevation of the P3CMA, and were representative of water levels in strata underlying the P3CMA. The lack of water-level data is therefore a major limitation for the numerical groundwater-flow simulation, and water levels simulated within the model should be regarded with caution. This is especially true in the northeastern section of the model where water levels are simulated to occur at elevations above the flooded portion of the coal-mine aquifer.

To compensate for the lack of water-level data, extensive base-flow surveys were conducted, resulting in multiple periods of base-flow measurements representing various hydrologic conditions at 96 locations (Appendix 3). Since the flux of water was the primary reason for developing the numerical simulation of groundwater flow, the base-flow measurements partially compensate for the lack of water-level data. However, future groundwater-modeling efforts should try to obtain as much water-level data as possible. These data are needed to verify the concept that the majority of water in upper layers percolates downward to underlying abandoned mine aquifers through subsidence fractures in overlying strata, and that the abandoned mine aquifers represent the significant water bearing horizon, with upper layers being more or less dewatered.

An additional substantial limitation is the lack of data for hydraulic properties of the hydrogeologic units in the study area, especially for vertical hydraulic conductivity (Kz). There are numerous publications of horizontal hydraulic (Kxy) conductivity data for similar coal-mine aquifers in the Appalachian Region, but little if any published data for Kz of typical sequences of sandstone, shale, coal, siltstone, claystone, and limestone are available. Thus, the model-calibrated results of Kz published in this report represent some of the only estimates available for coal-bearing strata in the Appalachian region.

The model presented in this report is a simplified mathematical representation of a complex natural groundwater-flow system modified by extensive mining in the Elkhorn Creek, North Fork, and adjacent watersheds. The model contains uncertainty associated with the approximations, assumptions, and simplifications that were made to translate the conceptual model into a numerical simulation. Although the numerical model provides a relatively good fit between simulated and measured water levels and groundwater flux, indicating that it reasonably represents groundwater flow, the model is most applicable to analysis of groundwater issues at the hydrologic conditions for which it was calibrated. Model simulations of higher or lower flow regimes will not be as accurate, as groundwater divides may shift from one watershed to another under different hydrologic conditions. This was evident in the extrapolation of the calibrated model for the 70th percentile flow duration to the lower-flow conditions of the 87th percentile flow duration. The network of mine locations that provide discharge to individual outflows are specified in the model by the drain locations, whereas the actual area providing water to an outflow may change with changing hydrologic conditions.

The boundary conditions for the model, especially the no-flow boundaries, were set prior to developing a full understanding of the significance of the geologic-structure contours. Future models should set external bounds of the model to the full practical up dip extent of adjacent mine workings, even if those mine workings extend far into adjacent surface watersheds. While only affecting a small proportion of the potential study area, less than 8 percent, the under-representation of interbasin transfer of water along the southern boundary of the model adds additional uncertainty and under-representation of flux of water within the model. Fortunately, the areas impacted were not substantial areas of emphasis within the model.

The simulation of inter-basin transfer of groundwater using the MODFLOW Drain package as presented in this report provides a unique solution to a very difficult problem. However, the approach is not without limitations and may not be appropriate for all mines or hydrogeologic settings. First of all, the approach is only applicable for free-flowing, above-drainage mines. If bedrock dips below local structure, as occurs in the northwestern portion of the study area, then the MODFLOW Drain package is not applicable. Also, the use of the MODFLOW Drain package for simulating interbasin transfer may or may not be applicable for hydrologic conditions substantially different than those for which the model was calibrated, as different drain cells would be active under differing hydrologic conditions. For the simulations discussed in this report, the bedrock interval overlying the P3CMA was shown to be locally devoid of water in overlying strata due to subsidence fracturing, the approach has not been tested in settings where the overlying bedrock is representative of perched conditions and may or may not be applicable for such conditions. Finally, since the elevations of drain nodes within the model are based on elevations derived from extrapolation of regional-scale structural contour maps, it is essential that structural contour maps used for simulating the base of a coal-mine aquifer be as accurate as possible, as any misrepresentation of dip can cause errors in simulating where water will discharge to the surface. Thus in areas of complex structure, the method may not be practical without accurate mine maps on which elevations for drain nodes may be assigned.

Groundwater Quality

Groundwater samples collected from 2 sites (1 well and 1 mine outfall) in the Elkhorn area were analyzed for approximately 100 water-quality constituents including common ions, trace elements, nutrients (including nitrate and phosphorus), indicator bacteria (E. coli and total coliform), volatile organic compounds (VOCs), semi-volatile organic compounds, radioactive elements (radon-222), stable isotopes (deuterium and oxygen-18), and constituents useful for age dating of water (tritium and chlorofluorocarbons). Results of the analyses were used to: 1) establish a baseline of groundwater-quality data for use in assessing potential changes over time; 2) assess current quality of groundwater in the P3CMA; 3) assess the current quality of groundwater in underlying unmined strata (well completed in the Pocahontas No.2 coal-seam and associated sandstones), and 4) characterize the age of water in these two hydrogeologic settings. Precipitation was also sampled for deuterium and oxygen-18 at the gaging station on Johns Knob Branch (station number 03212640). Water-quality data for these sites are presented in Appendix 5 of this report.

Field Measurements and Sampling Methods

Groundwater was sampled using the techniques described by Wilde and others (1999). The mine outfall (site Mcd-0210) was sampled with a submersible pump as close as possible to the point of discharge from the bedrock. A well (site Mcd-0204) was sampled using a submersible pump with Teflon discharge line (except for CFCs which were sampled with copper tubing). The well was purged to remove at least three volumes of water from the casing to ensure that formation water, and not water that had been stored in the casing was being sampled. Field measurements of pH, specific conductance, dissolved oxygen (DO), water temperature, and turbidity were continuously monitored during purging of the well and mine outfall, and samples were collected only after the values of these parameters stabilized. All samples were filtered and preserved in the field, and subsequently shipped to the U.S. Geological Survey National Water Quality Laboratory (NWQL) in Lakewood, Colorado, where they were analyzed for the constituents listed above. Carbonate alkalinity, bicarbonate alkalinity, and total alkalinity were measured in the field using the techniques described by Wilde and Radtke (1998). The Colilert© defined substrate method was used to determine concentrations of total coliform and E. coli in water samples (American Public Health Association/American Water Works Association/Water Environment Federation, 2005). Results of field and laboratory analyses are summarized in Appendix 5.

Dissolved gas samples were collected by placing a silicone rubber tube from the well discharge line into the bottom of a 160-mL glass serum bottle. The 160-mL bottle was then placed in the bottom of a 2-L container and allowed to overflow until completely submerged. While submerged, the bottle was capped with a rubber stopper to prevent gas exchange between the sample and atmosphere. Four samples were collected at each sampling site. Concentrations of dissolved N_2, Ar, O_2, CO_2, and CH_4 were measured by gas chromatography at the USGS Dissolved Gas Laboratory in Reston, Virginia. In replicate samples concentrations of dissolved N_2 and Ar generally agree to within less than 1 percent, and concentrations of O_2, CO_2, and CH_4 agree to within 1 to 2 percent (Busenberg and others, 1998).

Table 7. Drinking water standards and concentrations of water-quality constituents in water samples collected from the Pocahontas No. 3 coal-mine aquifer outfall (Mcd-0210) and from a well (Mcd-0204) completed in deeper underlying unmined strata, in the Elkhorn Area, McDowell County, West Virginia. [Regulatory requirements for maximum contaiminants levels, maximum contaminant level goals, secondary maximum containment levels, and non-regulatory health based screening levels are also provided.]

[mg/L, milligrams per liter, mg/L, micrograms per liter; mL, milliliters; <, less than; %, percent; mS/cm, microsiemens per centimeter; pCi/L, picocuries per Liter; nd, not detected; na, not available]

Constituent	Mcd-0210	Mcd-0204	Maximum contaminant level goal	Maximum contaminant level	Secondary maximum contaminant level	Health based screening level
Aluminum, µg/L	nd	4	na	na	50 - 200	na
Arsenic, µg/L	1.3	3.3	0	10	na	na
Barium, µg/L	36.6	81.5	2	2000	na	na
Beryllium, µg/L	nd	0.05	4	4	na	na
Cadmium, µg/L	nd	nd	5	5	na	na
Chromium, µg/L	nd	nd	100	100	na	na
Chloride, mg/L	0.87	0.93	na	na	250	na
Dissolved oxygen, mg/L	7.2	<1.0	na	na	na	na
E. Coli, colonies/100mL	1	nd	zero	na	na	na
Fluoride, mg/L	0.16	0.15	4	4	2	na
Iron, µg/L	nd	5620	na	na	300	na
Lead,µg/L	nd	nd	zero	15 *	na	na
Manganese, µg/L	nd	571	na	na	50	na
Mercury, µg/L (inorganic)	nd	nd	2	2	na	na
Nickel, µg/L	2.9	1.2	na	na	na	100
Nitrate, mg/L	nd	nd	10	10	na	na
Nitrite,mg/L	nd	nd	1	1	na	na
pH, standard units	6.6	6.8	na	na	6.5-8.5	na
Radon-222, pCi/L	23	21	na	300 [1]	4000 [1]	na
Selenium, µg/L	1.5	nd	0.05	50	na	na
Specific conductance, µs/cm	665	490	na	na	na	na
Sulfate, mg/L	143	70.7	na	na	250	na
Thallium, µg/L	nd	nd	0.5	2	na	na
Total Coliforms, colonies/100 mL	340	6	zero	5.0% #	na	na
Total Dissolved Solids, mg/l	418	311	na	na	500	na
Turbidity (NTU)	1.3	0.5	na	5 [2]	na	na
Zinc, µg/L	3.4	nd	na	na	5	2000
Benzene, µg/L	nd	nd	zero	5	na	na
1,1,1-Trichloroethane, µg/L	nd	nd	200	200	na	na
1,2-Dichloroethane, µg/L	nd	nd	zero	5	na	na
1,2-Dichloropropane, µg/L	nd	nd	zero	5	na	na
1,3-Dichlorobenzene	nd	nd	na	na	na	600
Dichlorodifluoromethane	nd	nd	na	na	na	1000
Dichloromethane, µg/L	nd	nd	zero	5	na	na
Ethylbenzene, µg/L	nd	nd	700	700	na	na
Styrene, µg/L	nd	nd	100	100	na	na
Toluene, µg/L	nd	nd	1000	1000	na	na
Trichlorofluoromethane, µg/L	nd	nd	na	na	na	2000
Vinyl chloride, µg/L	nd	nd	zero	2	na	na
Xylenes, µg/L (total)	nd	nd	10000	10000	na	na

* Action level for lead is 15 µg/L

No more than 5.0% of samples are total coliform-positive in a month.

[1] The proposed maximum contaminant level for radon in drinking water is 300pCi/L, with an alternate maximum contaminant level of 4,000 pCi/L if a radon mitigation program is in effect.

[2] For systems that use conventional or direct filtration, at no time can turbidity go higher than 1 NTU and samples for turbidity must be less than or equal to 0.3 NTU in at least 95 % of samples in a month. Systems that use filtration other than conventional or direct filtration must follow state limits, which must include turbidity at no time exceeding 5 NTU.

Specific Conductance, pH, and Temperature

The pH of water from both the mine outfall (Mcd-0210) and the well completed in strata below the P3CMA (Mcd-0204) was near neutral, with pH values of 6.6 and 6.8, respectively (Table 7 and Appendix 5). The specific conductance and concentration of total dissolved solids were slightly higher in water from the mine outfall (Mcd-0210) at 665 µS/cm and 418 mg/L, than in water from the well tapping deeper unmined strata (Mcd-0204) at 490 µS/cm and 311 mg/L. The higher specific conductance and dissolved solids content of water from the coal-mine aquifer indicates that water from the mine is slightly more mineralized than water from the deeper undisturbed and unmined strata. This is not surprising given the amount of rubble, collapsed overburden, and collapsed coal pillars that are exposed to weathering in abandoned underground coal mines. The disturbance of the rock and coal seam exposes more minerals to weathering processes than occurs in undisturbed strata. Water temperature was similar for both sites, with the water from the mine outfall being slightly cooler at 12.5^{o} C than the water in the underlying strata at 12.7^{o} C.

Turbidity, Dissolved Oxygen, and Redox Potential

The turbidity of both the water from the P3CMA (1.3 NTU) and from the deeper undisturbed strata (0.5 NTU) is very low (Table 7 and Appendix 5). There is, however, a marked difference in the dissolved oxygen content and oxidation reduction potential of the two sites. Water from the P3CMA outfall (site Mcd-0210) had water with high dissolved oxygen content (7.2 mg/L) and an oxidation reduction potential (262 mV) indicative of highly oxic conditions. Water from the well completed in deeper undisturbed/unmined strata (Mcd-0204) had no detectable oxygen content (<1.0 mg/L) and a redox potential (-90.0 mV) indicative of reducing conditions. The redox state of the waters is reflected in their chemical composition, which are quite different, especially with respect to trace metals which will be discussed later in this report. Reduction and oxidation (redox) processes have a significant effect on the quality of water in the two hydrogeologic settings.

Alkalinity, Water Hardness, and Major Ions

The water discharging from the P3CMA is very hard (207 mg/L) and water from the well completed in the deeper strata that includes the Pocahontas No. 2 Coal seam (Table 7 and Appendix 5) is hard (140 mg/L). Alkalinity for water discharging from the abandoned coal mine is also higher (189 mg/L) than water produced from the well completed in the deeper undisturbed strata (163 mg/L). Since the water from both sites is coming from a similar series of interbedded sandstones, shales, and coal-mine aquifers, the higher hardness (207 versus 140 mg/L) and total dissolved solids content (418 versus 311 mg/L) of the P3CMA outfall water is likely due to increased exposure to minerals and weathering processes of rock and coal present due to collapsed pillars, mine voids, and subsided overburden in the P3CMA, than would occur in deeper undisturbed strata.

The highly oxygenated water characteristic of the P3CMA outfall and the water from the highly reduced deeper strata exhibits a similar calcium magnesium bicarbonate signature (Figure 35), reflecting the similar types of rocks found in both hydrogeologic settings. Siderite, an iron carbonate mineral, was found in high concentration in the source rocks in the study area as documented in petrographic analyses conducted for this study and previously discussed. The high proportion of carbonate minerals likely is responsible for the buffering capacity of the water, and is possibly one of the primary reasons why water from coal measures in the southern coalfield province in West Virginia does not typically produce acid mine drainage (AMD). Waters from both sources contain a substantial calcium, sodium, and potassium signature. Water from the P3CMA, however, also has a dominant sulfate signature, which is obvious when comparing sulfate concentrations of its highly oxygenated water (143 mg/L) to that from the undisturbed/unmined deeper strata (70.7 mg/L). The water quality and sustained cold temperature of groundwater derived from mine outfalls discharging from the P3CMA contribute to the naturally reproducing trout fishery in Elkhorn Creek.

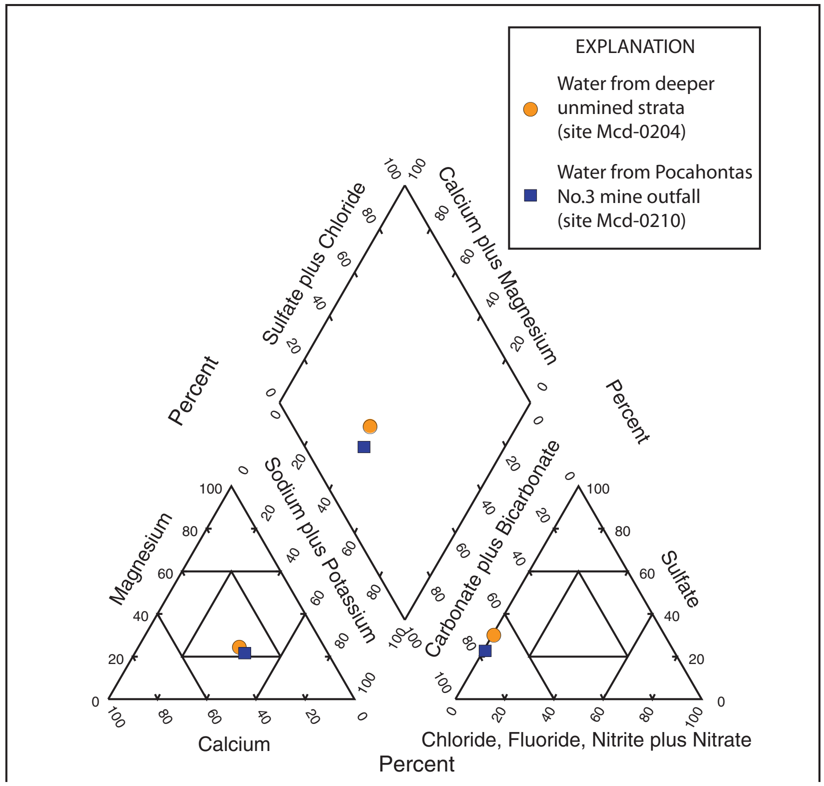


Figure 35. Piper plot showing the major ion content of water samples collected from the Pocahontas No. 3 coal-mine aquifer outfall (Mcd-0210) and from deeper unmined strata (Mcd-0204) in the Elkhorn area, McDowell County, West Virginia.

