CHAPTER 3: HYDROLOGY OF THE APPALACHIAN BITUMINOUS COAL BASIN

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INTRODUCTION

The bituminous coal fields of the Appalachian Coal Basin have certain pervasive features that influence hydrology, including discontinuous flat-lying sedimentary rocks of contrasting permeability, incised topography, a shallow weathered rock zone, dendritic stream patterns, and similar patterns of rock fracturing. These features allow for the development of regionally valid conceptual groundwater flow models. Also, the limits of the basin align closely with the margins of the Appalachian Plateaus physiographic province. The province's physical geography permits certain regional generalizations regarding groundwater/surface water interactions. Therefore, local and site-specific hydrologic studies often have basin-wide applicability.

While certain general concepts have been developed, the basin's groundwater hydrology is very complex. This complexity is related to the area's inter-fingering lithologies and to the prevalence of secondary permeability features. On the Plateaus, discrete fractures, partings, or fracture zones can significantly influence groundwater flow within small areas, such as individual coal mining sites. Due to these complicating elements, regional conceptual models, while useful, should not substitute for site-specific hydrologic studies. The following narrative outlines some of the significant groundwater studies within the basin, briefly describes surface water drainage, outlines hydrologic impacts from mining, and emphasizes important basin-wide hydrologic characteristics.

Geologic Setting

The Appalachian Coal Basin follows the spine of the Appalachian Mountains through nine states from Pennsylvania to Alabama, covering an area of approximately 72,000 square miles. It is 175 miles wide at the widest part in Pennsylvania and Ohio, and 35 miles wide at the narrowest part in Tennessee (Figure 3.1). The rocks are predominately flat-lying, consisting of sandstone, conglomerate, siltstone, shale, claystone, limestone and coal (Miller et al., 1968). The bituminous coal seams are contained in relatively flat-lying Pennsylvanian and Permian age clastic strata. The outline of the Pennsylvanian system is approximately co-extensive with the border of the Appalachian Plateau physiographic province. Rocks of Permian age and younger Pennsylvanian rocks of the Monongahela, Conemaugh and Allegheny Groups are confined to an elliptical area in Pennsylvania, Ohio, West Virginia, and Maryland. The oldest Pennsylvania rocks, the Pottsville Group, extend from western Pennsylvania to northern Alabama. Glacial outwash deposits of Pleistocene age occur at the surface in the valleys of northern Pennsylvania, and along the Allegheny and Ohio Rivers.

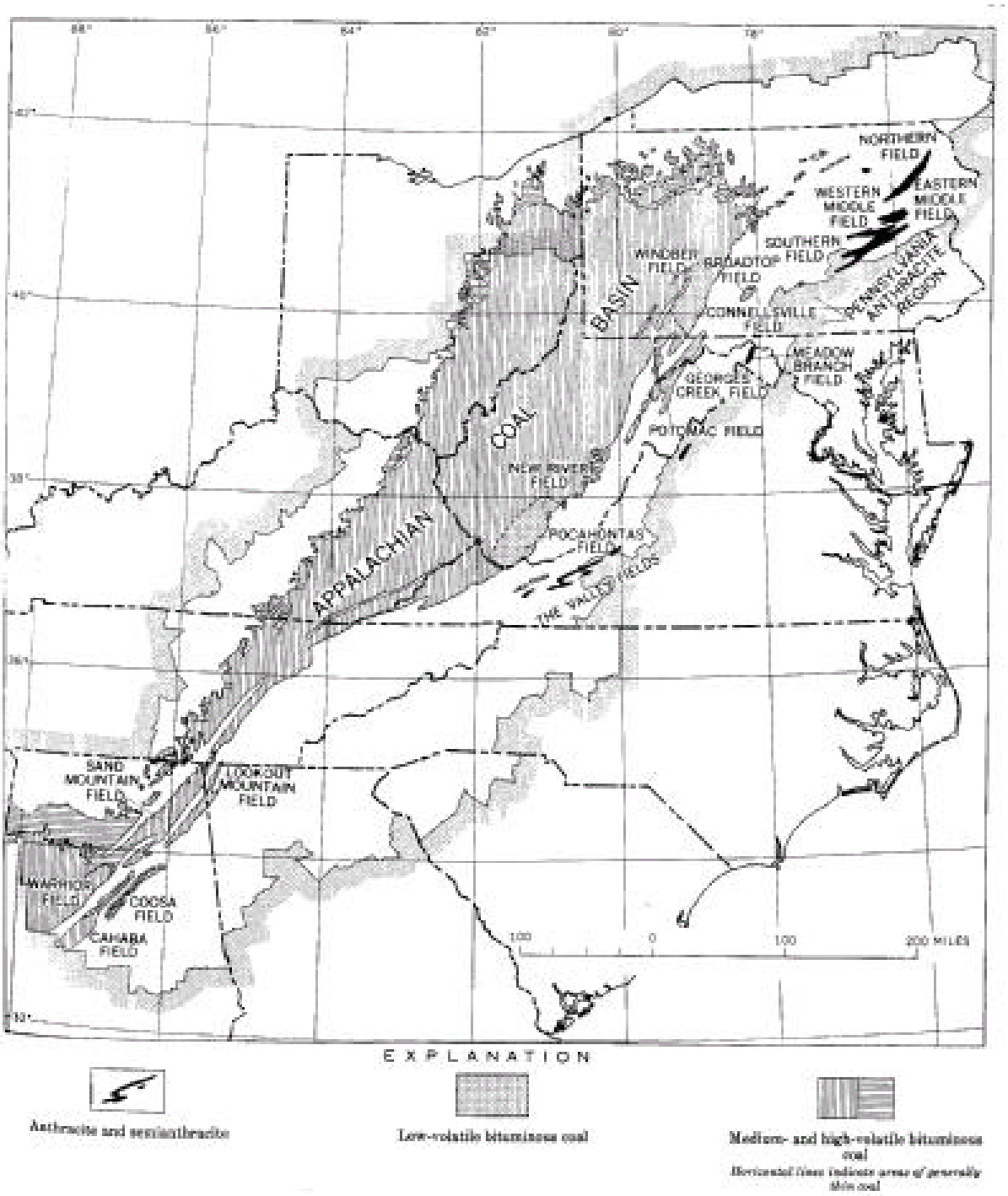

Figure 3.1. The Appalachian Coal Fields

The coal-bearing rocks in the basin are folded into several hundred small subsidiary synclines and anticlines, and, on the eastern edge of the basin, a few coal-bearing synclines are separated structurally from the main part of the basin (Arndt et al., 1968). Hills have been subjected to stress-relief and unloading forces that have intensified fracturing and bedding-plane separations, and subsequently, weathering. This physical weathering, coupled with chemical weathering, has resulted in higher permeabilities within the weathered zone (Hawkins et al., 1996).

Physiography and Surface Drainage

The mineable coal seams are located primarily in the Appalachian Plateau physiographic province. The Appalachian Plateau province is a high upland dissected by many incised, dendritic streams. The topography can be generalized as a series of loping, uplifted, dissected plateaus that are topped by resistant layers (Fenneman, 1938). The eastern edge of the Appalachian Plateau province is an escarpment that rises abruptly 1,000-3,000 feet above a valley that bounds it on the east. This eastern ridge is the highest section of the Appalachian Plateau, with elevations ranging up to 4,800 feet in parts of West Virginia. Relief in the western part of the province, in central and southwest Pennsylvania, West Virginia, eastern Kentucky, and northern Tennessee is 500-1,500 feet. This area is carved into small steep-sided hills. Slopes of 45° are common and steep slopes, some vertical, prevail along the major rivers (Davies, 1968).