Trace Elements

The difference in the quality of the water from the P3CMA and the undisturbed deeper strata is readily apparent with respect to trace metals concentrations (Table 7 and Appendix 5). As mentioned previously, the oxygen content of the water controls the oxidation and reduction processes that occur within the aquifer. The reducing conditions present in the anoxic deeper undisturbed strata results in substantially higher concentrations of trace metals than is present in highly oxygenated water discharging from the P3CMA. Metals in water from the P3CMA outfall have either been largely removed by redox processes and flushed from the mine, or deposited in sediment and mineral deposits, especially oxyhydroxides within the P3CMA. Concentrations of iron, manganese, barium, and arsenic in water from the P3CMA outfall were <9, <0.8, 36.6, and 1.3 µg/L, respectively. In water from the deeper mined strata however, concentrations were much higher at 5,620, 571, 81.5, and 3.3 µg/L, respectively.

Concentrations of iron and manganese (Table 7) exceeded U.S. Environmental Protection (USEPA) secondary maximum contaminant levels (SMCLs) at the well tapping the deeper undisturbed/unmined strata (Mcd-0204), but were below method detection limits in water from the P3CMA outfall (Mcd-0210). SMCLs are based on aesthetic considerations such as taste, odor, and staining of plumbing fixtures, rather than health standards.

Radon-222

Radon-222 is a radioactive gas derived from the natural radioactive decay of the element radium (Otton and others, 1993). Radon is a known carcinogen, and the primary health effects of long-term exposure to air with a high concentration of radon, is an increased risk of lung cancer. The USEPA maximum contaminant level (MCL) for radon in indoor air is 4 picocuries per liter (pCi/L). The proposed USEPA MCL for radon in drinking water is 300 pCi/L, with an alternate maximum contaminant level (AMCL) of 4,000 pCi/L, if indoor air mitigation programs are established to minimize the risk of inhalation (U.S. Environmental Protection Agency, 1999). The concentrations of radon-222 in the mine outfall (Mcd-0210) and the well tapping deeper unmined strata (Mcd-0204) were 23 and 21 pCi/L respectively, far below the proposed 300 pCi/L drinking water MCL (Table 7 and Appendix 5). Radon-222 is typically found in groundwater in areas with predominantly shale bedrock. The southern coalfields of West Virginia are typified by massive sequences of sandstone with interspersed coal seams and limestone; shale is less common.

Nutrients and Bacteria

Nutrient compounds analyzed for in water samples sampled for the study include nitrate, nitrite, ammonia, phosphorus and orthophosphate. Nutrients and bacteria share some common sources, primarily fecal material from animals and humans. Synthetic fertilizers, commonly used in agricultural applications, are an additional source of ammonia, nitrite, nitrate, phosphorus, and orthophosphate.

Nitrogen and Phosphorus Compounds

None of the nutrient compounds were present in water samples collected from the P3CMA outfall (Mcd-0210) and the well tapping deeper unmined strata (Mcd-0204) in concentrations exceeding USEPA MCLs. Most of the nutrient compounds, including nitrate and nitrite, were not detected in either sample (Appendix 5 and Table 7), and the highest level detected in either sample was only 0.418 mg/L of ammonia in the well tapping the deeper unmined strata. The general lack of nutrients in groundwater within the study area reflects land-use practices as there are no agricultural activities, septic system return flows, or wastewater treatment plant return flows, that would provide a source of nutrients to groundwater. Unfortunately, direct discharge of sewage effluent from residential homes is common, and nutrient contamination of surface water is a serious problem in the region (Wastewater Treatment Coalition of McDowell County, 2005). Leakage of streamflow to deeper aquifers could occur in areas where underground mining has fractured the overburden strata underlying streams, providing a pathway for surface water to percolate into deeper aquifers. The deeper coal seams in the study area have not been mined and the threat of bacterial or nutrient contamination of groundwater is therefore diminished.

Indicator Bacteria

Indicator bacteria samples were collected from both the well tapping the deeper unmined strata (Mcd-0204) and the P3CMA outfall (Mcd-0210) (Table 7 and Appendix 5). The indicator bacteria sampled included total coliform and E. coli. The presence of these bacteria in groundwater is an indicator of potential microbial contamination. Potential sources of contamination in the study area are primarily from wildlife, especially deer, bear, turkey and other smaller animals such as squirrels and various birds. Another source of potential bacterial contaminant is direct discharge of untreated sewage into Elkhorn Creek, which unfortunately, is a common practice within the study area (Wastewater Treatment Coalition of McDowell County, 2005). Fortunately, these discharges occur primarily along the margins of Elkhorn Creek and the North Fork, and therefore do not pose a risk of contamination of the P3CMA in the immediate study area.

Water samples collected from the well tapping deeper bedrock strata (Mcd-0204) had less than detectable concentrations of E. coli and only 6 total coliform colonies per 100 milliliters of sample (col/100 mL). Bacteria data retrieved from the USGS National Water Information System

(NWIS) database for 22 additional wells sampled in similar hydrogeologic settings in McDowell and Wyoming Counties in West Virginia had similar bacteria occurrences, with average and median E. coli concentrations of <1.5 and <1 col/100 mL, respectively, and average and median total coliform concentrations of 17 and <2 col/100 mL, respectively (data available at http://waterdata.usgs.gov/wv/nwis/nwis).

Water samples collected at the P3CMA outfall (Mcd-0210) had detections of 1 col/100 mL of E. coli and 340 col/100 mL of total coliform. Bacteria data retrieved from the USGS NWIS database for 211 water samples collected at 176 streams sampled in similar hydrogeologic settings in McDowell and Wyoming Counties in West Virginia had average and median fecal coliform (E. coli data were not available) concentrations of 4,400 and 1,200 col/100 mL, respectively, and average and median total coliform concentrations from 4 samples of 530 and 470 col/100 mL, respectively, (data available at http://waterdata.usgs.gov/wv/nwis/nwis). Thus, the water from the mine outfall is more similar to that of stream water than of groundwater, suggesting rapid infiltration of recharge from near surface sources may be affecting the P3CMA.

In 2008 both Elkhorn Creek and the North Fork were listed in the West Virginia Department of Environmental Protection's 303-D list of impaired streams; the listing is primarily for elevated fecal coliform content (West Virginia Department of Environmental Protection, 2008). A report prepared by the Wastewater Treatment Coalition of McDowell County (2005) estimated that as much as 67 % of the population of McDowell County lacks adequate wastewater treatment. The high proportion of the population with inadequate or no sewage treatment results in untreated sewage being discharged to receiving streams.

Even though streams in the area have been heavily impacted by poor sewage disposal practices, groundwater is much less likely to be contaminated and can provide adequate supplies of water for public and private supply. Unfortunately, the connections between streams and groundwater, especially where stream beds have been fractured as a result of underground mining beneath streams, can provide direct pathways to underlying aquifers. In the study area, the P3CMA is at an elevation above the local streams, a plausible explanation of why the outfall from the P3CMA was much less contaminated than streams in the region.

Organic Constituents

The Elkhorn Creek study area is not an agricultural area. No active farms are present in the study area and the only agricultural activity is a few small gardens tended by local residents. Therefore, pesticides were not analyzed for in water samples collected for the study. However, some organic compounds are used in the mining industry, mainly to maintain and clean equipment, or in blasting. Therefore, a suite of 36 volatile organic compounds (VOCs) were analyzed in samples collected from the P3CMA outfall (Mcd-0210) and the well tapping deeper unmined strata (Mcd-0204). Of the 36 VOCs analyzed, none were detected (Table 7 and Appendix 5).

Groundwater Age Dating Constituents

Environmental tracers are used to assess the residence time and sources of groundwater recharge to aquifers. The term "residence time" is defined as the approximate time elapsed since a water sample was isolated from air in the unsaturated zone (Plummer and Busenberg, 2000). Residence time of a groundwater sample is a model-calculated approximation based on the measured concentrations of an

Table 8. Dissolved-gas and isotope data for water samples collected from the Pocahontas No. 3 coal-mine aquifer outfall (Mcd-0210) and from a well (Mcd-0204) completed in deeper underlying unmined strata, in the Elkhorn Area, McDowell County, West Virginia.

[nd, not determined; °C, degrees Celsius; δ, delta; mg/L, milligrams per Liter; ft NAVD88, feet above North American Vewrtical Datum of 1988]

Station Number	Station name	Sampling Date	δ Deuterium (per mil)	δ Oxygen-18 (per mil)	Nitrogen (mg/L)	Argon (mg/L)	Oxygen (mg/L)	Carbon Dioxide (mg/L)	Methane (mg/L)	Recharge Elevation (ft, NAVD88)	Recharge Tempera-ture (°C)
372322081241501	Mcd-0204	07-20-10	-49.1	-7.97	17.4	0.6	0.2	65.6	0.1	2,860	10.0
372313081234101	Mcd-0210	07-20-10	-51.5	-8.07	16.4	0.6	6.7	85.6	0.0	2,870	10.4
03212640	Johns Knob Branch Precipitation	07-20-10	-27.3	-4.84	nd	nd	nd	nd	nd	nd	nd

environmental tracer, and its validity increases with the number of tracers used. According to Plummer and Busenberg (2000), the groundwater residence time must be determined with consideration of chemical sorption, biodegradation, and physical mixing processes that can alter age interpretations. Understanding these processes and classifying an aquifer in terms of vulnerability often require a multiple-tracer approach.

Dissolved Gases

Groundwater samples were collected for analysis of dissolved gases at Mcd-0204 and Mcd-0210 to estimate groundwater-recharge temperatures. The temperature of water recharging aquifers is measured or estimated as accurately as possible from N_2-Ar solubility data (Heaton, 1981). Groundwater recharge temperatures are needed to calculate air-equilibrium chlorofluorocarbon (CFC) concentrations in a sample. The recharge temperature estimates for the Mcd-0204 and Mcd-0210 samples were 10.0°C and 10.4°C, respectively (Table 8); mean annual air temperature 17 miles from Elkhorn at Bluefield, West Virginia is 11.9°C, and ranges from a minimum mean monthly air temperature of 0.4°C in January to a maximum mean monthly air temperature of 22.0°C in July (National Oceanic and Atmospheric Administration, 2011). Recharge temperature estimates suggest substantial recharge occurs during the Spring and Fall, when ambient air temperatures are slightly cooler than average annual air temperatures.

Like the N_2 and Ar data, dissolved methane (CH_4) concentrations can be used to identify samples for which input parameters into CFC-age calculations need careful consideration. Dissolved gas data for the well tapping deeper unmined strata (Mcd-0204) show low concentrations of methane (0.1 mg/L), which suggest reducing conditions. No methane was measured in the P3CMA outfall (Mcd-0210). The absence of methane in the sample from the P3CMA outfall is not surprising, as oxygen levels of 6.7 mg/L may indicate substantial groundwater and air interaction within the abandoned workings, and may have stripped low-level methane from solution.

The presence of methane in deeper groundwater of the Elkhorn area is an indicator of reducing environments, which can cause degradation of CFCs and other gases, and can affect calculations of groundwater recharge temperature and age. In coal-bearing strata reducing environments are common, CFCs are degraded, and the CFC tracer method yields apparent ages that are older than the actual age of the sample (McCoy and Kozar, 2007; Nelms and others, 2003).

Chlorofluorocarbons

The three CFC compounds (CFCs) commonly used to estimate the apparent age of groundwater are CFC-11 (trichlorofluoromethane), CFC-12 (dichlorofluoromethane), and CFC-113 (trichlorotrifluoroethane). A comprehensive discussion of CFC data-collection techniques, laboratory-analysis methods, and applications is presented in a report on statewide assessment of groundwater age in West Virginia (McCoy and Kozar, 2007).

Initially, CFC recharge dates are evaluated using piston, or unmixed flow models. Piston flow models represent a slug of water moving from recharge to discharge zones along a defined flow path without dispersive mixing in the direction of flow (Busenberg and Plummer, 1992). These models are based on CFC concentration alignment in atmospheric growth curves (Busenberg and Plummer, 1992) and the assumption that infiltrating waters are in equilibrium with the troposphere at the time they reach the saturated zone. The assumption is generally valid in areas where the unsaturated thickness does not exceed 30 feet (Cook and Solomon, 1995). If one or more of the CFC concentrations are not in concordance, then the sample either is contaminated, is degraded, or can be described as a binary mixture of young and old (pre-CFC) fractions (Plummer and Busenberg, 2000). In the case of binary mixtures, one of the CFCs appears to give the sample a younger age than that indicated by a piston flow model. The ratio of any two CFCs (CFC-11/CFC-12, CFC-11/CFC-113, and CFC-113/CFC-12) can be used to determine apparent young age and young-age fractions of uncontaminated binary mixtures. Final apparent CFC groundwater-age determinations were based on: (1) mixing ratios if any combination of the three CFC compounds fell within mixing and piston flow boundaries and were not degraded or contaminated; (2) piston-flow models if data plot along the piston-flow line; or (3) piston-flow models if only a single tracer was suitable for dating.

CFC analytic results from Mcd-0204 (well tapping deeper strata below the P3CMA) and Mcd-0210 (the P3CMA outfall) in Table 9 show substantial differences for all three CFC compounds. Although not shown in Table 9, the variability in ranges of CFC concentrations for replicate samples was less than 10 percent. Contamination of CFC-113 was noted in the sample from Mcd-0204, and degradation of CFC-11 was noted in the sample from Mcd-0210. Tracer values noted as contaminated or degraded were not used to model apparent groundwater ages. Contamination can occur from introduction of domestic or industrial waste to the groundwater, or from atmospheric sources. Degradation of CFC-11 is ascribed to either microbial degradation in samples containing less than 1 mg/L dissolved oxygen or mixing of aerobic and anaerobic waters in the borehole at the time of sampling (Burton and others, 2002). Variations in CFC concentrations also result from microbial degradation under anoxic or methanogenic conditions. CFC-11 is particularly susceptible to degradation in aquifers of the Appalachian Plateaus, where reducing environments are common.

Table 9. Chlorofluorocarbon data for water samples collected from the Pocahontas No. 3 coal-mine aquifer outfall (Mcd-0210) and from a well (Mcd-0204) completed in deeper underlying unmined strata, in the Elkhorn Area, McDowell County, West Virginia.

[pg/kg, picograms per kilogram; contam, contaminated; degr, degraded; %, percent; nd, not determined. CFC-11 (trichlorofluormethane, $CFCl_3$); CFC-12 (dichlorodifluoromethane, CF_2Cl_2); CFC-113, (trichlorotrifluoroethane, $C_2F_3Cl_3$)]

Station Number	Station Name	Sampling Date	Concentration in Solution			CFC-11 Age (years)	CFC-12 Age (years)	CFC-113 Age (years)	CFC-12/113 Age (years)	% young in Mix from CFC-113	Estimated date of recharge	Estimated age of water (years)
			CFC-11 (pg/kg)	CFC-12 (pg/kg)	CFC-113 (pg/kg)							
372322081241501	Mcd-0204	07-20-10	32.0	24.0	14.9	49.8	49.6	contam	nd	nd	1961	49.6
372313081234101	Mcd-0210	07-20-10	204.7	211.0	40.5	degr	27.8	26.8	26.2	94.6	1985	26.2

Groundwater ages calculated for Mcd-0204 and Mcd-0210 were 49.6 yrs and 26.2 yrs, respectively (Table 9). The sample from Mcd-0210 was analyzed as a binary mixture, of which, 95% is considered a maximum of 26.2 yrs old. The presence of methane in the sample from Mcd-0204 suggests that model results for that well should be considered as a maximum age; CFCs typically degrade in the presence of methane.

Interpreting mixtures in methanogenic environments is difficult because CFC-11 and CFC-113 are typically completely degraded, whereas CFC-12 is only partially degraded (Happell and others, 2003; Böhlke and Krantz, 2003). In these reducing environments where CFCs are degraded primarily by dechlorination reactions that produce hydrochlorofluorocarbons (HCFCs), the CFC method produces apparent ages that are older than the actual age of the water sample. Measurement of other environmental tracers is often helpful to support CFC age interpretations in methanogenic environments.

Deuterium/Oxygen 18

Water samples were analyzed for the stable isotopes deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$) (Table 8, Figure 36). The initial sample collection in July, 2010 included an outfall from the P3CMA (Mcd-0210), a well tapping deeper unmined strata (Mcd-0204), and precipitation at the USGS gaging station (03212640) on Johns Knob Branch. Only the mine outfall (Mcd-0210) was resampled on March 3, 2011. Isotope samples were analyzed by the USGS Stable Isotope Lab in Reston, Virginia. The conventional standard for reporting $\delta^{18}O$ and δ^2H values is as delta (δ) or per million (‰) enrichment or depletion of isotopic composition relative to the Vienna Standard Mean Ocean Water (VSMOW) reference standard. Results are typically shown with regards to Craig's (1961) Global Meteoric Water Line (GMWL) ($\delta^2H = 8\ \delta^{18}O + 10$). The samples from Elkhorn were used to qualitatively assess the timing and potential sources of recharge to the Pocahontas No. 3 coal-mine outfall (Mcd-0210).

A range of monthly precipitation values at Mcd-0210 were estimated using the Online Isotopes in Precipitation Calculator (OIPC) (Bowen, 2011; Bowen and others, 2005). The estimated values are based on a global dataset and require only latitude, longitude, and elevation data inputs to the OIPC (www.waterisotopes.org, accessed May 12, 2011). Estimated precipitation values from the OIPC were validated by the measured isotopic composition of precipitation at the Johns Knob Branch gage (Figure 36). The estimated precipitation values show a local meteoric water line (LMWL) expressed by the equation $\delta^2H = 7.24\ \delta^{18}O + 6.13$ (Figure 36).

Pronounced seasonal differences in estimated stable isotope composition of precipitation at Elkhorn are prescribed to fractionation of stable isotopes by Rayleigh distillation and annual temperature fluctuations (Kendall and Caldwell, 1998). Precipitation in cooler months becomes progressively depleted (more negative) in $\delta^{18}O$ and δ^2H relative to precipitation falling during warmer months of the year. At a local scale, the seasonal variation in isotopic composition of precipitation can be used to assess the relative components of seasonal precipitation in groundwater samples (Figure 37).

The isotopic composition of groundwater can also be influenced by mixing with waters derived from precipitation at varying elevation and times of the year, or water that may have experienced a certain degree of evaporative enrichment. Precipitation at higher elevations would tend to shift estimated monthly values to the left along the LMWL. Local relief in eastern parts of the study area may exceed 1,000 feet. Using OIPC estimates, the stable isotope composition in precipitation at Mcd-0210 was compared with that of an arbitrary high elevation location near Coaldale in the eastern part of the study area. The comparison resulted in a minimal shift of approximately -0.5 per mil for monthly precipitation composition along the LMWL. Evaporative enrichment result in an evolution of water along a slope of approximately 5 (a dimensionless number) away from GMWL; the slope of the GMWL is approximately 8 (Figure 36).

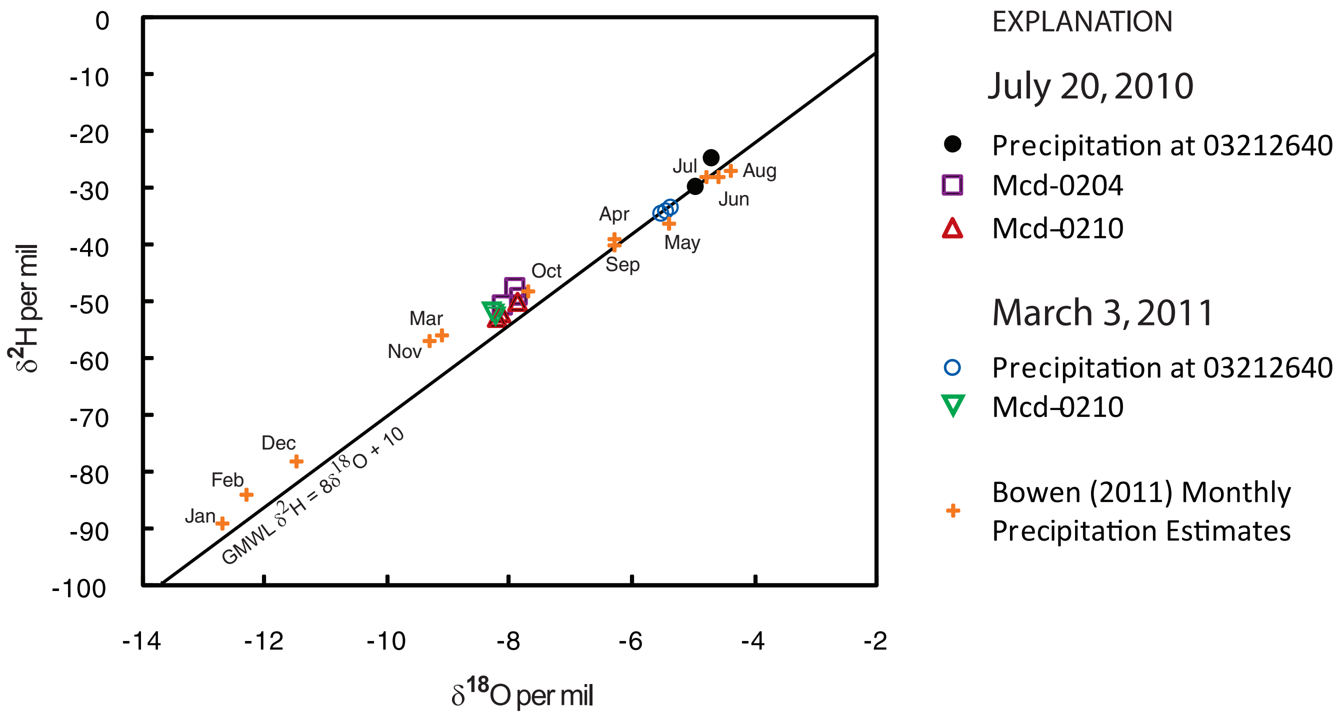


Figure 36. Relation of oxygen-18 ($\delta^{18}O$) and deuterium (δ2H) isotopes for sites sampled in the Elkhorn area, McDowell County, West Virginia.

Values of $\delta^{18}O$ and δ^2H in water samples from the P3CMA outfall (Mcd-0210) and the well tapping deeper unmined strata (Mcd-0204) show a grouping along the LMWL (Figure 36). Mcd-0204 and Mcd-0210 values fall near mid-range between the heaviest isotopic estimates of precipitation in warmer summer months and the lightest isotopic estimates of precipitation in colder winter months. Samples from the mine outfall at Mcd-0204 for July 20, 2010 and March 3, 2011 show no variation. The consistency between the location of the Mcd-0204 and Mcd-0210 samples on the plot in Figure 36 suggests similar sources or timing of recharge to groundwater in the P3CMA (Mcd-0210) and deeper unmined underlying strata (Mcd-0204). Because the groundwater samples in Figure 33 do not deviate from the LMWL, the dominant source of

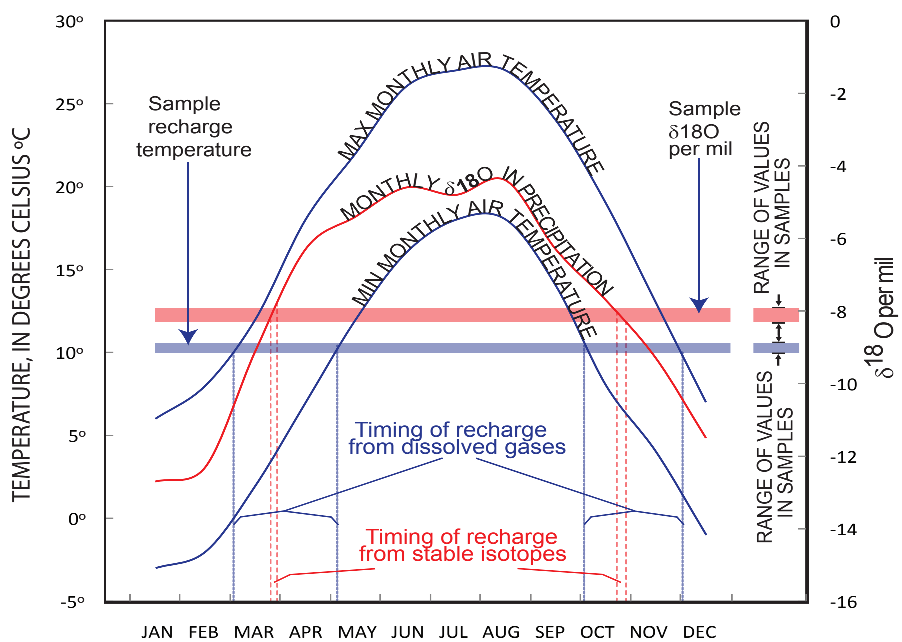


Figure 37. Range of temperature and timing of recharge determined from dissolved gas and stable isotope analyses for sites sampled in the Elkhorn area, McDowell County, West Virginia.

recharge is meteoric water of recent origin. The reason for the slight bias of the isotope samples towards warmer periods is unclear, although the bias may imply that recharge occurs during warmer periods of the Spring or Fall and is potentially coincident with periods of high runoff.

The results of the Mcd-0204 and Mcd-0210 isotopic samples in relation to seasonal precipitation in Figure 33 corroborates recharge temperature estimates that suggest a majority of groundwater recharge probably occurs under moderate climate conditions in the Spring and Fall. Intersecting the range of observed ground-water recharge temperature from dissolved gas analysis (10-10.4ºC) with the curve of minimum and maximum monthly air temperature shows that recharge occurs between March and May or October and November (Figure 37). An overlapping, yet shorter period of recharge during March or October is suggested by intersecting the range of observed $\delta^{18}O$ in groundwater samples (-7.86‰ to -8.29‰) to monthly estimates in precipitation (Bowen, 2011). The seasonal recharge pattern suggested by dissolved gas and isotope analysis is supported by seasonal highs in the hydrograph of Johns Knob Branch (Figure 15).

Alternatively, the general absence of variation in isotopic composition of Mcd-0210 between July 2009 and March 2010 could suggest thorough mixing of precipitation either within the abandoned mine, overlying perched aquifers, or along tortuous phreatic pathways associated with stress-relief, bedding-plane, and mining-induced fractures. Seasonal signals could also be masked by a large recharge source area that potentially incorporates flow from structurally up-dip underground mines extending six miles to the east. Additional temporal data are needed to refine interpretations of seasonal variation in isotopic signature of precipitation and groundwater in the study area.

Continuous Measurements of Water Quality

A water-quality monitor was placed in the outfall from the P3CMA approximately 300 yards upstream of the Johns Knob Branch gaging station (03212640). Water temperature, specific conductance, pH, and dissolved oxygen data from the monitor and precipitation and discharge data from the Johns Knob Branch gaging station are shown in Figure 38. Between noon on June 12th, 2010 and 4:00 PM on June 14th, more than four inches of rain fell. Johns Knob Branch showed a significant rise in flow, both as a result of increasing mine-outfall discharge and surface-water runoff. However, turbidity of the water in the mine outfall never increased to a visually detectable level, indicating that surface runoff was not mixing with the shallow precipitation rapidly recharging the mine aquifer through the network of stress-relief fractures. Specific conductance and dissolved oxygen show a rapid response to precipitation, while the temperature data show a somewhat delayed response. These responses indicate that shallow stress-relief fractures quickly convey water to the P3CMA. This corroborates results of the tracer test discussed earlier, that rapid travel times are possible in abandoned mine aquifers. However, chlorofluorocarbon-age dating techniques indicate groundwater ages on the order of 25 years, suggesting that a much older component of groundwater is slowly percolating downward through numerous layers of overburden strata. Thus, groundwater flow in the P3CMA contains both rapid more recent and slower much older flow components.

Summary and Conclusions

This report presents the results of a three-year assessment of the hydrogeology of the Elkhorn area, McDowell County, West Virginia, and includes: (1) revision of the conceptual model of groundwater flow in abandoned above-grade underground coal-mine aquifers; (2) discussion of borehole geophysical logs and water-level data collected during the study; (3) presentation of data from straddle-packer and single-well aquifer tests conducted to determine hydraulic properties of individual fractures

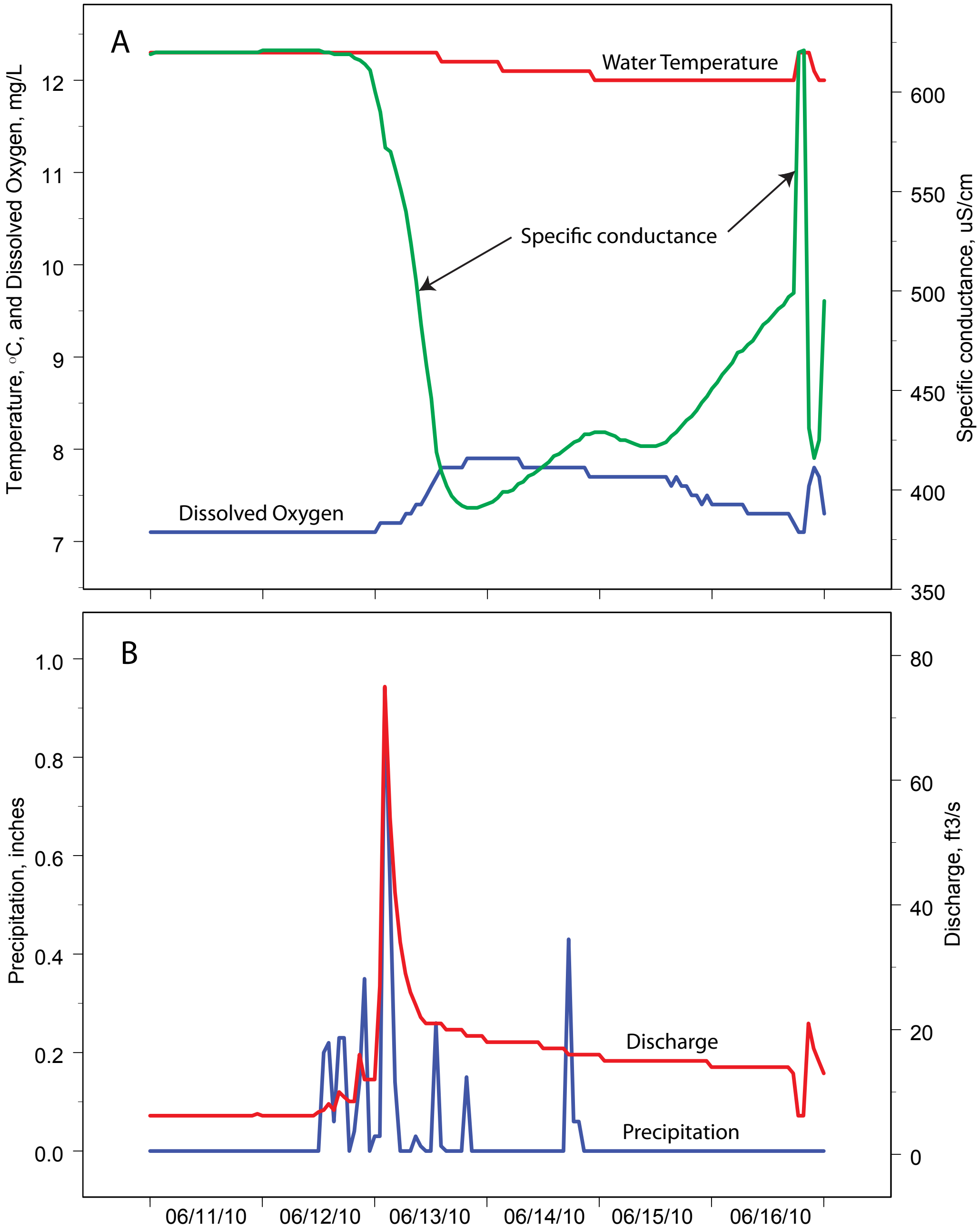


Figure 38. Plot showing relation of temperature, specific conductance, and dissolved oxygen to precipitation and discharge at A) the Pocahontas No. 3 coal-mine aquifer outfall (Mcd-0210) and B) the Johns Knob Branch gaging station, in the Elkhorn area, McDowell County, West Virginia.

and rock types and to estimate bulk hydraulic conductivity for the aquifer; (4) assessment of the yield and long-term availability of water from existing mine outfalls; and (5) analysis of the water-quality and geochemistry of the abandoned mine aquifer.