The surface drainage network generally follows a dendritic pattern indicating minimal underlying structural control. The underlying geology does however exert some control on the degree of valley downcutting and thus on the gradient of individual streams and sections of streams. In the north, the more easily eroded, subhorizontal rocks of the Plateau section have allowed streams and rivers to reduce the land to gentle slopes resulting in mild stream gradients along the valleys of the Ohio, Allegheny, and Monongahela Rivers. Runoff rates for this region are among the highest in the country. Average annual runoff ranges from 10 – 30 inches, generally increasing from north to south (Schneider, 1965). The numerous sub-basins of the Plateau Section are characterized by rounded hills and steep-sided valleys. These tributary streams generally have steeper gradients and more V-shaped valleys than the master streams. To the east, along the anticlines of the Allegheny Mountain Section, the more resistant folded bedrock results in drainage patterns that parallel the ridges, with major rivers cutting through in only a few locations. The gaps where streams cut the ridges are often localized by geologic structure. Stream gradients in this section are therefore significantly steeper than on the adjacent plateau. Unconsolidated deposits (alluvium) overlie the bedrock in some locations, particularly along major stream valleys within the Plateau Section. Stoner et al. (1987) describe typical seasonal streamflow variation in their report on the water resources of southwestern Pennsylvania:

> "…The hydrographs show a typical low flow in October and early November; an increase in flow in late November and December as evapotranspiration decreased and winter rains and snowfall increased; a decrease in flow in late December and January when ice formed on the streams; an increase in flow in February due to thawing and an increase in rainfall; a slight decrease in flow in March due to a decrease in precipitation; an increase in flow in April resulting from increased rainfall and snow melt; a decrease in flow in May as rainfall decreased and evapotranspiration increased; and unusually high flow in June due to large amounts of rainfall; and generally low flow

in July, August, and September, interrupted by high flows in late July and early September caused by thunderstorms."

Climate

In the Appalachian Basin, the average annual temperature in the north is about 50° F (~10° C) ranging up above 60° F (>15° C) in the south. Precipitation also increases from north to south, with rainfall averaging 35 inches (90 cm) in northern Pennsylvania to more than 55 inches (140 cm) in Alabama (Schneider, 1965; Weeks et al., 1968). Precipitation averages about 47 inches annually, much above the national average for regions of comparable size. Most is derived form eastward-moving air masses that lose moisture as they are forced upward over the mountainous areas. High precipitation thus tends to occur along the western sides of mountain ranges, and distinct rain shadows are found east of them. The annual infiltration rate of water is generally sufficient to consistently flush groundwater through the shallow rock strata from recharge to discharge points. This flow tends to leach out the soluble products of the more weatherable minerals.

In general, less than 15 inches (38 cm) of the average precipitation infiltrates the groundwater system, with evaporation and transpiration accounting for roughly 20 inches (51 cm) annually (Becher, 1978). The remaining precipitation directly runs off to surface waterways. These numbers are estimates; actual amounts vary depending on geology, soils, vegetation, and topography.

GROUNDWATER

Regions such as the Appalachian coal measures with their small basins, marked relief, and humid climate generally develop a groundwater system that can be readily broken into distinct parts: local (shallow), intermediate, and regional (deep) (Poth, 1963). The contrast in permeability between the various lithologic units creates a series of alternating aquifers and aquitards. This results in a predominance of lateral groundwater movement within the coal measures. However, well-developed joints systems commonly serve to augment vertical communication.

Flow Systems

The effects of topography, geologic structure, and stratigraphy control the groundwater flow patterns. Williams (1982) describes general groundwater flow on the Northern Appalachian Basin:

> "Three general flow systems are recognized within the high-to-intermediate-relief model. Shallow flow systems convey groundwater over short distances, tens to hundreds of meters, and respond rapidly to chemical and physical changes within the environment. Groundwater within intermediate flow systems travels distances of hundreds to thousands of meters and has response times ranging from months to decades. Deep flow systems transport groundwater distances of thousands to tens of thousands of meters from points of recharge to discharge, with travel times measured in years to hundreds of years."

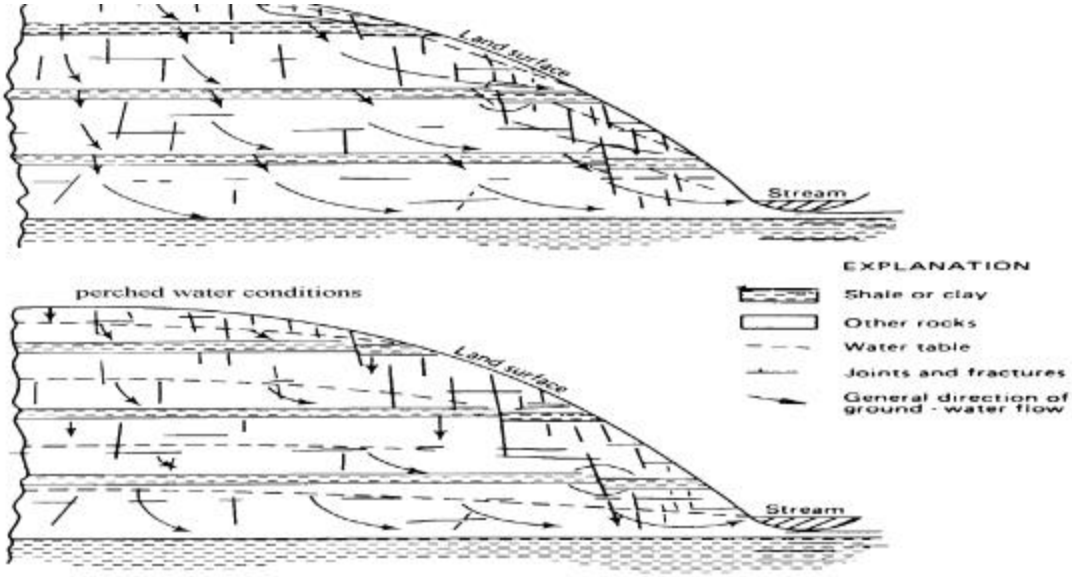

Figure 3.2. Idealized perched and semi-perched groundwater conditions (modified from Ward and Wilmoth, 1986)

The shallow flow system underlies hills, discharges to local streams, and, to some extent, leaks downward into the deeper, intermediate system. Contrasts in the permeability of successive strata can result in marked deflection of flow lines and in greater horizontal flow components than in homogeneous aquifers. In some areas, shallow systems include water that is "perched" above beds of lower permeability (Figure 3.2). This groundwater may then move laterally due to permeability contrasts, and discharge as springs above stream level.

Poth (1963) describes the shallow groundwater as circulating in a series of "hydrologic islands". The water table located within the ridges between surface drainageways tends to become depressed to the level of the surface streams. However, semi-perched zones occur routinely within the ridges due to the numerous low permeability units. The dissected nature of the bedrock surface has resulted in hills, largely surrounded by valleys containing perennial streams. These hills constitute the hydrologic islands (Figure 3.3). A discrete groundwater flow system operates within each hydrologic island and is hydrologically segregated from the local groundwater flow systems in adjacent islands. The base of the local flow system (particularly for islands adjacent to first and second order streams) is a distance below the level of the stream valleys bordering the island. It is defined by the maximum depth at which groundwater originating within the hydrologic island will flow upward to discharge in the adjacent stream valley. Recharge to the local system is completely from within the hydrologic island. Discharge from the local system is into the adjacent stream valleys and via leakage into deeper intermediate and regional groundwater flow systems. In areas adjacent to larger streams and rivers, local groundwater that leaks downward may co-mingle with intermediate or even regional flow, which is rising to discharge within the valley. This shallow flow system is the most active groundwater circulation area, and contributes water to the vast majority of domestic wells.

A prominent subsystem within the region's shallow groundwater flow system is a weathered regolith of approximately 10–20 meters in depth. It is a highly transmissive zone consisting of soil, unconsolidated sediment, and weathered, highly fractured rock. Weathering has removed most soluble minerals, and groundwater flowing through this material picks up little mineral matter. Because of the open nature of the