Previous conceptual models by Wyrick and Borchers (1981) and Sheets and Kozar (2000) were revised based on the results of this investigation. The revised conceptual model is comprised of three basic components; 1) a thin veneer of near vertical fractures draping the topography as a result of stress relief due to isostatic rebound, accompanied by increased permeability due to arching of strata causing separation of bedding planes in valleys; 2) a ridge-core flow system comprised of very low permeability sequences of sandstone and shale interspersed with coal seams, which are stacked in a vertically layered sequence forming perched aquifers under natural conditions; and 3) alteration of the ridge-core flow system due to extensive underground mining forming extensive coal-mine aquifers over a broad region. Subsidence from mining results in fracturing of overburden strata allowing water from overlying strata, especially the more permeable coal seams, to drain downward to the Pocahontas No. 3 coal-mine aquifer (P3CMA). Groundwater flow to springs or mine outfalls from above-drainage mines is primarily dip-controlled rather than topographically controlled. Abandoned underground mines along dip of the coal form a vast network of hydrologically interconnected mine entries that can extend far beyond surface drainage boundaries, resulting in interbasin transfer of water from adjacent watersheds.

Geologic mapping and analysis of borehole logs from wells completed in the study area allowed development of a structure contour map for the base of the Pocahontas No. 3 coal seam which was used to represent the aquifer within a numerical groundwater-flow model. Results of borehole geophysical logging also provided data from which a stratigraphic column was developed. The borehole geophysical data confirmed the conceptual model hypothesis that intervals of bedrock above the P3CMA were more or less devoid of water. Petrographic analysis of thin sections from rock samples collected in the study area confirmed that the rocks have very little primary permeability, thus secondary permeability in joints, bedding planes, coal cleats, and vertical fractures resulting from mine subsidence and stress relief provide the majority of groundwater storage and are preferential routes for flow of groundwater. Petrographic analysis also revealed that rocks in the study area contain a high proportion of quartz (as high as 61%) and siderite (as high as 14%), an iron carbonate mineral. This likely explains the exceptional buffering capacity of water from the P3CMA, and is also likely responsible, in addition to the cool water temperatures maintained by mine discharge, for the prolific trout fishery within the Elkhorn Creek watershed.

Monthly measurements in seven wells installed for the study indicate that water levels stay within or slightly above the top of the P3CMA. This is a result of abandoned mines acting as a broad regional sink for groundwater, with groundwater flowing within or at the base of the P3CMA. Extensive field mapping did not locate any seeps or springs along strip-mine benches above the elevation of the P3CMA, and monthly water level measurements in the seven monitoring wells showed that little water was observed in overlying strata. Only during a period of substantial snow melt and rainfall, was any substantial amount of water observed in overlying strata. As a result, the water levels show very little fluctuation due to changes in recharge, but changes in discharge from the P3CMA may be substantial.

Analyses of streamflow hydrographs indicate an average groundwater recharge rate for the study area of 9.1 in/yr. Base-flow recession indices computed as part of hydrograph analyses indicate that approximately 66% of streamflow in mining areas results from groundwater discharge to streams, discharge from mine outfalls being a substantial proportion of the base flow.

Hydraulic properties for rocks characteristic of the study area were determined from straddle-packer aquifer tests, from reviews of pertinent literature, and by evaluation of aquifer tests conducted for wells in the study area. Results of straddle-packer tests show that individual fractures or bedding planes, have extremely low bulk transmissivity, ranging from nearly impermeable strata (1 x 10-9 ft^2/d or less) to 5.9 x 10-2 ft^2/d, with a median of 1.7 x 10-5 ft^2/d. Literature reviews for studies conducted in similar hydrogeologic settings indicate bulk hydraulic conductivity for coal-mine aquifers ranges from 8.6 x 10-4 ft/d to as high as 4.9 ft/d, with median of 7 x 10-1 ft/d. Specific capacity derived estimates of hydraulic conductivity from aquifer tests indicate hydraulic conductivity of fractures in stress-relief dominated portions of the aquifer to range from 4 to 12 ft/d. These data were used as initial estimates of hydraulic conductivity for the numerical groundwater-flow model developed for the study area.

To further refine the conceptual understanding of groundwater flow, water samples were collected from an outfall from the P3CMA and from a well tapping deeper unmined strata and analyzed for deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$) isotopes and for chlorofluorocarbons (CFCs). A fluorometric dye-tracer test was conducted in a well just up gradient from the mine outfall to assess transit time within the P3CMA. This test was used to estimate average residence time of groundwater within and through the various portions of the P3CMA. The CFC and isotope data provide insight into groundwater-flow processes occurring within the ridge-core flow system and the overlying strata which has been fractured due to subsidence of the mine. Results of the CFC age-dating analyses indicate that the average age of groundwater from the P3CMA is approximately 26 years, and groundwater from deeper unmined strata below the P3CMA is much older at approximately 50 years. The CFC data also indicate a substantial mixing within the P3CMA of a larger proportion of older groundwater with a smaller proportion of relatively young groundwater. The isotope data showed little variability, suggesting thorough mixing of precipitation either within the P3CMA or along tortuous phreatic pathways associated with stress-relief, bedding-plane, and mining-induced subsidence fractures. Seasonal signals from streams are also likely masked by a groundwater recharge source area that incorporates flow from structurally up-dip underground mines extending three miles to the east of surface-water drainage divides. The fluorometric dye-tracer test indicated a transit rate of approximately 4,500 ft/d. This rapid transit rate is near the mine outfall, and the dye was likely injected in a well that taps the vast network of stress-relief fractures draping the surface. Dissolved oxygen, water temperature, and specific conductance data for a monitor placed in the outfall from the P3CMA also indicate a very rapid response to precipitation. Thus, the P3CMA receives water from two primary sources, an older component of slow recharge through the ridge-core flow system and a much younger component derived from near surface stress-relief fractures.

Geochemical data collected from the outfall from the P3CMA and the well tapping deeper underlying unmined strata is limited, but seems to indicate two distinct hydrogeochemical regimes. The first is a highly oxygenated (above local stream grade) regime within the P3CMA, and the second is an anoxic (below local stream grade) regime in the deeper unmined strata. The oxygen content of the water controls the oxidation and reduction processes that occur within the two regimes. The reducing conditions present in the anoxic deeper unmined below grade regime results in significantly higher concentrations of trace metals than are present in water discharging from the highly oxygenated above-grade P3CMA. Metals in the P3CMA (iron and manganese concentrations of <9 and <0.8 µg/L respectively) have either been largely removed by redox processes and flushed from the mine, or are likely present in sediment and mineral deposits, especially oxyhydroxides within the P3CMA. In groundwater from the deeper unmined below-grade strata, concentrations of iron and manganese were very high at 5,620, and 571 µg/L respectively, both exceeding drinking water SMCLs. Groundwater from the above-grade P3CMA is slightly more susceptible to bacterial contamination (1 col/ 100 mL of E. coli and 340 col/100 mL of total coliform) due to increased permeability within the P3CMA and overlying subsided strata, than is water from the deeper unmined below-grade strata (E. coli was not detected and only 6 total coliform col/100 mL). However, the P3CMA is protected to a degree from the major source of bacterial contamination in the study area, untreated domestic sewage discharges to Elkhorn Creek, because it is at a higher elevation than Elkhorn Creek.

A numerical groundwater-flow model of the Elkhorn area was developed to assess the feasibility of the conceptual model and to provide estimates of groundwater availability from the abandoned underground coal-mine aquifer under differing hydrologic conditions. The model was constructed to evaluate the use of regional drainage area versus discharge relations to define source water areas contributing to mine discharges. Three methods were evaluated to model the coal-mine aquifer: (1) a uniform high permeability layer, (2) highly permeable zones within a low permeability bedrock matrix to simulate abandoned mine workings, and (3) an internal head-dependent boundary using drains to simulate abandoned mine workings. Only the boundary condition method using drains to simulate mine entries effectively simulated interbasin transfer of groundwater, by allowing groundwater to be controlled by the dip of the mine rather than surface topography. The model was calibrated to a series of base-flow measurements made at various mine outfalls and in receiving tributary streams draining the study area. Aquifer properties were optimized using the parameter estimation code PEST. Sensitivity analyses conducted on the numerical model showed that 1) recharge, 2) the horizontal hydraulic conductivity of a) the simulated abandoned mine workings in layer 2 of the model and b) stress-relief fractures in layers 2 and 3 of the model, and 3) both the horizontal and vertical hydraulic conductivity of the Pennsylvanian-age bedrock hydrogeologic unit in layers 3 and 4 of the model, were most sensitive and most important to model calibration. The conductance of drains simulating streams and abandoned mine workings within the model were insensitive to variation and therefore were manually calibrated and were not adjusted during the parameter estimation process. Also, results of parameter estimation indicate that vertical hydraulic conductivity is likely much lower than previously believed, and the ratio of vertical to horizontal hydraulic conductivity may be as low as 1:1,000 for underclay beneath the Pocahontas No. 3 coal seam, 1:10 for fractured overburden above abandoned underground mine workings, and approximately 1:1 for deeper undisturbed strata indicative of regional bedrock aquifers.

Results of the groundwater-flow model confirm the validity of using regional discharge versus drainage area relations to define source areas to above-drainage mine discharges. For the 38th, 70th, and 87th percentile flow duration of streams in the region, mean measured groundwater discharge was estimated to be 1.30, 0.47, and 0.39 $ft^3/s/mi^2$, respectively, and median measured groundwater discharge was estimated to be 1.49, 0.46, and 0.37 $ft^3/s/mi^2$, respectively. These values can be multiplied by the area that contributes recharge to groundwater to compute volumetric flow rates.

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APPENDIX 1:

Water Level Data

Figure 1. Water-level data from 7 wells completed in the bedrock aquifers in the Elkhorn area, West Virginia (LSD, land surface datum; NAD 83, North American Datum of 1983; ft, feet; NAVD 88, North American Vertical Datum of 1988)

Local well number	Latitude (NAD 83 degrees, minutes, seconds)	Longitude (NAD 83 degrees, minutes, seconds)	Water-level measurement date	Water-level (ft below LSD)	Height of measuring point (ft above land surface)	Altitude of measuring point (ft above NAVD 88)	Altitude of land surface (ft above NAVD 88)	Elevation of water level (ft above NAVD 88)
Mcd-0203	37 23 08.2	81 23 44.7	20090823	23.22	0.00	2,063.29	2,063.29	2040.07
			20100820	12.93				2050.36
			20100923	16.93				2046.36
Mcd-0207	37 23 23.0	81 23 20.5	20090823	129.20	2.20	2,201.64	2,199.44	2070.24
			20090922	129.62				2069.82
			20091020	129.52				2069.92
			20091119	129.08				2070.36
			20091217	129.07				2070.37
			20100119	129.12				2070.32
			20100212	129.11				2070.33
			20100316	129.12				2070.32
			20100419	129.70				2069.74
			20100517	129.60				2069.84
			20100615	129.00				2070.44
			20100719	129.98				2069.46
			20100820	130.50				2068.94
			20100923	na				na
Mcd-0206	37 23 14.2	81 23 20.0	20090820	375.70	2.90	2,456.53	2,453.63	2077.93
			20090922	375.76				2077.87
			20091020	375.90				2077.73
			20091119	375.89				2077.74
			20091217	375.52				2078.11
			20100119	374.72				2078.91
			20100212	375.01				2078.62
			20100316	368.80				2084.83
			20100419	378.17				2075.46
			20100517	375.30				2078.33
			20100615	345.40				2108.23
			20100719	375.58				2078.05
			20100820	375.87				2077.76
			20100923	376.10				2077.53
Mcd-0205	37 24 24.6	81 24 12.8	20090823	167.37	1.95	2,216.19	2,214.24	2046.87
			20090922	167.94				2046.30
			20091020	168.07				2046.17
			20091119	167.86				2046.38
			20091217	167.21				2047.03
			20100119	159.35				2054.89
			20100212	166.47				2047.77
			20100316	166.29				2047.95
			20100419	166.96				2047.28
			20100517	166.92				2047.32
			20100615	166.45				2047.79
			20100719	167.40				2046.84
			20100820	na				na
			20100923	na				na
Mcd-0204	37 23 22.2	81 24 14.7	20090821	17.88	2.60	2,043.73	2,041.13	2023.25
			20090823	17.88				2023.25
			20090922	18.74				2022.39
			20091020	19.20				2021.93
			20091119	19.39				2021.74
			20091217	19.01				2022.12
			20100119	18.70				2022.43
			20100212	18.34				2022.79
			20100316	18.14				2022.99
			20100419	19.08				2022.05
			20100517	19.29				2021.84
			20100615	17.70				2023.43
			20100719	18.01				2023.12
			20100820	19.22				2021.91
			20100923	20.10				2021.03
Mcd-0208	37 23 38.3	81 24 48.9	20090821	491.80	2.05	2,498.67	2,496.62	2004.82
			20090922	492.37				2004.25
			20091020	492.60				2004.02
			20091119	492.74				2003.88
			20091217	492.57				2004.05
			20100119	491.63				2004.99
			20100316	489.69				2006.93
			20100419	491.24				2005.38
			20100517	491.46				2005.16
			20100615	489.85				2006.77
			20100719	491.51				2005.11
			20100820	492.19				2004.43
			20100923	492.83				2003.79
Mcd-0209	37 23 40.4	81 23 43.2	20090822	481.00	1.70	2,547.49	2,545.79	2064.79
			20090922	482.20				2063.59
			20091020	482.40				2063.39
			20091119	481.56				2064.23
			20091217	481.20				2064.59
			20100119	480.92				2064.87
			20100212	480.80				2064.99
			20100316	480.57				2065.22
			20100419	480.71				2065.08
			20100517	480.90				2064.89
			20100615	480.50				2065.29
			20100719	481.10				2064.69
			20100820	482.01				2063.78
			20100923	483.61				2062.18

*na indicates that the water level could not be measured due to well being dry, or water level at a depth that could not be determined.