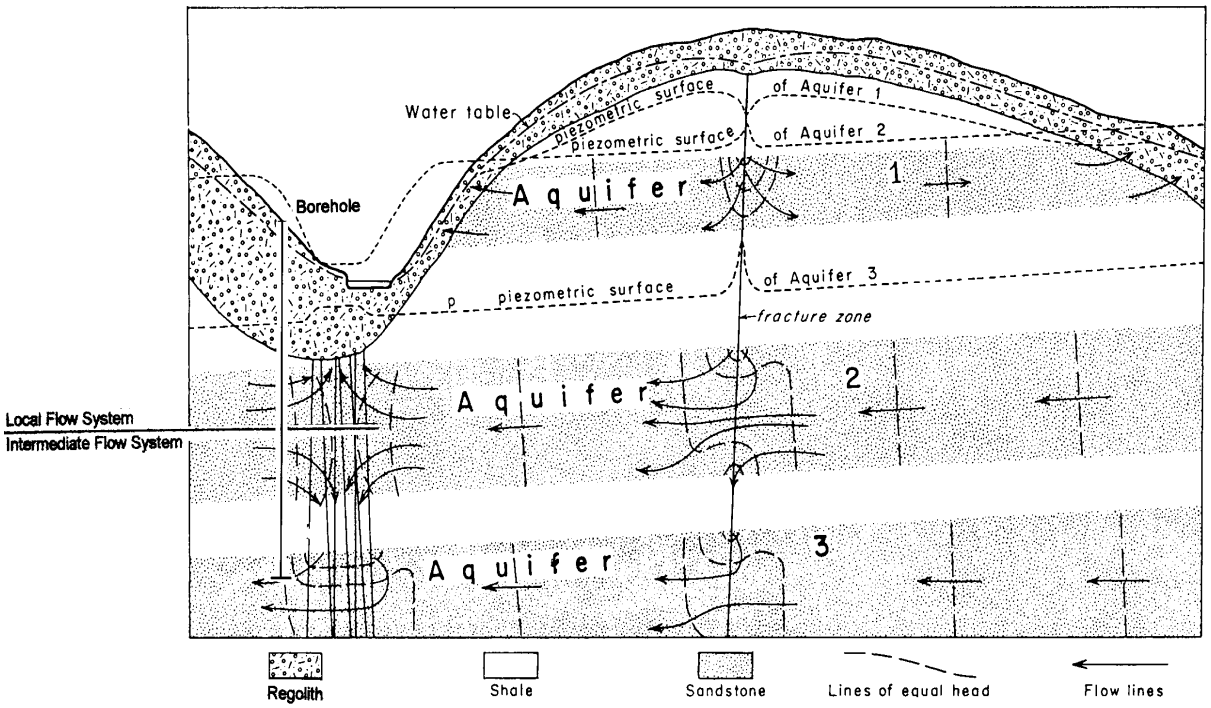

Figure 3.3. Groundwater flow in and beneath a "hydrologic island" (modified from Poth)

fractures within this zone, the groundwater "flow-through" time is short and this subsystem allows a significant portion of recharge to short-cut to local discharge points. Various hydrologic tests have shown hydraulic conductivities within this zone to be one to two orders of magnitude greater than in zones that are only marginally deeper (Schubert, 1980).

Water chemistry within the weathered regolith subsystem should not be used to characterize groundwater under deeper cover, which flows through unweathered rock. For example, rock units closer to the ridge center may contain groundwater with significant alkalinity due to circulation through unweathered calcareous strata. In comparison, an outcrop spring at the same stratigraphic interval shows little or no alkalinity because it is largely fed by groundwater that traveled an abbreviated path through leached and weathered rock along the "rind" of the hill.

Recharge to the weathered regolith subsystem is through ridge-top and valley-wall fractures. Groundwater flows through the interconnected bedding-plane partings and fractures to springs flanking the hillsides (frequently at coal outcrops) and into stream channels. Much of the water that enters this shallow subsystem never penetrates to the nearby ridge-cores, nor to deeper flow systems. Residence time is as short as days to a week (Hawkins et al., 1996).

Lithology and regional joint sets control flow within the ridge-cores. The ridge-core subsystem receives recharge through the weathered regolith subsystem and through the stress-relief fracture system. Groundwater flow is through tectonic fractures, bedding-plane partings, and to a much lesser degree, intergranular porosity. Low permeability units (such as claystones and shales) exert more control within the ridge cores due to the lack of stress-relief joints and weathering, which control groundwater movement along the margins of the hills. Because the integrity of these low permeability layers has not been

compromised fully in the ridge cores, as may be the case along the hillsides, groundwater can mound on these layers. It then either flows laterally to mix with groundwater within the stress-relief/weathered regolith subsystem and discharges to the local stream valley; or leaks downward to an intermediate or regional flow system.

Residence times and response times to precipitation events within the ridge cores are intermediate between those for the weathered regolith subsystem and deeper systems. The ridge-core subsystem is part of the local flow system because it is part of the hydrologic island that discharges into the valley adjacent to the local recharge area.

The intermediate groundwater flow system is recharged via multiple shallower (local and intermediate) systems and at the drainage basin divide of the defining recharge area. Flow passes beneath two or more hydrologic islands and discharges in valleys above the lowest level of the drainage basin. Flow rates and residence times are generally between those of local and regional groundwater flow systems, probably varying from years to decades, depending on the level of the intermediate system and the length of the flow path. A deep, regional groundwater flow system, which lies beneath the level of the hydrologic islands and intermediate flow system, operates independently of the shallower systems. Highly mineralized water occurs naturally at depths of less than 500 feet over large sections of the basin. The base of the regional system is the fresh water/saline water contact. Recharge to the regional system is from major drainage basin divides and leakage from multiple shallower (local and intermediate) systems.

Fractures

Superimposed on these flow systems (particularly on the shallow system) are additional distinct flow zones (subsystems) defined by the density, interconectedness, and aperture of rock fractures. Fractures and bedding-plane partings are commonly the main groundwater flow paths. The characteristics of the fractures (width, spacing, and frequency) differ between, but may be consistent within, various stratigraphic units. Therefore, it is appropriate to consider the stratigraphic units as the aquifers. Joint permeability is particularly significant, if not dominant, in shallow rock strata (15-50 meters) and may increase permeability values by ten to a thousand times when compared to intergranular permeability values taken alone (Parizek, 1971). Sames and Moebs (1989), working in the eastern Kentucky coal field identified vertical weathered joints ("hillseams") as important groundwater avenues. Fracture zones (areas where numerous fractures dissect the rock mass) are common and can have a profound impact on groundwater flow. Fracture zones are typically 7-12 meters in width (Gold, 1980) and depths can range into the hundreds of meters.

Hydraulic conductivities associated with fracture zones are often several orders of magnitude higher than unfractured rock. These features commonly counteract the layered heterogeneity of the coal measures by augmenting vertical conductivities allowing for significant vertical communication within the system, particular on local scales. Additionally, rock types with relatively low primary permeabilities can become significant water producers due to interconnected fractures. Because of the importance of secondary permeability features to groundwater flow in this setting, the classic use of terms such as aquifer, aquitard, and confining layer can be confusing. A single lithologic unit, such as a shale, can be characterized as either an aquifer or an aquitard over a relatively short lateral distance depending on conditions such as proximity to the shallow

weathered zone, proximity to stream valleys, and magnitude of open joints (generally decreasing with depth).

Valley-related stress-relief fracturing is another important secondary permeability feature. Stress-relief fractures are a fracture network unrelated in age and orientation to tectonic stresses. They are often the most transmissive part of an aquifer. The fracture network has been attributed to "de-stressing" of rocks during downcutting of streams and the formation of the steep and narrow valleys characteristic of the Plateau region (Wyrick and Borchers, 1981). Wyrick and Borchers studied two valley-related stress-relief systems on the Appalachian Plateau in West Virginia and determined that the fractured rock parallels topography. Hydrologic studies in the area have shown that the stress-relief zone is more transmissive than other surficial or bedrock units. Wyrick and Borchers state:

> "… ground water occurs mainly in horizontal bedding-plane fractures under the valley floor and in nearly vertical and horizontal slump fractures along the valley wall. The aquifer is under confined conditions under the valley floor and unconfined conditions along the valley wall. The fractures pinch out under the valley walls, which form impermeable barriers. Tests of wells near the valley center indicated a change in storage coefficient as the cone of depression caused by pumping reached the confined-unconfined boundaries; the test also indicated barrier-image effects when the cone reached the impermeable boundaries."

Water levels in wells in the stress-relief zone respond quickly to precipitation events (Hawkins et al., 1996). Wyrick and Borchers (1981) determined that stress-relief fractures significantly affect the surface water hydrology in Appalachian Plateau valleys. Their study in the Black Fork valley in West Virginia showed that stream flow per square mile of drainage area increased 6-11 times downstream from the outcrop of stress-relief and bedding-plane fractures in the stream bed.

Permeability

Groundwater within the area occurs under both water table (unconfined) and artesian (confined) conditions. The vast majority of groundwater circulates in the fractured near-surface bedrock, along stress-relief fracture networks, open joints, and within the weathered regolith zone. Water-bearing zones commonly consist of horizontal fracture openings that occur preferentially at lithologic contacts. Studies indicate that hydraulic conductivity decreases with increasing depth at the rate of an order of magnitude for every 30 meters (Stoner et al., 1987). Water availability and well yield are a function of the number, openness, and interconnectedness of fractures, which in turn is related to proximity to the surface. The yields of bedrock wells generally increase in conjunction with the number and size of water-conveying fractures intercepted. Medium- and coarse-grained sandstone can show significant pore space permeability depending on the degree of cementation between grains and the presence of shale lenses. Many of the lithologies are laterally discontinuous and permeability changes considerably over short distances.

Brown and Parizek (1971) conducted laboratory tests on rock cores using a permeameter to determine vertical and horizontal primary permeability of various rocks within the coal measures of Clearfield County, Pennsylvania. The reported horizontal and vertical permeabilities of shales, claystones, and siltstones were 0.0004 gpd/ft^2 and 0.0001 gpd/ft^2, respectively. Rock cores near Elkins, West Virginia had somewhat

higher conductivities, ranging from 0.0004 to 1.0 gpd/ft^2, as reported by the U.S. EPA (1977). Brown and Parizek followed up their laboratory work by conducting field pumping tests on the same horizons in order to better account for secondary permeability. The pumping tests yielded coefficients of permeability ranging from 0.12 to 680 gpd/ft^2, averaging about 61 gpd/ft^2. Coefficients determined by Schubert (1978) via pumping tests on the Plateau of western Pennsylvania were lower and ranged from 0.023 to 2.20 gpd/ft^2.

Hobba (1991), working in Preston County, West Virginia, conducted aquifer tests on shallow middle and upper Pennsylvania rocks, including the Upper Freeport coal. Hobba describes his hilltop study site as follows:

> "Two aquifers occur within 65 feet of land surface at the test site. The overburden aquifer is the water-table aquifer and it consists of about 50 feet of mainly shale and sandstone beds. The leaky confined coal aquifer lies immediately below the overburden, and it consists of 4.5 feet of coal. Water occurs in both joints and intergranular openings in the overburden aquifer. Sandstones that contain both intergranular and joint openings are commonly filled with secondary minerals and the vertical joints and horizontal bedding plane joints are poorly developed; thus, the sandstones yield little water to wells. In general, shales do not yield large quantities of water, except in area where the rocks are intensely fractured."

Constant-head permeability tests were run at 10-foot intervals throughout the overburden above the coal. The most permeable rock was within 33 feet of the land surface. Testing conducted on the 4.5-foot coal seam indicated that it is almost as transmissive as the 50-foot overburden aquifer. Hobba concluded that major and minor fracture sets create anisotropic hydraulic characteristics that favor groundwater movement parallel to the major fractures in both the coal and the overburden. He also found that the orientation of maximum transmissivity in the coal approximately parallels the direction of face cleats in the coal.

Groundwater Availability

Over most of the area, sufficient water for domestic purposes can be obtained from bedrock wells drilled to the 75-250 feet range. These bedrock wells are naturally low yielding. Well yields can range up to 100 gallons per minute (gpm) or more but are typically below 10 gpm with a large percentage below 3 gpm. Yields large enough for industrial or municipal purposes can be difficult to obtain. Large capacity wells have been successfully developed near or at the intersection of fracture traces to increase the likelihood of fracture-enhanced groundwater flow to the well bore. Bedrock wells often exceed recommended drinking water concentrations for iron. Wells in valleys, where the water table is closer to the land surface, have more available drawdown than wells of the same depth of hills and hillsides, and tend to be less vulnerable to negative impacts caused by groundwater level fluctuations.

Working in the Stillwater Basin on the Appalachian Plateau of east central Ohio, Walker (1962) found considerable variability in yield of bedrock wells. Certain sandstone aquifers supplied up to 25 gpm. However, most bedrock aquifers were found to supply only enough water for domestic uses, generally less than 3 gpm. Jones (1988), also working in eastern Ohio, reported bedrock well yields ranging from 2 to 10 gpm, compared to glacial outwash and alluvial zones along stream valleys, which yielded up to 200 gpm

but typically averaged 20 gpm. Wahl et al. (1971), in their report on Winston County, Alabama, describe the groundwater resources in the Cumberland Plateau's Pennsylvanian coal-bearing rocks as follows:

> "The Pottsville Formation consists of about 1200 feet of sandstone, shale, and coal. Groundwater in the Pottsville occurs in openings along fractures and bedding planes and in permeable sandstone. The quantity of water available from an individual well in the Pottsville depends on the number, size, and extent of water-bearing openings or the permeability and thickness of saturated sandstone penetrated by the well. …The number and size of water-bearing openings decrease with depth and in general only small amounts of additional water are obtained by drilling below a depth of about 350 feet. "

Wahl reports that even those wells that were developed in highly productive sandstone zones rarely yield over 50 gpm and commonly produce 5 to 10 gpm. Causey (1961), working in Etowah County, Alabama, reported low well yields of generally less than 5 gpm for Pottsville Formation units. Moore (1990) also reports generally low yields (10 gpm) for the Pennsylvanian rocks of the Cumberland Plateau of northern Alabama, with a few relatively high-yield wells developed in fracture zones.

In general terms, wells along major anticlines and in valleys tend to be higher producers due to relatively extensive fracturing. Stoner et al. (1987) outlines the following generalities regarding topographic position versus well yield for the coal measures of southwestern Pennsylvania:

> "Hilltop wells – wells are commonly drilled only to the depth of sufficient yield. Increasing the well depth for added yield or storage commonly results in water-level decline and sometimes complete loss of well yield. Also, an uncased deep well can often reduce the yield of a nearby shallow well.
>
> Hillside wells – In addition to procedures for the hilltop setting, wells need to be sited at some distance from potential contamination points such as septic tanks, trash dumps, or stock pens located upgradient. At many hillside locations, springs are a suitable alternative to wells as a potable water supply….
>
> Valley wells – Highly mineralized groundwater is shallowest beneath valleys. This condition commonly limits the depth of valley wells to be used for domestic supply. High-yielding shallow wells are possible in the alluvium of major valleys, but groundwater is susceptible to contamination by surface activities. Tightly cased deep wells in large valleys may be free flowing…. Of all the topographic positions, wells in valleys have the greatest probable success of producing high well yields. These high yields are commonly due to fracturing beneath the valley bottom. This fracturing is expected to diminish beneath adjacent hills, thereby limiting the effective areal extent and yield of such aquifers…"

Over the entire study area, alluvium, particularly along major rivers, is generally highly permeable and can yield large quantities of water to wells. However, permeability may change significantly over short distances because of changes in the degree of sorting. Wells penetrating the coarse basal layers of alluvium generally obtain the largest yields (Poth, 1973). Well yields in the 500-gpm range are not uncommon. For example, the narrow flood plain adjacent to the Ohio River may yield 500 to 1000 gpm to properly developed wells

(Schmidt, 1959) and yields of up to 800 gpm are obtained from wells tapping thick alluvial deposits in Ohio County, West Virginia (Robison, 1964). In contrast, thin or fine-grained alluvial deposits, such as those along most small to moderate size streams, have relatively low water-yielding capacities. In Harrison County, West Virginia, alluvial deposits are minor sources of groundwater owing to their thinness, and yields of only 2-3 gpm can be obtained (Nace and Bieber, 1958). In general, water obtained from alluvium is hard, has high iron, manganese, and dissolved-solids content.

Because sandstone typically contains both intergranular and joint openings, it generally yields the most water to wells. However, where the pores are filled with secondary minerals and jointing is relatively undeveloped, sandstone will transmit little water. Williams et al. (1993) ranked hydraulic conductivity from highest to lowest among bedrock water-bearing units: (1) coal, (2) sandstone, (3) siltstone and shale, and (4) limestone.

WATER CHEMISTRY

Groundwater

Because of differences in rock mineralogy, residence time, and influence of the brine underlying the composite flow system, the chemistry of groundwater in different flow systems and subsystems varies. For example, groundwater that has come in contact with sandstone and shale containing pyrite remains soft, but is more acidic and higher in concentrations of iron and hydrogen sulfide than in non-pyritic rocks. Water in limestone or calcareous aquifers is usually a calcium magnesium bicarbonate type. Sodium chloride and other brines occur below a depth of several hundred meters in all hydrostratigraphic units, and waters above this saline water are usually hard (Back, 1988).

Poth (1963) and Rose and Dresel (1990) identify three stages of “flushing” that roughly correspond with the three levels of the previously outlined flow systems. The deepest zone, directly affected by concentrated brines, which exist at depth throughout all areas west of the Allegheny Front, is a NaCl-rich diluted brine zone. This zone is diluted with surface water that has leaked from shallower flow systems, but retains appreciable amounts of both Na and Cl. This chemical signature is indicative of the more regional flow systems described previously.