APPENDIX 2:

Borehole-Geophysical Logs

Figure 1. Borehole-Geophysical Logs for Borehole Mcd-0203, collected on August 16, 2009, Elkhorn, WV

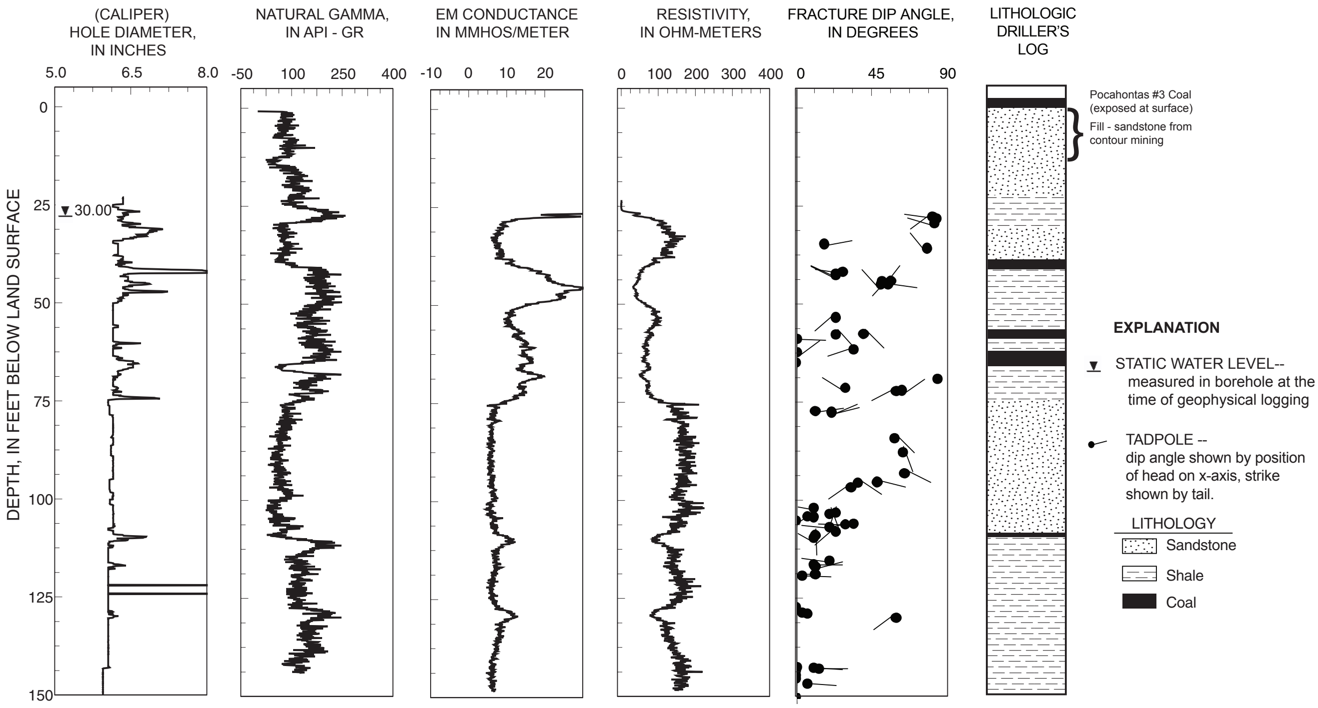


Figure 2. Borehole-Geophysical Logs for Borehole Mcd-0204, collected on August 21, 2009, Elkhorn, WV

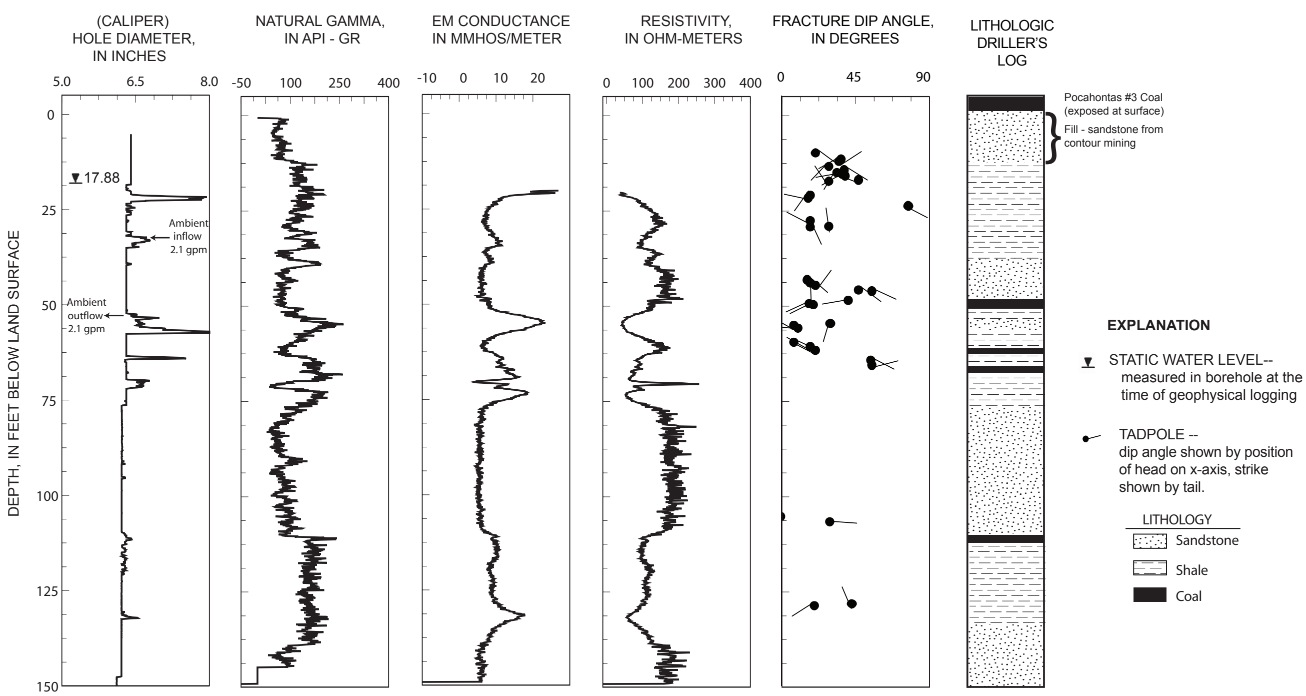


Figure 3. Borehole-Geophysical Logs for Borehole Mcd-0205, collected on August 23, 2009, Elkhorn, WV

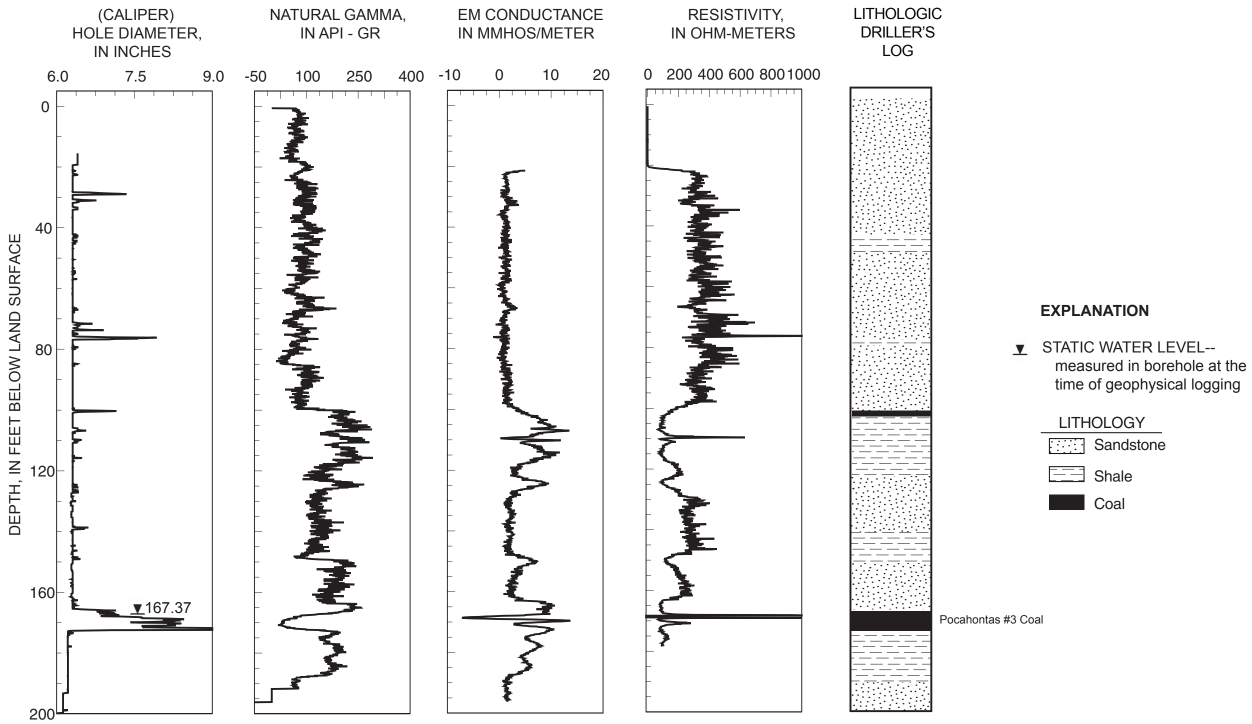


Figure 4. Borehole-Geophysical Logs for Borehole Mcd-0206, collected on August 20, 2009, Elkhorn, WV

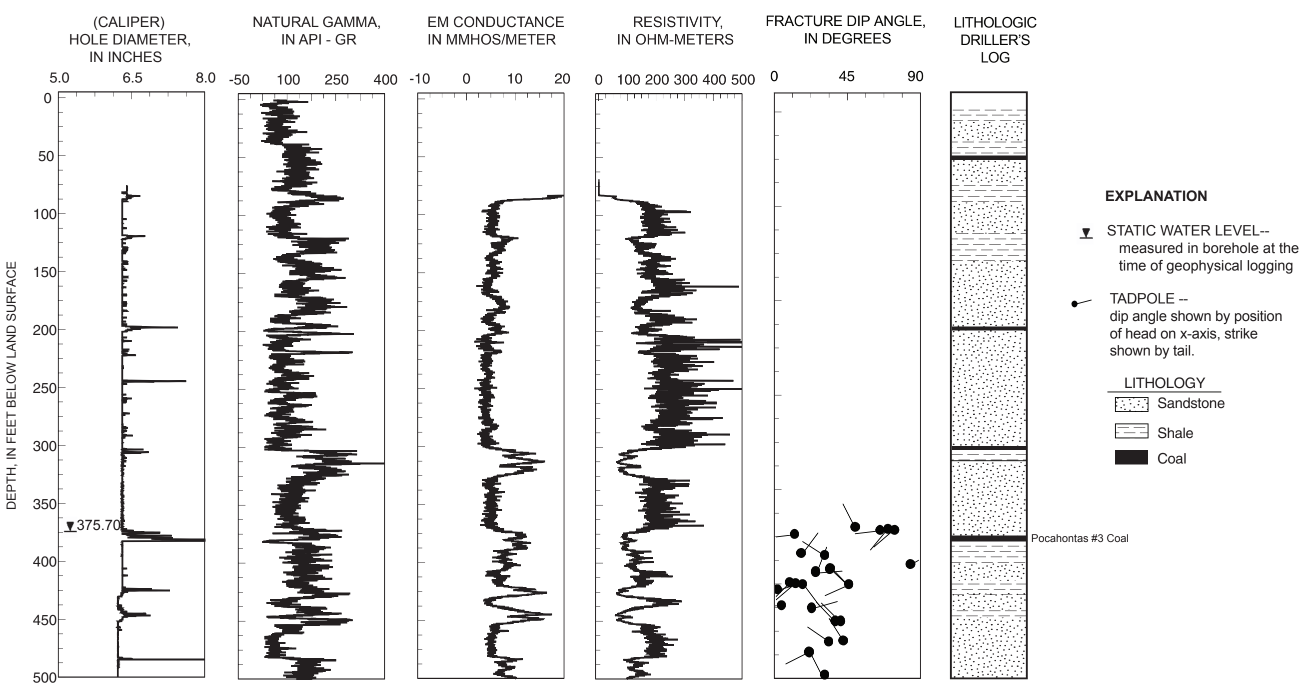


Figure 5. Borehole-Geophysical Logs for Borehole Mcd-0207, collected on August 19, 2009, Elkhorn, WV

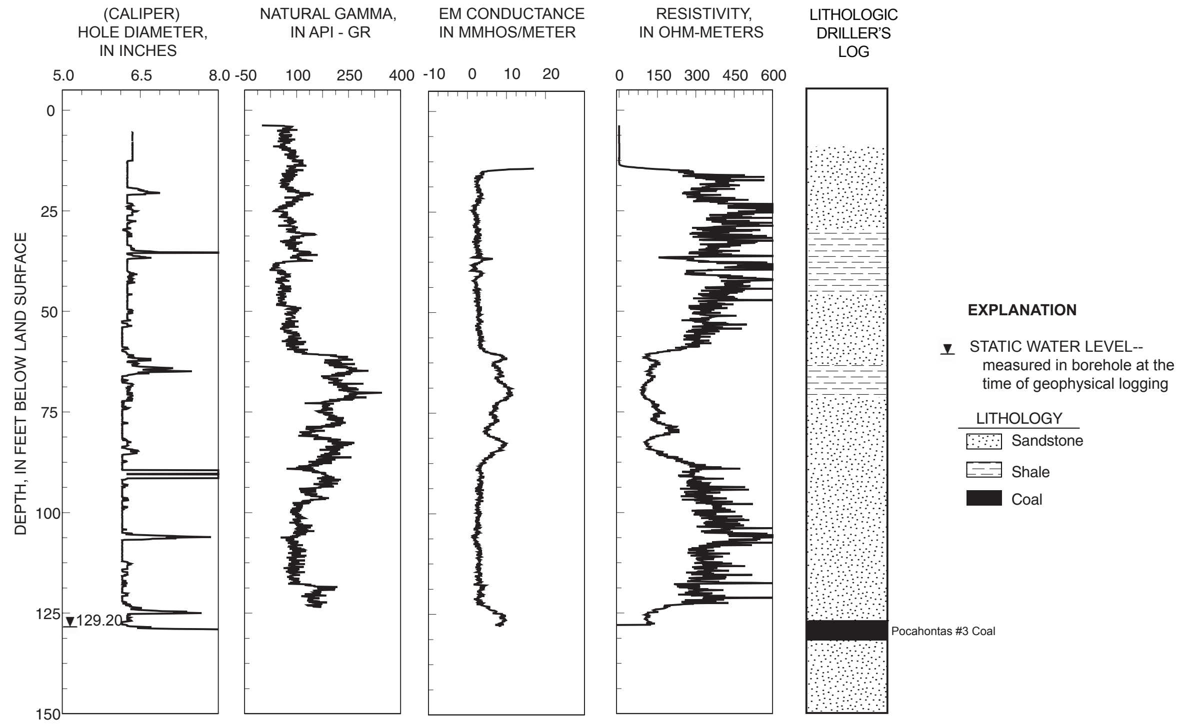
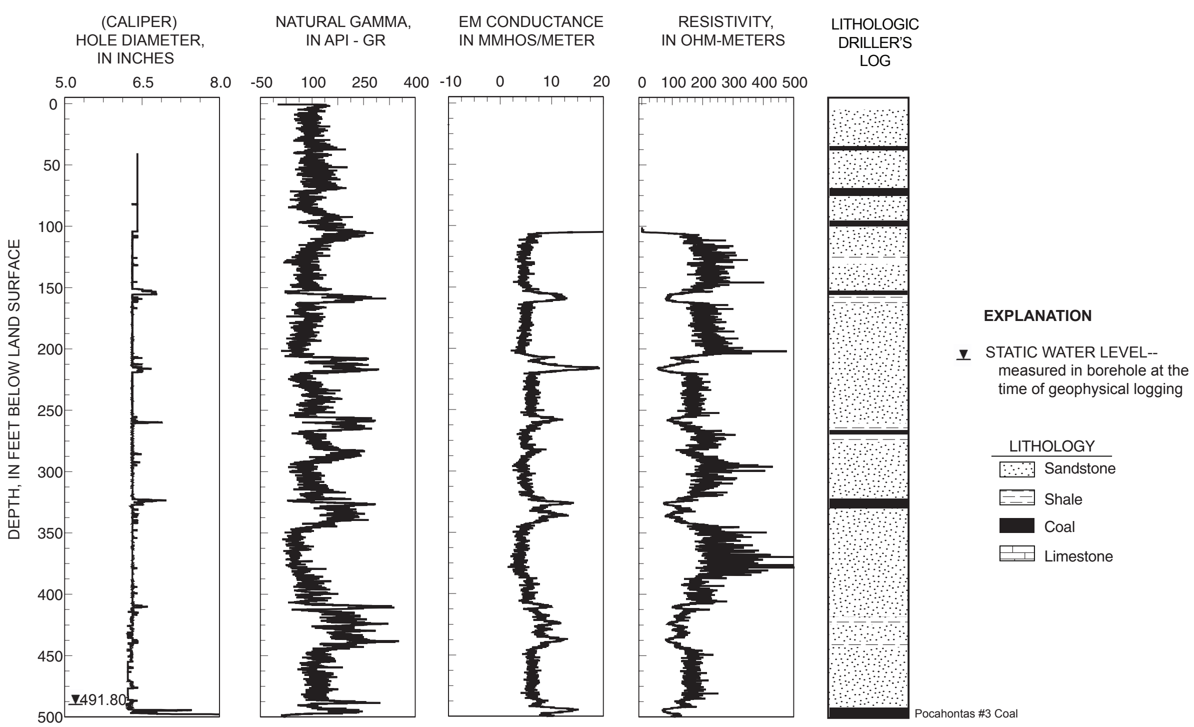
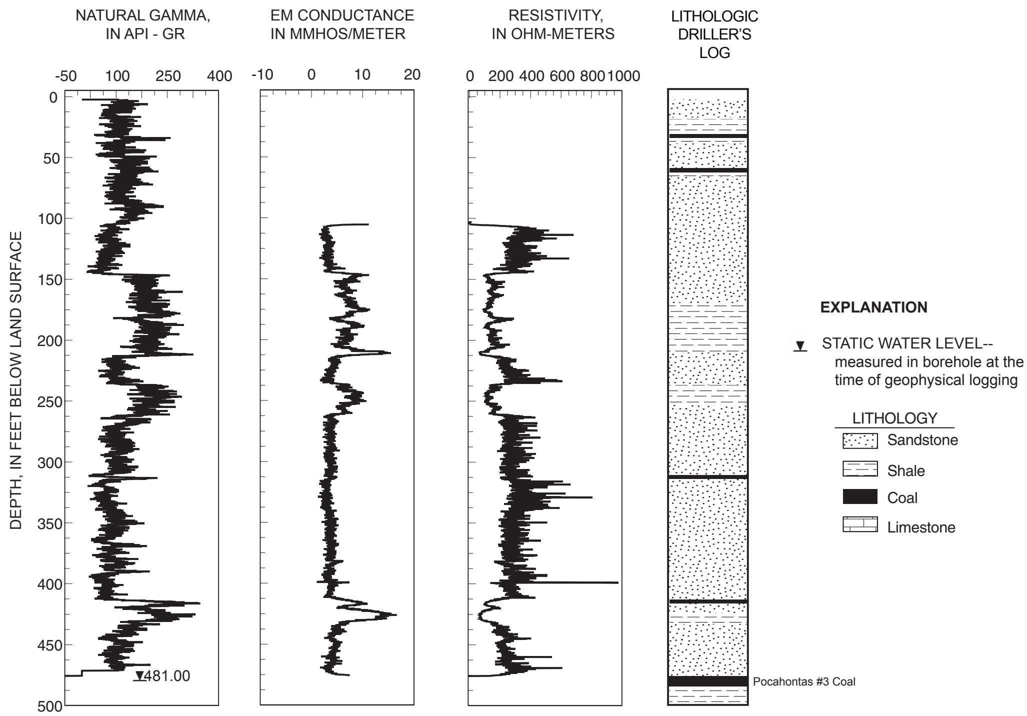


Figure 6. Borehole-Geophysical Logs for Borehole Mcd-0208, collected on August 21, 2009, Elkhorn, WV



Appendix 2 Figure 6. Borehole-geophysical logs for borehole Mcd-0208, collected on August 21, 2009, Elkhorn, West Virginia.