A shallower system (intermediate zone) exists in which Cl has been removed by flushing with surface waters, but considerable Na remains adsorbed to clays and similar materials, leading to the Na-HCO_3 waters that are commonly found at intermediate depths. The elevated Na is a result of cation exchange, with Na released from the exchange sites in response to replacement by Ca, Mg, and possibly Fe (especially with mine waters) (Winters et al., 1999). Piper (1933) outlined this process:

> “…Many of the water-bearing beds - whether they are sandstone, shale, or limestone - contain soft sodium bicarbonate water where they lie at intermediate depths. This soft water is believed by the writer to represent calcium bicarbonate water that has exchanged its calcium and magnesium for sodium by reaction with base-exchange silicates in the rock as it has percolated downward along the dip of the water-bearing bed. The hardness due to the bicarbonate of calcium and magnesium is

removed in proportion to the completeness of the exchange reaction, and the water finally passes into the sodium bicarbonate type…"

In the uppermost zone, Na is completely flushed leaving a Ca-HCO_3 water typical of shallow groundwater. The shallow flow system is further divided (Brady et al., 1996) into a low dissolved-solids zone associated with the stress-relief/weathered regolith subsystem, and a zone with higher dissolved solids associated with unweathered rock (ridge cores).

Because stream valleys function as sumps for the discharge of groundwater, the contact between the fresh and saline groundwater probably "cones up" beneath the streams, and lies at successively greater depths away from the streams. Mining activity and practices for controlling water quality or quantity may alter the depth to saline water and the amount of discharge of saline water to the streams (Hobba, 1987).

Wunsch (1993) developed a conceptual hydrochemical-facies model for an unmined ridge based on site-specific data from eastern Kentucky. According to Wunsch (1993, p. 72):

…"The model shows four zones where the major cations and anions comprising the water type for a particular water sample could be predicted with a high degree of probability. The model shows a depressed salt-water interface below the ridge due to downward movement and accumulation of fresh water. The hydrostatic pressure imparted on the salt water is transmitted in the salt-water zone, causing it to rise at locations where fractures breech confining layers (valley bottoms)…"

Data collected at numerous mining sites in southwestern Pennsylvania support Wunsch's hydrochemical model for shallow groundwater flow on the dissected Appalachian Plateau of Pennsylvania (Callaghan et al., 1998). Callaghan et al. provide ranges for water quality for a shallow "rind of hill" system, ridge cores, and intermediate flow systems at a site in southwestern Pennsylvania (Table 3.1).

Surface Water

Generally, the streams draining the Appalachian Plateau contain three types of water, based on major cation and anion concentrations. A calcium-magnesium-bicarbonate type typically dominates in streams draining the limestone and dolomite areas of the Plateau in Tennessee and northern Alabama. Streams containing calcium-sulfate waters with bicarbonate and chloride (dissolved solids less than 150 ppm) drain large portions of West Virginia and eastern Kentucky. Streams containing calcium-sulfate type water that is hard to very hard, with dissolved-solids concentrations from 100 to 2000 ppm, drain the heavily mined areas of southwestern Pennsylvania, northern West Virginia, eastern Kentucky, eastern Ohio, and north-central Tennessee (Schneider, 1965).

Table 3.1. Typical groundwater chemistry ranges for various flow systems (mg/l).

Flow system	# of samples	Alkalinity	Sulfate	Ca	Mg	Na	Spec. Conductivity (umhos/cm)
Rind of hill	22	2 – 38	14 - 45	5 - 38	1 – 7	2 - 13	50 – 136
Ridge core	11	80 – 199	39 - 75	40 - 70	9 – 12	2 - 17	300 – 470
Intermediate	26	8 – 861	108 - 2850	2 – 246	---------	191 - 945	1220 - 4500

CONCEPTUAL GROUNDWATER MODELS

Kipp and Dinger (1987) presented a conceptual model of groundwater flow in the Wolfpen Branch basin in Kentucky:

> "Groundwater flow in the basin is complex. Within the interiors of the hills, water is stored and transmitted in intergranular pore spaces of the predominantly sandstone bedrock. These rocks are saturated, but wells produce little water. Lithologic cores indicate that saturated sandstone zones are separated by relatively impermeable claystone units associated with major coal seams, which limit the vertical movement of water. These confining layers cause lateral flow to the hillsides where ground water may discharge as springs or seeps or move vertically downward through the confining zones via secondary porosity consisting of fractures and bedding-plane openings. Continuous water-level records indicate that bedrock wells monitoring the valley walls and bottom respond quickly to rainfall events, evapotranspiration, and mining activity. This suggests high hydraulic conductivity and direct connection to infiltration from the surface. Lithologic cores indicate that secondary fracture permeability, possibly created by stress-relief fracturing, is responsible for the increased hydraulic conductivity along hillsides and valley bottoms, and controls much of the shallow groundwater flow in the basin. This shallow ground water represents the principal portion of the active groundwater flow system."

Harlow and LeCain (1993), working in coal-bearing Late Mississippian and Pennsylvanian rocks of southwestern Virginia, confirm many of the same hydrologic conditions. They developed a conceptual groundwater flow model using borehole geophysical logging, water quality sampling, and pneumatic straddle-packer assemblies. The following summary highlights some of their findings:

> "…Coal seams had a median transmissivity of 0.15 ft^2/d, whereas other rock types and lithologic contacts had median transmissivities less than or equal to 0.001 ft^2/d. All rock types tested usually were permeable to a depth of approximately 100 feet; however, at depths greater than 200 ft only coal seams consistently had measurable permeability (transmissivity greater than 0.001 ft^2/d). Injection testing of intervals immediately adjacent to coal seams usually indicated lower transmissivity than that obtained when the coal seams were isolated within the test interval, indicating that most lateral groundwater flow is associated with the coal seams. Potentiometric-head measurements for these coal seams coupled with the presence of low-transmissivity intervals between the seams indicate that some of the coal seams could be partly saturated, confined, or semi-confined, and, in some instances, water could be perched above these coal seams.
>
> The mean depth to standing water below land surface was 221 feet in core holes located on hilltops, 109 feet in core holes located on hillslopes, and 39 feet in core holes located in valleys. Potentiometric-head measurements indicate downward flow on hilltops, lateral and downward flow on hillslopes, and upward, lateral, and downward flow in valleys. Because of the high topographic relief (600 – 1000 feet) in the area, groundwater flow systems are of small areal extent. Head relations indicate that high topographic areas function as recharge areas: water infiltrates through the surface, percolates into the regolith, and moves downward and laterally through the fractures in the shallow bedrock. Permeability decreases with increasing depth, and most water may move laterally

> along fractures or bedding planes, or through coal seams until encountering more permeable rock through which to move downward. If more permeable rocks are not encountered, water continues to move laterally, discharging as a spring or seep on the hillside. Where vertical permeability is appreciable, water follows a stair-step path through the regolith, fractures and bedding planes, and coal seams, discharging to streams and (or) recharging permeable coal seams at depth. …"

Harlow and LeCain's study supports the finding of Williams et al. (1993) that coal seams, sandstones, and lithologic contacts were the most transmissive zones with siltstones and shales having the lowest transmissivities. They confirmed that transmissivities of all rock types generally decreases with depth as fracture aperture and number decrease. Their aquifer test data indicated that the horizontal conductivity of coal is a function of depth and probably decreases under ridges due to increased overburden pressure. Regarding topographic setting, they found that hilltops had sharp downward gradients, hillslopes had downward gradients, commonly with shallow zones exhibiting intervals of equal head, and valley wells typically exhibited shallow intervals of equal head below which head measurements indicated downward gradient. Although valleys serve as discharge zones for shallow and intermediate groundwater in this setting, many wells did not show distinct upward gradients. The few wells tested that showed upward gradients were adjacent to streams, possibly indicating this signature is detected only in very close proximity to the stream. This confirms the observations of Callaghan et al. (1998) regarding the locating of piezometers in discharge zones on the Appalachian Plateau of southwestern Pennsylvania. Callagahan reports that upward gradients associated with stream valleys will be detected routinely only where the piezometers are in proximity to the stream, i.e. the discharge area is very small compared to the recharge and lateral flow zones.