Figure 7. Borehole-Geophysical Logs for Borehole Mcd-0209, collected on August 22, 2009, Elkhorn, WV



APPENDIX 3:

Base-flow Measurements of Streamflow

Appendix 3. Base-flow Measurements of Streamflow

Map ID Number	Site Name	Latitude (degree-minutes-seconds)	Longitude (degree-minutes-seconds)	Discharge in ft^3/s @ low flow	Date discharge measured	Discharge in ft^3/s @ medium flow	Date discharge measured	Discharge in ft^3/s @ high flow	Date discharge measured
1	Headwaters of Elkhorn Creek (Mine Q from south)	37° 22' 02.1"	81° 20' 34.2"		9/8/10	1.17	10/22/09	2.13	4/28/09
2	Trib to Elkhorn Creek from South nr County Line	37° 22' 01.7"	81° 20' 49.5"	0.222	9/8/10	0.349	10/22/09		
3	Large mine Q from south to Elkhorn Creek	37° 22' 12.4"	81° 21' 09.3"	0.361	9/8/10	0.680	10/22/09		
4	Trib to Elkhorn Creek from north	37° 22' 23.1"	81° 21' 12.2"	0.160	9/8/10	0.487	10/22/09		
5	Trib to Elkhorn Creek @ Maybeury Post Office	37° 22' 08.3"	81° 22' 05.4"	1.74	9/8/10	2.78	10/22/09		
6	Elkhorn Creek just below MayBeury Post Office	37° 22' 09.2"	81° 22' 06.8"	5.55	9/8/10	7.84	10/22/09		
7	Trib to Elkhorn Creek from south @ Maybeury	37° 22' 12.0"	81° 22' 27.7"	0.016	9/8/10	0.055	10/22/09		
8	Trib to Elkhorn Creek from south @ Switchback	37° 22' 10.4"	81° 22' 54.6"		9/8/10	0.038	10/22/09		
9	Elkhorn Creek above Turkey Run Branch	37° 22' 17.6"	81° 23' 00.0"	5.05	9/8/10	8.67	10/20/09		
10	Turkey Run Branch @ mouth	37° 22' 17.0"	81° 22' 58.7"	0.037	9/8/10	0.080	10/20/09	0.169	4/28/09
11	Turkey Run Branch upstream of Elkhorn Creek	37° 22' 25.6"	81° 22' 52.5"	0	9/8/10	0.006	10/20/09	0	4/28/09
12	Trib to Elkhorn Creek from south	37° 22' 15.9"	81° 23' 19.8"	0.093	9/8/10	0.173	10/22/09		
13	Unnamed Trib	37° 22' 16.2"	81° 23' 32.3"	0.121	9/8/10				
14	Elkhorn Creek upstream of Switchback School	37° 22' 22.3"	81° 23' 25.5"	5.66	9/8/10	7.73	10/20/09	23.8	4/28/09
15	Trib above culvert @ Switchback School	37° 22' 32.7"	81° 23' 32.6"	0.003	9/8/10	0.065	10/20/09		
16	Culvert #3 near Elkhorn	37° 22' 39.4'	81° 23' 31.2"	0.030	9/8/10	0.016	10/20/09	0.224	4/28/09
17	Small Culvert to Elkhorn Creek just above mobile home	37° 22' 43.0"	81° 23' 31.7"	0.006	9/8/10		10/20/09		
18	Culvert #2 near Elkhorn	37° 22' 51.9"	81° 23' 37.0"	0.015	9/8/10	0.106	10/20/09	0.878	4/28/09
19	Culvert #1 near Elkhorn	37° 22' 55.9"	81° 23' 39.4"	0.118	9/8/10	0.047	10/20/09	0.236	4/28/09
20	Elkhorn Creek 200' above Johns Knob Branch	37° 23' 03.7"	81° 23' 49.0"	6.62	9/8/10	8.61	10/20/09		
21	Trib to Elkhorn Creek downstream of Johns Knob Branch	37° 23' 05.2"	81° 23' 54.2"	0.015	9/8/10	0.046	10/20/09		
22	John's Knob Branch	37° 23' 06.3"	81° 23' 49.3"	2.82	9/8/10	3.13	10/20/09	6.00	4/28/09
23	Outflow from 2' diameter concrete culvert	37° 23' 08.6"	81° 24' 04.0"	0.18	9/8/10	0.213	10/20/09		
24	Creek @ Russian Orthodox Church	37° 23' 13.2"	81° 24' 20.1"	0.075	9/8/10	0.071	10/20/09	0.211	4/27/09
25	Elkhorn Creek at Elkhorn PSD Water Plant	37° 23' 12.1"	81° 24' 28.3"	8.81	9/8/10	11.5	10/20/09		
26	Flow from 2-inch pipe at Elkhorn PSD Water Plant	37° 23' 12.9"	81° 24' 26.4"	0.137	9/8/10			0.065	4/28/09
27	Small Seep behind Elkhorn Head Start	37° 23' 05.1"	81° 24' 44.5"	0.014	9/8/10	0.024	10/20/09		
28	Elkhorn Creek @ Post Office	37° 23' 07.0"	81° 24' 47.6"	8.98	9/8/10	13.2	10/20/09	33.6	4/28/09
29	Creek upstream of Chruch Hollow Road	37° 23' 09.0"	81° 25' 06.2"	0.408	9/8/10	0.533	10/20/09		
30	Elkhorn Creek at Upland PSD Water Plant	37° 23' 12.5"	81° 25' 07.3"	10.1	9/8/10	12.6	10/20/09		
31	Small seep 50 feet downstream of railroad tracks	37° 23' 13.7"	81° 25' 05.3"	0.005	9/8/10	0.005	10/20/09	0.054	4/28/09
32	McDowell County PSD Upland Plant (flow from northern side of Elkhorn Creek)	37° 23' 17.5"	81° 25' 13.0"	0.131	9/8/10		10/20/09	0.351	4/28/09
33	McDowell County PSD Upland Plant (total flow from both sides of Elkhorn Creek)	37° 23' 17.5"	81° 25' 12.3"					0.728	4/28/09
34	Trib by Upland Baptist Church	37° 23' 20.3"	81° 25' 19.2"	0.372	9/8/10	0.61	10/20/09		
35	Small tributaries	37° 23' 24.7"	81° 25' 12.7"			0.176	10/20/09		
36	Unnamed tributary	37° 23' 24.9"	81° 25' 06.9"					0.044	4/27/09
37	Ditch upstream of railroad tracks	37° 23' 25.8"	81° 25' 13.8"	<.05		0.091	10/20/09	0.231	4/27/09
38	Culvert from Railroad tracks on right side @ Elkhorn	37° 23' 29.4"	81° 25' 15.3"	0.051	9/8/10	0.067	10/20/09		

Appendix 3. Base-flow Measurements of Streamflow (continued)

Map ID Number	Site Name	Latitude (degree-minutes-seconds)	Longitude (degree-minutes-seconds)	Discharge in ft^3/s @ low flow	Date discharge measured	Discharge in ft^3/s @ medium flow	Date discharge measured	Discharge in ft^3/s @ high flow	Date discharge measured
39	Culvert discharge from 2 directions	37° 23' 32.6"	81° 25' 14.1"					0.138	4/27/09
40	Small Creek on north side of railroad tracks	37° 23' 38.9"	81° 25' 16.5"	0.038	9/8/10	0.057	10/20/09	0.114	4/27/09
41	Small creek north side of railroad tracks	37° 23' 40.5"	81° 25' 17.3"	0.055	9/8/10	0.026	10/20/09		
42	Elkhorn Mainstem	37° 23' 41.3"	81° 25' 20.0"	9.97	9/8/10	15	10/20/09		
43	Small trib south of US higway 52	37° 23' 42.2"	81° 25' 20.9"	0	9/8/10	0.017	10/20/09		
44	Culvert	37° 23' 45.6"	81° 25' 16.2"					0	4/27/09
45	Outflow from 2.5 foot diameter concrete culvert	37° 23' 54.9"	81° 25' 14.4"	0.009	9/8/10	0.025	10/20/09	0.042	4/27/09
46	Seep 10 feet upstream of entrance to concrete culvert	37° 23' 59.1"	81° 25' 10.0"	0.021	9/8/10	0.027	10/20/09		
47	Elkhorn Mainstem	37° 24' 00.6"	81° 25' 10.7"	10.04	9/8/10	15	10/20/09		
48	Mine seeps	37° 24' 04.6"	81° 24' 58.3"					0.511	4/27/09
49	Culvert on right bank of Elkhorn Creek	37° 24' 08.1"	81° 25' 06.2"	0.13	9/8/10	0.189	10/20/09		
50	Elkhorn Creek @ White Church	37° 24' 15.9'	81° 25' 12.1'	11.2	9/8/10	15.5	10/20/09		
51	Mouth of creek on right bank	37° 24' 18.1"	81° 25' 14.1"	0.291	9/8/10	0.429	10/20/09	1.52	4/28/09
52	Mine discharge from #3 strip bench (B)	37° 24' 29.9"	81° 24' 59.2"	0.166	9/9/10				
53	Mine discharge from #3 strip bench (A)	37° 24' 30.7"	81° 24' 57.1"	0.098	9/9/10				
54	Culvert Q from south @ Bell Street near Kyle Post Office	37° 24' 25.8"	81° 25' 33.5"	0	9/9/10	0	10/20/09		
55	Elkhorn Creek @ old railroad abutment	37° 24' 34.2"	81° 25' 31.4"	11.8	9/8/10	16.1	10/20/09		
56	Elkhorn Creek 300 feet above mouth	37° 24' 53.6"	81° 25' 45.7"	13.5	9/8/10	16.5	10/20/09	44	4/28/09
57	North Fork 300 feet above mouth	37° 24' 55.2"	81° 25' 47.2"	6.52	9/9/10	9.07	10/21/09	28.8	4/27/09
58	Tributary from right	37° 25' 14.0"	81° 25' 30.4"	2.95	9/9/10	3.14	10/21/09		
59	Tributary at bridge	37° 25' 12.3"	81° 25' 26.9'	0.064	9/9/10	0.04	10/21/09	0.333	4/27/09
60	Tributary at small bridge	37° 25' 10.9"	81° 25' 17.5'	0.021	9/9/10				
61	Mine seep	37° 25' 09.6"	81° 25' 04.3"					0.05	4/27/09
62	Water fall from rock outcrop	37° 25' 12.2"	81° 25' 03.7"	0.012	9/9/10	0.018	10/21/09		
63	Mine seep	37° 25' 11.9"	81° 25' 03.7"					0.093	4/27/09
64	Cilvert at west rock outcrop	37° 25' 18.8"	81° 25' 00.6"	0	9/9/10	0.012	10/21/09		
65	Trib 150 feet downstream of bridge on gravel road	37° 25' 28.5"	81° 24' 56.2"	3.12	9/9/10	5.89	10/21/09		
66	Small seep on left bank	37° 25' 08.8"	81° 24' 28.7"	0	9/9/10	0	10/21/09	0.005	4/27/09
67	Small seep 10 feet upstream of corrugated culvert	37° 25' 05.6"	81° 24' 19.1"		9/9/10	0.005	10/21/09		
68	Northfork Mainstem	37° 25' 06.9"	81° 24' 14.8"	3.24		5.94	10/21/09		
69	Small trib to North Fork	37° 24' 56.1"	81° 23' 26.1"	0.591		0.836	10/21/09		
70	Culvert inflow to North Fork from north	37° 24' 49.3"	81° 23' 22.6"	0	9/9/10	0.002	10/21/09	0.009	4/27/09
71	Small seep on right bank	37° 24' 48.4"	81° 23' 20.2"	0	9/9/10			0	4/27/09
72	Small seep on right bank	37° 24' 48.1"	81° 23' 20.1"			0	10/21/09		
73	Unnamed seep	37° 24' 43.6"	81° 23' 14.6"	0.048	9/9/10				
74	Inlet to 4 foot diameter corrugated culvert	37° 24' 25.1"	81° 22' 58.3"	0.075	9/9/10				
75	Mainstem Elkhorn Creek below trib from south	37° 24' 23.4"	81° 23' 01.7"	2.22		4.5	10/21/09		
76	Small creek	37° 24' 22.7"	81° 23' 00.9"			0.131	10/21/09		
77	Concrete drainage ditch coming off strip mine	37° 24' 21.2"	81° 22' 55.8"		9/9/10	0.009	10/21/09		

Appendix 3. Base-flow Measurements of Streamflow (continued)

Map ID Number	Site Name	Latitude (degree-minutes-seconds)	Longitude (degree-minutes-seconds)	Discharge in ft^3/s @ low flow	Date discharge measured	Discharge in ft^3/s @ medium flow	Date discharge measured	Discharge in ft^3/s @ high flow	Date discharge measured
78	Culvert under highway up hill on south side of North Fork	37° 24' 16.1'	81° 22' 52.1'	0.055	9/9/10	0.205	10/21/09		
79	Culvert From south side of North Fork	37° 24' 09.7'	81° 22' 48.2'	0.001	9/9/10	0.038	10/21/09		
80	Trib to North Fork from Grapvine Hollow	37° 24' 06.0'	81° 22' 41.2"	1.17	9/9/10	2.03	10/21/09	7.33	4/27/09
81	North Fork northern tributary	37° 24' 06.6"	81° 22' 40.7"	0.86	9/9/10	2.76		7.19	4/27/09
82	North Fork below Grapevine Hollow tributary	37° 24' 06.0"	81° 22' 42.8"	2.03	9/9/10	4.79	10/21/09	14.52	4/27/09
83	Seep right side of North Fork	37° 23' 48.8"	81° 22' 36.0"	0.388	9/9/10	0.723	10/21/09		
84	Mine seep from right bank	37° 23' 47.2"	81° 22' 33.6"	0.005	9/9/10	0.05	10/21/09		
85	North Fork downstream rom mine seep	37° 23' 44.7"	81° 22' 32.5"	0.503	9/9/10	0.97	10/21/09		
86	Mine seep from bench on left side of North Fork	37° 23' 39.6"	81° 22' 30.0"	0.041	9/9/10	0.053	10/21/09	0.138	4/27/09
87	North Fork Mainstem below culvert Inflow	37° 23' 39.6"	81° 22' 26.3"	0.38	9/9/10	0.83	10/21/09		
88	Culvert outflow	37° 23' 39.3"	81° 22' 23.0"			0.023	10/21/09		
89	Culvert overflow from north side of Northfork	37° 23' 38.9"	81° 22' 22.7"	0.002	9/9/10				
90	Unnamed tributary	37° 23' 38.5"	81° 22' 23.7"					2.9	4/27/09
91	Unnamed tributary	37° 23' 34.6"	81° 22' 04.5"					3.1	4/27/09
92	North Fork Mainstem 20 feet below gasline crossing	37° 23' 34.4"	81° 21' 59.2"	0.29	9/9/10	0.68	10/21/09	0.062	4/27/09
93	North Fork below large mine discharge	37° 23' 35.9"	81° 21' 53.4"	0.308	9/9/10	0.44	10/21/09	2.55	4/27/09
94	Drain from roadside 22 feet downstream of large mine discharge	37° 23' 35.2"	81° 21' 54.0"	0.006	9/9/10	0.007	10/21/09		
95	North Fork above large mine discharge	37° 23' 36.5"	81° 21' 51.7"	0.052	9/9/10	0.173	10/21/09		
96	Seep above North Fork	37° 23' 39.1"	81° 21' 48.8"	0	9/9/10	0.009	10/21/09	0.117	4/27/09

APPENDIX 4:

Dye Tracer Test Data

Figure 1. Fluorometer Readings For Samples Manually Collected At Site OF1.