Studies conducted in the eastern Kentucky coal field confirm the complex nature of groundwater flow in this setting and the importance of shallow fracture-controlled flow on the Plateaus. Minns (1993), working in a first-order watershed in eastern Kentucky, concluded:

> " …the majority of bedrock groundwater is obtained from fracture zones that are generally within 200 feet of the surface where relatively direct connection to infiltrating groundwater exists. Fractures, coal beds, and bedded strata alter flow paths largely by differences in fracture density that may be lithologically dependent. This creates contrasting conductivities among layers. …A conceptual model for local and regional groundwater flow suggests that local flow systems develop in response to topography: however, the local flow system is contained within the shallow-fracture zone. Flow that does not discharge via the shallow-fracture zone enters the regional flow system. Regional groundwater flow is primarily downward beneath upland areas toward the fresh-saline-water interface. The interface is generally located at its deepest point beneath upland regions and slopes upward toward third-order or larger streams. Regional groundwater flow roughly parallels the interface; consequently, third-order or larger streams are discharge zones for regional flow."

Similarly, work conducted by Wunsch (1993) reinforces the dominant role secondary permeability features play in shallow groundwater movement. Based on data from water-injection packer tests and downhole camera investigations at an unmined ridge in the eastern Kentucky coal field, Wunsch found that only coal seams, vertical fractures, joints, and bedding-plane splits and partings possessed sufficient hydraulic conductivities to transmit significant amounts of water.

HYDROLOGIC EFFECTS OF MINING

It is estimated that millions of cubic meters of groundwater are diverted from natural flow systems every day via drainage from abandoned mines and pumpage from active mines (Sgambat et al., 1980). Mines below the water table in regional groundwater recharge areas can qualitatively and quantitatively impact both shallow and deep aquifers. Mines above the water table in regional recharge areas generally pose more of a water quality problem than quantity problem and may, in some cases, increase groundwater recharge rates over those occurring prior to mining. In discharge areas, mines that intersect the water table can pollute shallow aquifers exposed in highwalls. They can draw down water levels in both shallow and deep aquifers that underlie the mine or that are exposed in highwalls. (Parizek, 1978).

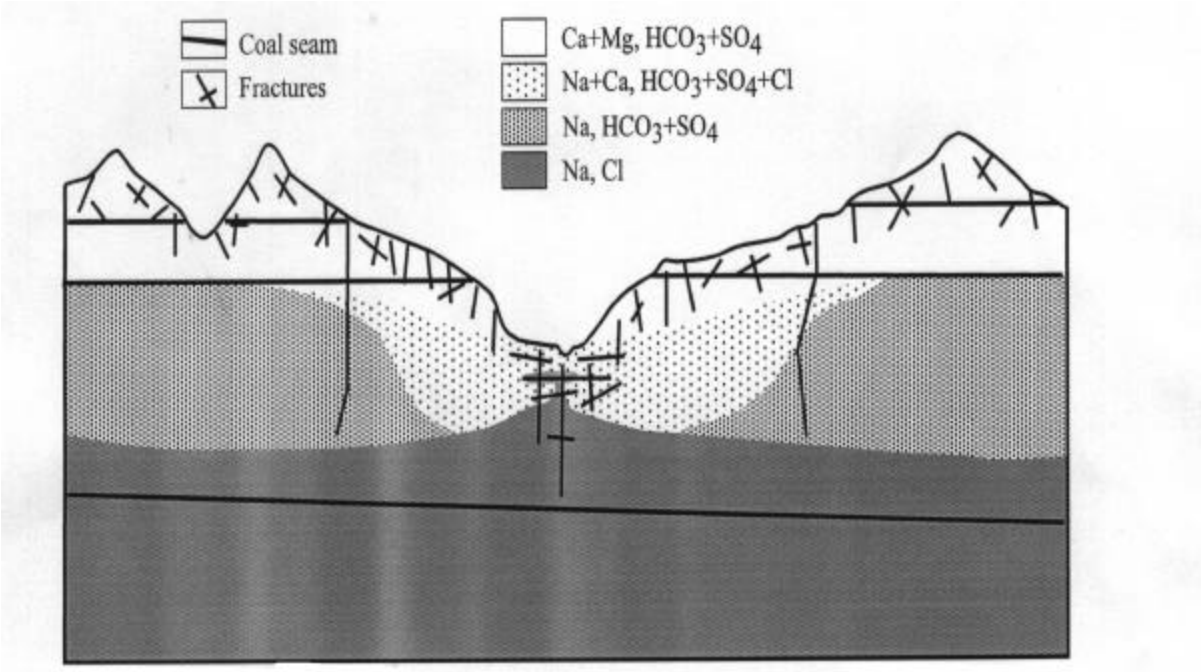

Figure 3.4. Conceptual model of hydrochemical facies (Wunsch, 1993).

The significance of changes in flow systems following mining will vary with the size of the flow system, the position of the mine within the flow system and relative to the initial water table, and the mining-induced fracturing pattern and its interaction with natural fracture sets.

Underground Mining

The hydrologic effects of underground mining are briefly discussed here because they include watershed-wide and even regional scale impacts on groundwater flow systems. Expansive interconnected underground workings act as man-made aquifers with high hydraulic conductivities, and therefore must be accounted for when characterizing groundwater flow systems.

Underground mines can intercept and convey surface water and groundwater. When excavated below the water table, mine voids serve as low-pressure sinks, inducing groundwater to move to the openings from

the surrounding saturated rock. This dewaters nearby rock units via drainage of fractures and water-bearing strata in contact with the mine workings. More remote water-bearing units and surface water bodies can also be affected, depending on the degree of hydrologic communication. Mines located above stream levels serve as free drains and highly permeable aquifers. They promote perched water table formation in poorly permeable overburden deposits, facilitate dewatering of roof rock, and often produce giant man-made springs at mine openings (Parizek, 1978). The extent and severity of the impact on the local surface water and groundwater systems depends on the depth of the mine, the topographic and hydrogeologic setting, and the hydrologic characteristics of the adjacent strata.

In the flat-lying sedimentary rocks of the eastern bituminous coal measures, underground mining is routinely accompanied by overburden movement, rock fracturing, dilation of joints, and separation along bedding planes. Rock movements occur vertically above the mine workings and at an angle projected away from the mine's edge. Mining-induced fracturing within this angle can result in hydrologic impacts beyond the margins of the mine workings. The zone along the perimeter of the mine that experiences hydrologic impacts is said to lie within the "angle of dewatering" or "angle of influence" of the mine. Angle of influence values of 27 to 42 degrees have been reported for the coal fields of northern West Virginia and southwestern Pennsylvania (Carver and Rauch, 1994; Tieman and Rauch, 1991).

Dixon and Rauch (1988) observed stream depletion associated with longwall mining at three mine sites in West Virginia. Dewatering was less severe at mines with greater overburden thickness. Recovery times for stream flow ranged from eight months to five years. Tieman and Rauch (1987) found that streams located above regional base level and undermined by longwall panels less than two and one-half years old were partly to completely dewatered during base-flow conditions. They found that streams located above regional base level and also above panels at least three years old had normal flow. Water lost from streams often did not penetrate to the mine, but instead migrated downward through probable subsidence fractures to near regional base level, where it migrated laterally through a sandstone unit to discharge at a master stream over the mine. Carver and Rauch (1994) drew the following conclusions regarding impacts to streamflow, based on their study of a longwall mine in West Virginia.

> "…Subsidence from longwall mining typically reduced stream discharge for 2-3 years. Panels positioned beneath upland catchment areas and not under streams caused no apparent stream dewatering…. Monitored stream reaches within the angle of draw zone of an adjacent panel did not normally become dewatered for panels older than 2.3 years. However, stream reaches in basins less than 200 acres in size often experienced dewatering for up to 3.1 years after undermining…. After 2-3 years since subsidence, recovered streams display lower high base flow and higher low base-flow discharge, or more uniform base-flow discharge, compared to unsubsided streams….Water diverted from affected streams and supplies remained in the shallow groundwater flow system and probably did not penetrate deeper than local base level, as shown by the reported low groundwater inflow rate to the mine and by the fact that most impacted streams had returned to "normal" down-gradient flows. The lost waters probably moved downgradient as underflow through shallow aquifers and then returned to streamflow in unsubsided or recovered areas."

One important aspect of overburden movement, relative to the potential of high-extraction mining to impact surface waters, is the formation of surface extension zone fractures. An extension zone forms at panel edges and at the traveling panel face and is most pronounced near the surface. Surface extension zone fractures are typically 50 to 100 feet deep. This near-surface zone of increased permeability and storativity can result in shallow aquifer and surface water impacts even where overburden to seam ratios are considerable and there is no direct avenue for drainage to the mine.

Surface Mining

The impacts of surface mining are typically more local than those of underground mining. However, the cumulative impacts from numerous operations can have profound impacts on basin-wide runoff and infiltration, and can even shift the location of surface water and groundwater divides. Such minor shifts in surface water divides can cause significant changes in surface runoff characteristics in small watersheds. This can either increase or decrease total runoff and/or baseflow compared to pre-mining conditions. Shifts in surface water divides tend to be less significant in higher relief areas, such as the Appalachian Plateau, where existing topographic features dominate post-mining topography.

According to Parizek (1978), the effect on groundwater divides is less clear. Highly permeable mine spoil will augment groundwater drainage in a certain direction depending on other controlling factors, such as the dip and lithology of the mine floor. This will cause a shift in the groundwater divide, resulting in a reduction in baseflow or spring flow on the opposing side of the ridge.

Wyrick and Borchers (1981) gave the following reasons for fully assessing stress-relief systems during surface mine design on the Appalachian Plateaus.

> "Strip-mine benches in the Appalachian Plateau are cut through the slump-fracture zone along valley walls, which can affect hydrology significantly. First, aquifer recharge may be increased in several ways during mining by uncovering slump fractures, so that they intercept more surface runoff. The strip mine bench may be so sloped that it retains more runoff water, facilitating aquifer recharge. Second, reclamation regulations require backfilling benches. Such backfilling can seal slump fractures and reduce aquifer recharge if impermeable fill material is used. Third, exposing rocks to weathering and solution on the strip-mine bench can change the chemical quality of aquifer recharge markedly."

PRE-MINING WATER QUALITY AS A PREDICTION TOOL

Natural water quality in shallow groundwater flow systems of the Appalachian Basin results from the influences of three factors: the chemistry/mineralogy of the rock the water contacts, the flow path and the residence time. Shallow flow systems are the key to understanding pre-mining water quality. The recharge area for most springs is the weathered/leached regolith or highly fractured and weathered bedrock (Figure 3.4). The weathered zone is typically 20 to 40 ft (6 to 12 m) thick, but can extend deeper along fractures and is colored red, yellow, or brown due to iron oxidation. The weathered regolith and bedrock has been depleted of the most readily leachable (e.g., carbonate) and oxidizable (e.g., pyrite) minerals. Since this

weathered zone is near the surface, has limited thickness, and has higher permeability (induced by physical (fracturing) and chemical (leaching and oxidation) weathering), groundwater moves through this zone relatively rapidly. Hawkins et al. (1996) estimated the residence time as days to weeks. The lack of readily weatherable minerals and the short residence times result in spring water that is typically dilute.

Below the weathered regolith is a zone of largely unweathered bedrock (Figure 3.5). Weathering is restricted to some fractures and bedding-plane separations. Unweathered rock can contain readily soluble minerals, in particular carbonates, if they are part of the rock composition. The water flowing through the rock has a longer residence time because of lower permeabilities, and the slower flow rate allows longer contact with soluble minerals. The permeability is orders of magnitude less than that for the weathered zone and the residence time is measured in years (Hawkins et al., 1996). Groundwater that has passed through unweathered rock will typically have higher dissolved solids than water emanating from the weathered-rock/regolith zone.

The quality of groundwater from both weathered rock/regolith systems and unweathered rock systems can help to identify the presence or absence of carbonates within the area to be mined. Water chemistry can also shed light on the groundwater flow system. To evaluate the relationship between rock chemistry and water chemistry, Brady (1998a) studied several isolated hilltops where the only recharge was from precipitation, one of which will be reviewed here.

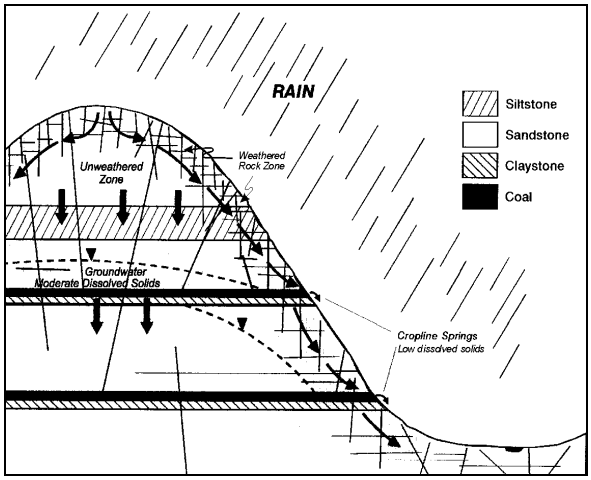

Figure 3.5. Schematic cross section showing conceptual shallow groundwater flow model, which includes the near-surface weathered-rock zone and the deeper unweathered-rock zone (modified from Hawkins et al., 1996).

Field pH and specific conductance were measured prior to mining in several uncased drill holes that were completed down to the upper Kittanning (UK) coal seam. Additionally, numerous UK cropline springs were sampled. Crop springs had alkalinities ranging between 1 and 9 mg/L. Unfortunately, alkalinity was not sampled in the drill holes, but it is a near certainty that the alkalinities were higher, judging from elevated pH and conductance. This hilltop has been mined and the mine is producing drainage with an average alkalinity of 380 mg/L.

The specific conductivity of the crop springs and shallow (near crop) wells had lower values (38 to 62 µS/cm) than the drill holes located toward the middle of the hill where depth to coal was greatest (158 to 221 µS/cm). The pH of the springs was also lower than the pH of the wells. NP is negligible in areas with less than 9 to 12 m of cover, evidently because of weathering. The higher pH and conductance increase are both coincident with an increase in NP. The water in deeper drill holes exhibited higher dissolved solids (reflected as specific conductance) than in cropline springs and holes with shallow cover, due to the increasing abundance of calcareous minerals with increasing overburden. The high NP strata are freshwater limestones and calcareous shales. The geology, stratigraphy, and overburden quality of this area is addressed in Brady et al. (1988), where the mine site is referred to as area "C."

Powell and Larson (1985) investigated water quality in an unmined watershed in a coal-producing region of the Appalachian Plateau of southwestern Virginia. The most common carbonate present was siderite, following by calcite and dolomite. Minor amounts of pyrite were generally associated with coal and adjacent rocks. They observed that water from springs typically had lower concentrations of alkalinity and dissolved solids than water from dug wells, which had lower alkalinity than drilled wells. With one exception, sulfate was less than 40 mg/L for springs, dug wells, and drilled wells. A few of the springs, and many of the deeper wells had high alkalinity (>100 mg/L). Springs with high alkalinity were unusual, indicating that most of the springs were from shallow groundwater sources.

A common misconception has been that water quality from cropline springs in unmined areas is typical of water associated with the coal seam. As already discussed, water associated with coal-cropline springs is typically much more dilute than water from the same coal seam under deeper overburden cover. The cropline springs and shallow wells represent water flowing through the near-surface weathered-rock zone. Calcareous rocks are typically absent or negligible within this weathered zone. Wells penetrating deeper overburden are completed in unweathered or less weathered rock with lower permeability. The combination of calcareous minerals and longer residence time for the groundwater results in significant dissolution of calcareous minerals forming bicarbonate alkalinity. Downward flow and substantially lower hydraulic conductivities probably result in little of this water reaching the cropline springs.

Pre-mining alkalinity in deeper drill holes provides a second confirmatory tool, along with acid-base accounting NP, to determine the relative presence or absence of calcareous rock and its distribution within the proposed mine area. As discussed by Brady (1998a), there appears to be a direct relationship between the amount of calcareous material preserved in the overburden and the alkalinity, conductivity, and pH of the pre-mine groundwater. In contrast, no relationship exists between MPA (i.e., % sulfur) and sulfate concentrations in the pre-mine groundwater. This is probably because of the very limited oxidation of pyrite under saturated conditions. Calcareous minerals are rather soluble in groundwater, while pyrite is not. Beneath the weathered zone, pyrite in unmined areas remains largely unoxidized. If elevated sulfate concentrations are found, it may indicate contamination from an adjoining mine or from an oil or gas well.