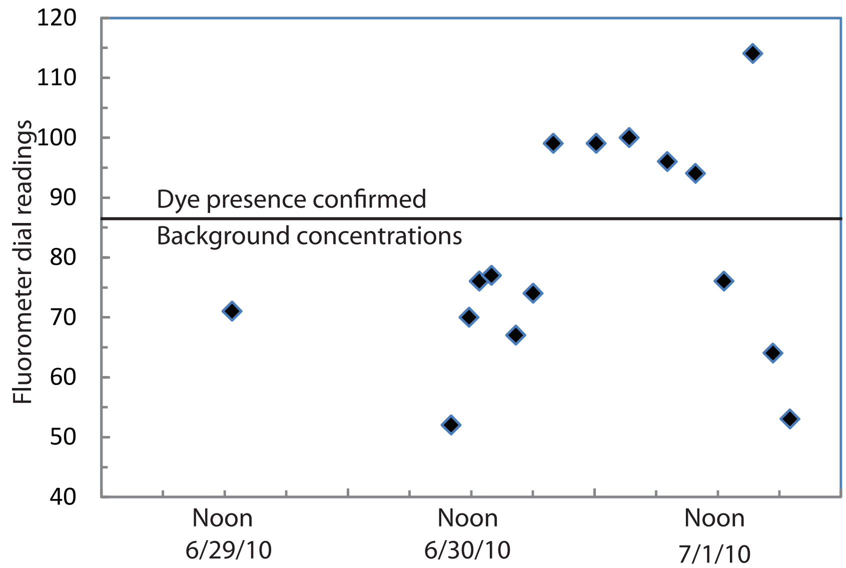


Figure 2. Fluorometer Readings For Samples Manually Collected At Site OF2.

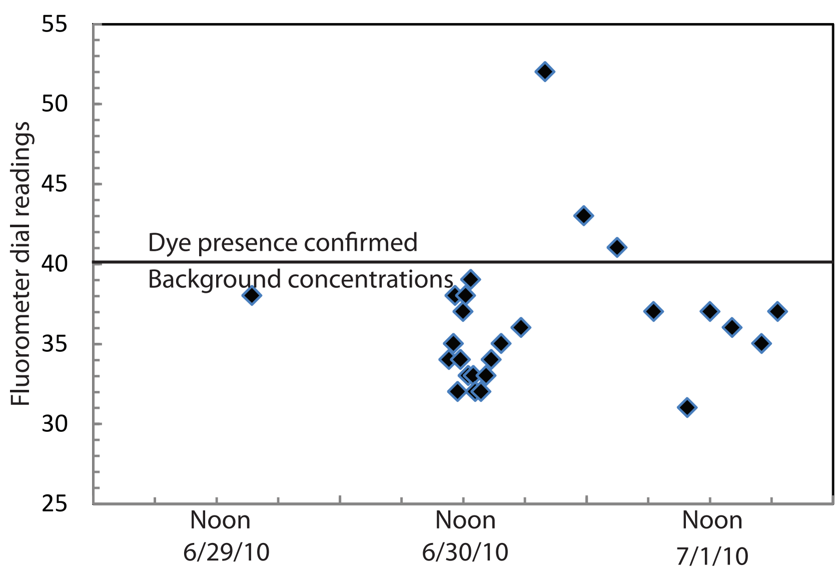


Figure 3. Fluorometer Readings For Samples Manually Collected At Site OF3.

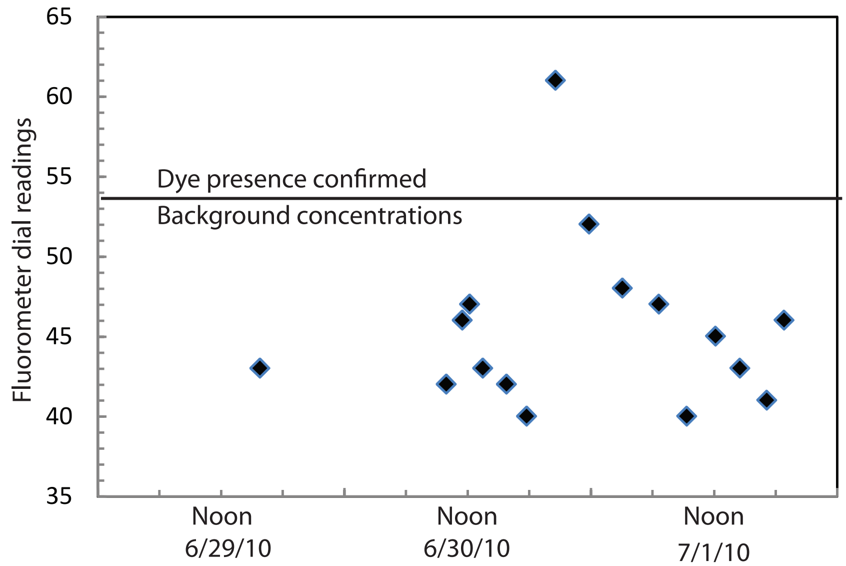
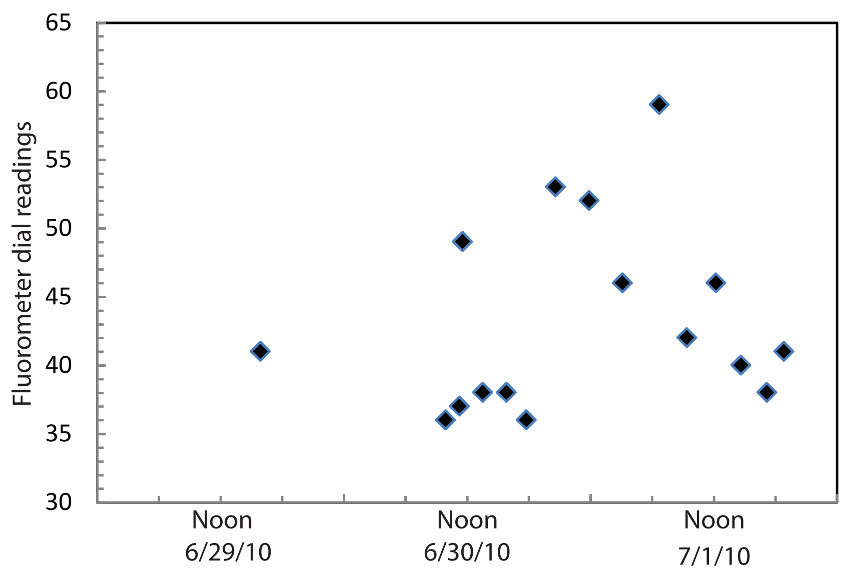
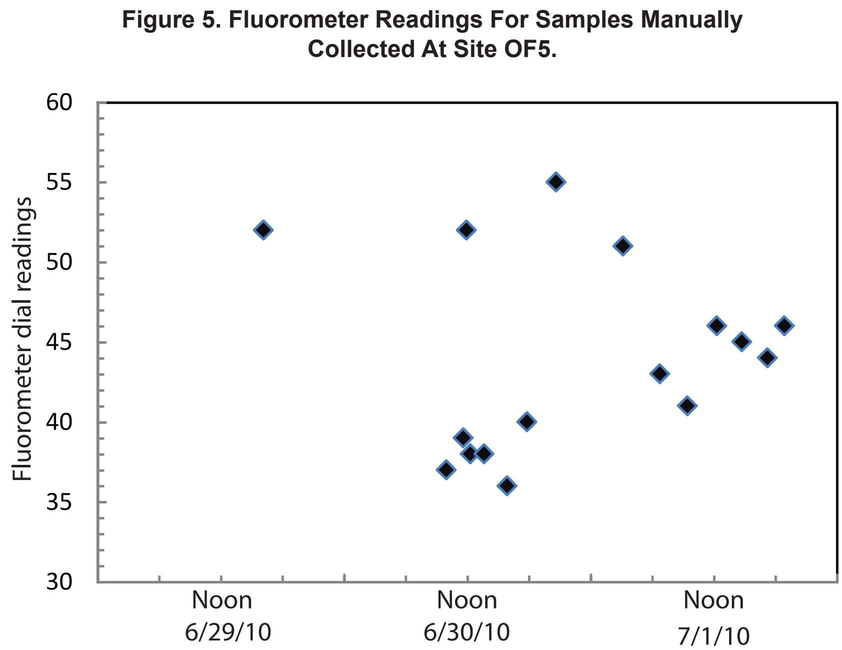
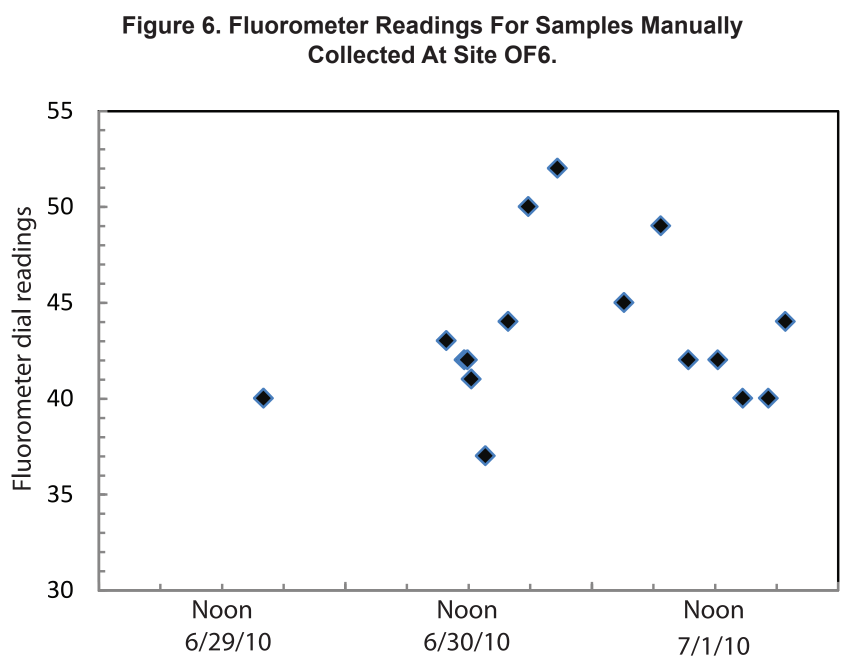


Figure 4. Fluorometer Readings For Samples Manually Collected At Site OF4.

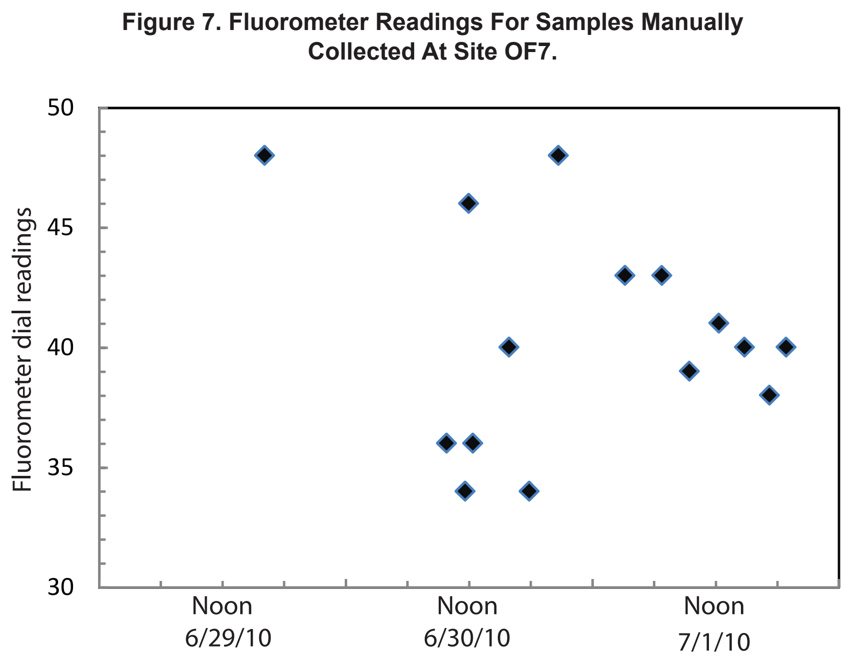




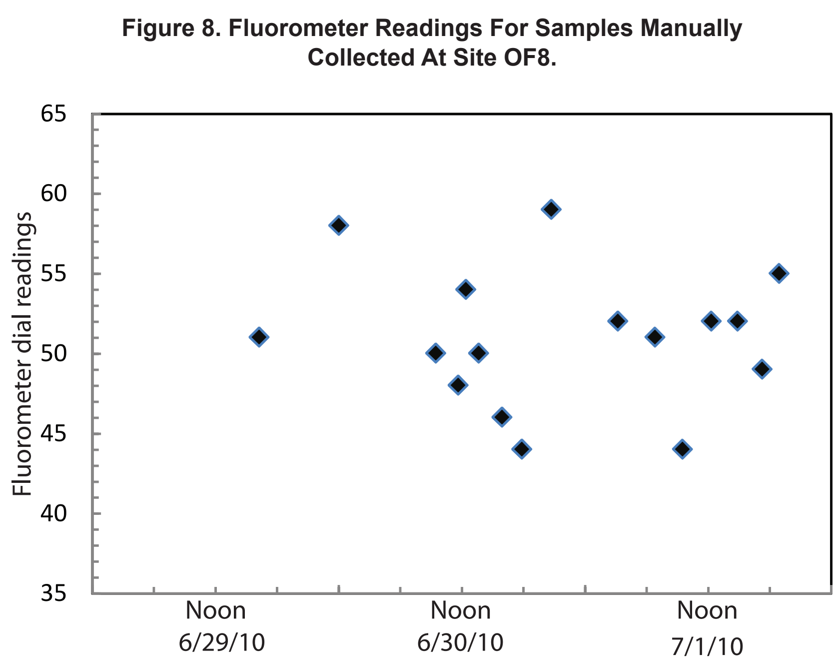
Appendix 4 Figure 5. Fluorometer readings for samples manually collected at site OF5a.



Appendix 4 Figure 6. Fluorometer readings for samples manually collected at site OF5b.

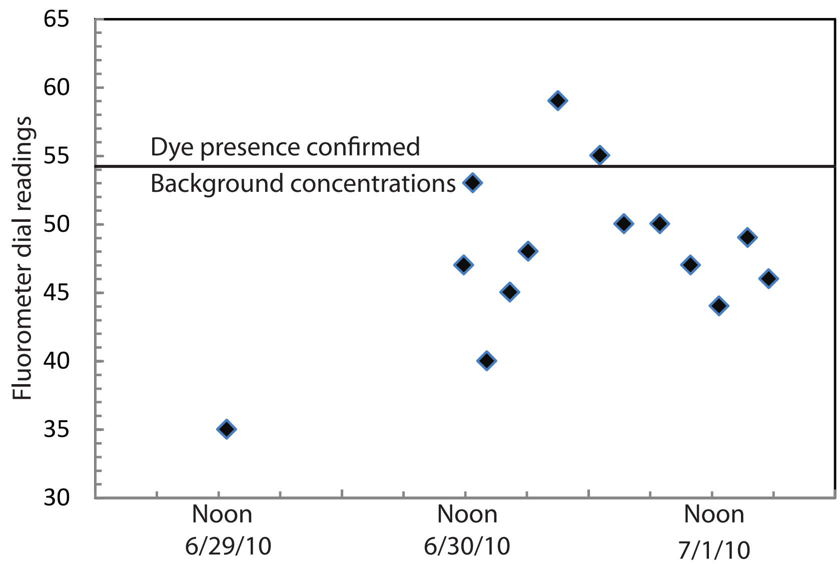


Appendix 4 Figure 7. Fluorometer readings for samples manually collected at site OF6.



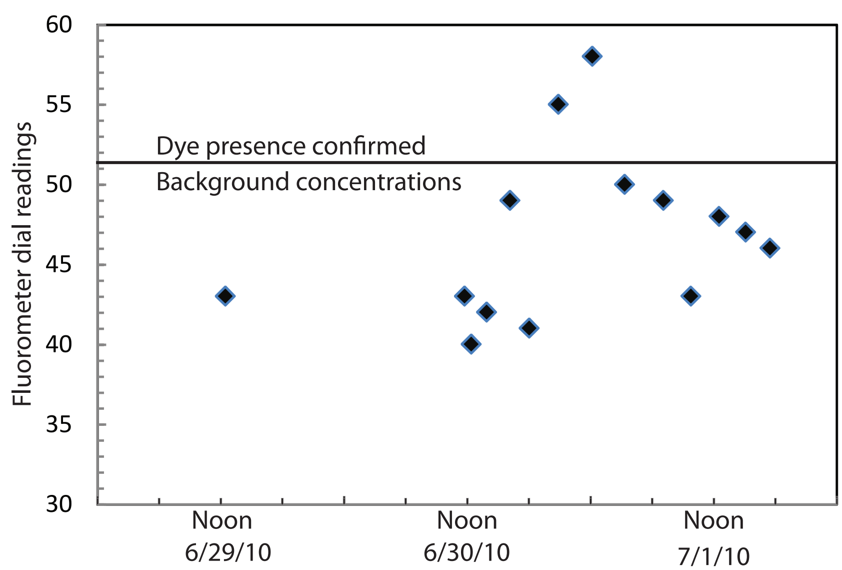
Appendix 4 Figure 8. Fluorometer readings for samples manually collected at site OF7.

Figure 9. Fluorometer Readings For Samples Manually Collected At Site OF9.



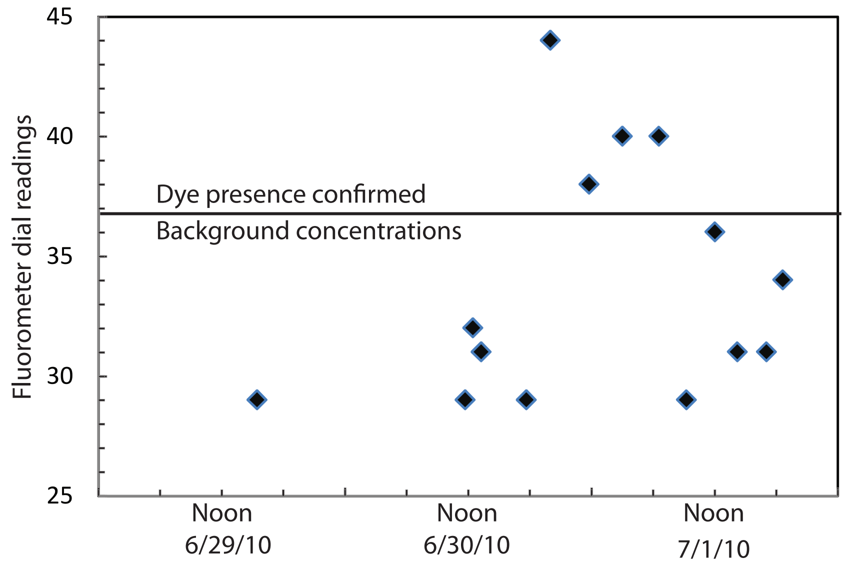
Appendix 4 Figure 9. Fluorometer readings for samples manually collected at site AS1.

Figure 10. Fluorometer Readings For Samples Manually Collected At Site OF10.



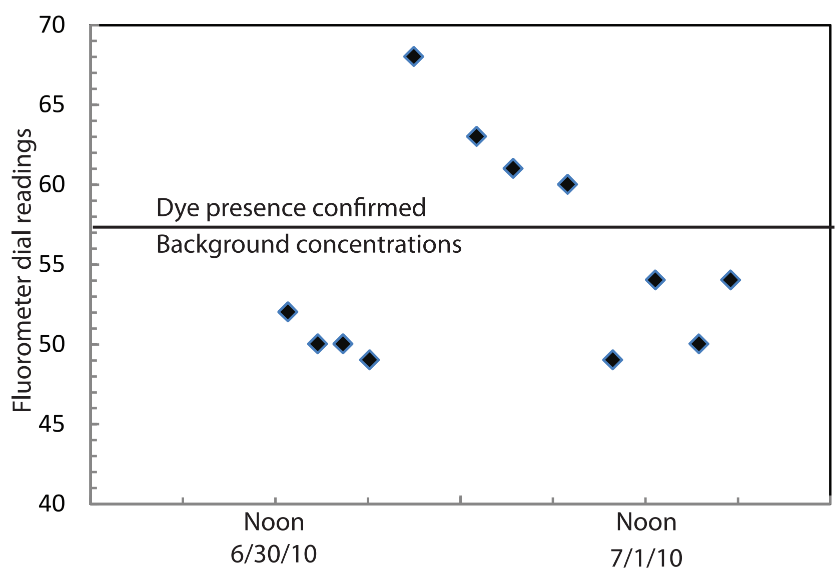
Appendix 4 Figure 10. Fluorometer readings for samples manually collected at site I2.

Figure 11. Fluorometer Readings For Samples Manually Collected At Site OF11.



Appendix 4 Figure 11. Fluorometer readings for samples manually collected at site I3.

Figure 12. Fluorometer Readings For Samples Manually Collected At Site OF12.



Appendix 4 Figure 12. Fluorometer readings for samples manually collected from Elkhorn Creek downstream of all dye monitoring locations.

Appendix 5. Water-Quality Data

Appendix 5. Water-quality data collected for an underground mine outfall (Mcd-210) and a well (Mcd-0204) in undisturbed bedrock strata, and isotope data for precipitation, in the Elkhorn, WV area.

Local Identifier	Station Number	Latitude	Longitude	Station Name
Precipitation @ Gage	03212640	37 23 06 N	081 23 49 W	John's Knob Branch @ Elkhorn, WV
Mcd-0210	372313081234101	37 23 13 N	081 23 40 W	Mcd-0210
Mcd-0204	372322081241501	37 23 22 N	081 24 14 W	Mcd-0204

Local Identifier	Date	Time	Barometric Pressure, mm Hg	Temperature, Air, °C	Depth to Water Level Below LSD, Meters	Depth to Water Level, Feet Below LSD	Dissolved Oxygen, Mg/L	Dissolved Oxygen, Percent of Saturation	Flow Rate, Instantaneous Gal/Min	pH, Water, Unfiltered Field, Std Units
Mcd-0210	07-20-10	1420	715	22.5	--	--	7.2	72	--	6.6
Mcd-0204	07-20-10	1115	715	23.0	5.51	18.08	<1.0	<10	3.8	6.8

Local Identifier	Date	pH, Water, Unfiltered Lab, Std Units	Specif. Conductance, Wat Unf Lab, uS/cm @ 25°C	Specif. Conductance, Wat Unf uS/cm @ 25°C	Temperature, Water °C	Turbidity White Light, Det Ang 90+/-30 Corrected NTRU	Altitude of Land Surface Feet	Depth of Well, Feet Below LSD	Hardness, mg/L	Oxidation Reduction Potential, mV	Pump or Flow Period Prior to Sampling, Minutes
Mcd-0210	07-20-10	6.9	666	665	12.5	1.3	2060	--	207e	262	--
Mcd-0204	07-20-10	7.0	473	490	12.7	0.5	2041	152.00	140e	-90.0	>170

Local Identifier	Date	1,2-Dichloroe-thane-d4, Surrog, Wat Unf % Recvy	14Bromofluoro-benzene Surrog. VOC Sch Wat Unf % Recovry	Touleneo-d8, Surrog, Sch2090 Wat Unf % Recovry	Dissolved Solids Dried @ 180°C Wat Flt mg/L	Dissolved Solids, Water, Tons/Acre-Ft	Total Solids Dried at 105°C Wat Unf mg/L	Calcium Water Unfltrd Recover-able, Mg/L	Magnesium, Water, Unfltrd Recover-able, mg/L	Potassium, Water, Unfltrd Recover-able, mg/L	Sodium, Water, Unfltrd Recoverable, mg/L
Mcd-0210	07-20-10	111	97.9	97.1	418	0.57	406	49.4	20.3	1.83	66.6
Mcd-0204	07-20-10	110	96.8	97.2	311	0.42	306	34.2	13.3	1.58	49.2

Local Identifier	Date	ANC, Wat Unf Fixed End Pt, Lab, mg/L as $CaCO_3$	Alkalinity, Wat Flt Inf Titr, Field, mg/L as $CaCO_3$	Bicarbonate, Wat Flt Infl Pt Titr, Field, mg/L	Bromide Water, Fltrd, mg/L	Carbon Dioxide Water, Unfltrd mg/L	Carbonate, Wat Flt Infl Pt Titr, Field, mg/L	Chloride, Water, Fltrd, mg/L	Fluoride, Water, Fltrd, mg/L	Hydrogen Ion, Water, Unfltrd Calcd, mg/L	Sulfate Water, Fltrd, mg/L
Mcd-0210	07-20-10	224	189	230	<0.02	94	<1	0.87	0.16	0.00025	143
Mcd-0204	07-20-10	182	163	199	<0.02	51	<1	0.93	0.15	0.00016	70.7

Local Identifier	Date	Ammonia, Water, Fltrd, mg/L	Ammonia, Water, Fltrd, mg/L as N	Nitrate + Nitrite Water, Fltrd, mg/L as N	Nitrate Water, Fltrd, mg/L	Nitrite Water, Fltrd, mg/L	Nitrite Water, Filtrd, mg/L	Nitrite Water, Fltrd, mg/L as N	Ortho-phosphate, Water Fltrd, mg/L	Ortho-phosphate, Water, Fltrd, mg/L as P	Phosphorus, Water, Unfltrd mg/L as P
Mcd-0210	07-20-10	<0.026	<0.020	0.12	<0.518	<0.117	<0.007	<0.002	E0.023	E0.007	<0.008
Mcd-0204	07-20-10	0.418	0.325	<0.04	<0.177	<0.040	<0.007	<0.002	<0.025	<0.008	0.045

Local Identifier	Date	Total Nitrogen, Wat Unf by Analysis, mg/L	E coli, Defined Substr Tech, Water, MPN/100 mL	Total Coliform, Defined Tech, MPN/100 mL	Aluminum, Water, Unfltrd Recoverable, µg/L	Barium, Water, Unfltrd Recoverable, µg/L	Beryllium, Water, Unfltrd Recoverable, µg/L	Cadmium Water, Unfltrd µg/L	Chromium, Water, Unfltrd Recoverable, µg/L	Iron, Water, Unfltrd Recoverable, µg/L	Lead, Water, Unfiltrd Recoverable, µg/L
Mcd-0210	07-20-10	0.10	1	340	<6	36.6	<0.04	<0.04	<0.42	<9	<0.06
Mcd-0204	07-20-10	0.30	>1	6	E4	81.5	0.05	<0.04	<0.42	5620	<0.06

Local Identifier	Date	Manganese, Water, Unfiltrd Recoverable µg/L	Mercury Water, Unfltrd Recoverable, µg/L	Nickel, Water, Unfltrd Recoverable, µg/L	Thallium, Water, Unfiltrd µg/L	Zinc, Water, Unfltrd Recoverable, µg/L	Antimony, Water, Unfltrd µg/L	Arsenic Water, Unfltrd µg/L	Selenium, Water, Unfltrd µg/L	1,2-Dichloro-ethane, Water, Unfltrd µg/L	1,2-Dichloro-propane Water, Unfltrd µg/L
Mcd-0210	07-20-10	<0.8	<0.010	2.9	<0.12	3.4	<0.4	1.3	1.5	<0.2	<0.1
Mcd-0204	07-20-10	571	<0.010	1.2	<0.12	<2.0	<0.4	3.3	<0.10	<0.2	<0.1

Appendix 5. Water-quality data collected for an underground mine outfall (Mcd-210) and a well (Mcd-0204) in undisturbed bedrock strata, and isotope data for precipitation, in the Elkhorn, WV area (*continued*).

Local Identifier	Date	1,4-Dichloro-benzene Water, Unfltrd µg/L	1,1,1-Trichloro-ethane, Water, Unfltrd µg/L	CFC-113 Water, Unfltrd µg/L	1,1-Dichloro-ethane, Water, Unfltrd µg/L	1,1-Dicloro-ethane, Water, Unfltrd µg/L	1,2-Dichloro-bezene Water, Unfltrd µg/L	1,3-Dichloro-benzene Water, Unfltrd µg/L	Benzene Water, Unfltrd µg/L	Bromo-dichloro-methane Water, Unfltrd µg/L	Chloro-benzene Water, Unfltrd µg/L
Mcd-0210	07-20-10	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Mcd-0204	07-20-10	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Local Identifier	Date	cis-1,2-Di-chloro-ethene, Water, unfltrd µg/L	Dibromo-chloro-methane Water, Unfltrd µg/L	Dichloro-difluoro-methane Water, Unfltrd µg/L	Dichloro-methane Water, Unfltrd µg/L	Diethyl Ether, Water, Unfltrd µg/L	Di-isopropyl Ether, Water, Unfltrd µg/L	Ethyl-benzene Water, Unfltrd µg/L	Methyl t-butyl Ether, Water, Unfltrd µg/L	Methyl tert-pentyl Ether, Water, Unfltrd µg/L	Meta- + Para-Xylene, Water, Unfiltered µg/L
Mcd-0210	07-20-10	<0.1	<0.2	<0.2	<0.2	-0.2	<0.2	<0.1	<0.2	<0.2	<0.2
Mcd-0204	07-20-10	<0.1	<0.2	<0.2	<0.2	-0.2	<0.2	<0.1	<0.2	<0.2	<0.2

Local Identifier	Date	Organic Carbon, Water, Unfltrd mg/L	o-Xylene, Water, Unfltrd µg/L	Styrene Water, Unfltrd µg/L	t-Butyl Ethyl Ether, Water, Unfltrd µg/L	Tetra-Chloro-ethene, Water, Unfltrd µg/L	Tetra-Chloro-methane Water, Unfltrd µg/L	Toulene Water, Unfltrd µg/L	Trans-1,2-Di-chloro-ethane, Water, Unfltrd µg/L	Tri-bromo-methane Water, Unfltrd µg/L	Tri-chloro-ethene, Water, Unfltrd µg/L
Mcd-0210	07-20-10	<0.6	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1	<0.2	<0.1
Mcd-0204	07-20-10	<0.6	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1	<0.2	<0.1

Local Identifier	Date	Tri-chlorofluoro-methane Water, Unfltrd µg/L	Tri-chloromethane Water, Unfltrd µg/L	Tri-halomethanes, Water, Unfltrd µg/L	Vinyl Chloride, Water, Unfltrd µg/L	Rn-222, Water, Unfltrd Pci/L	Deuterium/ Protium Ratio, Water, Unfltrd per mil	O-18/O-16 Ratio, Water, Unfltrd per mil
John's Knob Branch	07-20-10	--	--	--	--	--	-29.80	-4.96
Mcd-0210	07-20-10	<0.2	<0.1	<0.6	<0.2	23	-52.70	-8.20
Mcd-0204	07-20-10	<0.2	<0.1	<0.6	<0.2	21	-49.10	-7.86