To summarize, water quality is directly related to the flow path, the dissolution of minerals contacted by the groundwater, and the contact time of the water with the rock. Cropline springs and shallow wells (6-9 m deep) that have little or no alkalinity indicate shallow leached/weathered overburden. No significant calcareous strata (measured as NP) are likely to occur within this zone. Where calcareous rocks are

present, such as some deeper cover situations, the calcareous minerals will dissolve in the water and can be measured as alkalinity. Low alkalinity in well or spring water indicates the absence of calcareous strata within the groundwater flow path for that well or spring. It might be expected that sulfate would reflect the amount of pyrite that is present, but there is no relationship between the amount of pyrite and sulfate concentrations, indicating that pyrite oxidation prior to mining is typically negligible.

These findings have several important implications:

1. Coal cropline springs typically reflect very shallow flow through the regolith and do not necessarily reflect water quality under deep groundwater conditions.
2. Wells are needed to ascertain water quality in the deeper unweathered-rock zone.
3. There is a relationship between overburden NP and groundwater alkalinity. If alkalinity in wells is relatively high (> 50 mg/L), calcareous minerals are present in the flow system and probably near the water sampling point. Where alkalinity is low (< 15 mg/L), the rocks within the recharge area lack appreciable calcareous minerals.
4. Groundwater alkalinity can be used to help determine whether overburden sampling has been representative. If overburden analysis does not indicate significant calcareous rocks to be present, but water wells into the same units are alkaline, the sampling may not be representative of site conditions and additional drilling would be warranted. The combination of groundwater alkalinity and overburden NP can be used together to better define the extent of calcareous overburden.
5. Overburden sampling and water sampling must represent both shallow and deep overburden cover to adequately represent the entire mine site hydrology and overburden chemistry. Holes drilled at greater than the maximum cover to be mined may overestimate NP in the overburden that will be disturbed by mining.
6. There is no observed relationship between MPA in the overburden and sulfate or any other parameter in the groundwater. Sulfate in groundwater from unmined watersheds is typically less than 40 mg/L, regardless of location within the flow system (Brady, 1998a).
7. The above conclusions are probably applicable to a large portion of the Appalachian Plateau. However, its applicability to other areas is unknown.

State Practices

Of the states interviewed, only Pennsylvania and West Virginia actively use pre-mining water quality to help predict post-mining water quality. All do pre-mining water quality assessments, but they generally do so to establish a baseline that will allow them to detect changes in ground and surface water quality and quantity. Table 3.2 summarizes the text that follows.

Alabama requires at least 6 months of 1 sample per month, to include seasonal variation, for all surface streams and seeps and at least 1 ground water monitoring well. Water sample analyses must include iron, manganese, aluminum, sulfate, alkalinity, acidity, and temperature. Pre-mining ground water quality information must also be provided for the strata below the coal bed.

Indiana requires at least 6 months of 1 sample per month, to include seasonal variation, for all surface streams and seeps. Stream sampling must include data from both upstream and downstream of the permit

Table 3.2. State Requirements for Pre-mining Water Quality

STATE	PRE-MINING WATER SAMPLING REQUIREMENTS		COMMENTS
	SURFACE WATER	GROUNDWATER	
AL	A minimum of 6 months of 1 sample per month for streams and seeps. Water analysis: Fe, SO_4, Mn, Al, acidity, alkalinity, and temperature.	A minimum of 6 months of 1 sample per month from at least 1 monitoring well. Water analysis same as for surface water, but includes strata below the coalbed.	Performs pre-mining WQ assessments to establish a baseline for detecting any impacts on water quality and quantity.
IN	A minimum of 6 months of 1 sample per month for streams and seeps. Water analysis: flow, TDS or specific cond. TSS, pH, Fe, Mn, acidity, and alkalinity.	A minimum of 6 months of 1 sample per month from all wells. Water analysis same as for surface water.	Same as AL
KY	Surface waters should be sampled at each affected watershed.	6 samples over 6 months prior to mining; quarterly during mining. Must characterize each affected aquifer and hydrologic regime.	Same as AL
MD	At least 6 months of 1 sample per month or quarterly samples for 1 year. Should include: Fe, Mn, Al, SO_4, alkalinity, and acidity for surface streams.	Not required	Same as AL
OH	At least 6 months of 1 sample per month or one high flow and one low flow. Must include: flow, TDS or specific conductivity, TSS, pH, Fe, Mn, SO_4, hardness, acidity, and alkalinity.	All identified aquifers must be sampled under seasonal conditions on at least 10 (all if less than 10) wells. Analysis must include at least same parameters as surface water; more may be required.	Same as AL. Sampling requirements are being changed to insure that seasonal effects are fully assessed.
PA	2 samples of any surface flow or seep, with monitoring points chosen from background sampling points, which must be sampled monthly for 6 months, including at least 1 month of low flow. Must include: alkalinity, acidity, pH, Fe, Mn, SO_4, specific conductance, suspended solids, and Al for high quality streams.	Data can be from on-site or nearby residential wells and must be sampled during mining as a permit requirement. Analyses must include: pH, alkalinity, acidity, Fe, Mn, SO_4, specific conductance, and suspended solids. Results are compared with NP values for consistency.	Actively uses pre-mining water quality to help predict post-mining water quality. Performs pre-mining WQ assessments to establish a baseline for detecting impacts on water quality and quantity.
TN	A minimum of 6 months of monthly sampling for surface water, and may request 1 year of baseline data.	Well samples that are representative of undisturbed groundwater quality.	Same as AL
VA	At least 6 month baseline of sampling for surface water. Sampling must include upstream and downstream data.	At least a 6 month baseline of monthly sampling for groundwater quality	Same as AL
WV	A baseline of water quality and flow for all existing surface water for at least 6 months with 1 sample per month. Sampling and analysis according to OSMRE methods. Data are used with models to predict the probable hydrologic consequences.	Well level determinations (if landowners allow access). Sampling and analysis according to OSMRE methods. Data are used, with models, to predict the probable hydrologic consequences.	Actively uses pre-mining water quality to help predict post-mining water quality. Performs pre-mining WQ assessments to establish baseline to detecting any impacts on water quality and quantity.

area. Water samples must include flow, and be analyzed for: total dissolved solids (TDS) or specific conductance, total suspended solids (TSS), pH, total iron, total manganese, acidity, and alkalinity. Additional parameters may be required to adequately characterize the site. For groundwater, a minimum

of 6 months of 1 sample per month is required for operator installed wells and for residential/domestic wells in or within 1000 feet of the permit area. In addition to water level, samples must be analyzed for the same parameters as required for surface water samples.

Kentucky requires six ground water samples over a period of six months prior to mining, and quarterly during mining operations. The data should be adequate to characterize each affected aquifer and hydrogeologic regime. Surface waters should be sampled at each affected watershed.

Maryland requires at least 6 months of 1 sample per month or quarterly samples for one year that include iron, manganese, aluminum, sulfate, alkalinity, and acidity for surface streams.

Premining water quality assessments are performed in Ohio in order to establish a baseline for detecting any mining or reclamation impacts on ground and surface water quality and quantity and to assess the cumulative hydrologic impacts of the proposed operation. Ohio currently requires at least one sample per month for six consecutive months or two samples, one during a high flow period and one during a low flow period to determine seasonal variations, with the periods substantiated with supporting data. Only one sample is generally required from existing water impoundments (especially those from unreclaimed mining operations). The applicant must sample for pH, total acidity, total alkalinity, specific conductivity or total dissolved solids, total manganese, total sulfates, total iron, total suspended solids, total hardness, and flow. Other parameters may be required. Sites reviewed are generally within 1000 feet of the proposed operation, although the review area can be extended on a site-specific basis.

However, changes will likely be implemented in near future. Under the draft, one high flow window, one low flow window, and two intermediate flow windows have been defined, based on historic flow patterns. Each required surface water and ground water site (other than existing impoundments from previous unreclaimed mining) must be sampled in the high flow, the low flow, and one intermediate flow window.

All identified aquifers must be sampled under seasonal conditions. The applicant must sample for pH, total acidity, total alkalinity, specific conductivity or total dissolved solids, total manganese, total sulfates, total iron, total suspended solids, total hardness, flow (for springs and deep mine discharges)and static water level (for wells). Other parameters may be required. Sampling must be conducted on at least ten (all if less than ten), or 25% of the groundwater sites, whichever number is greater. Sites reviewed are generally within 1000 feet of the proposed operation, although the review area can be extended on a site-specific basis.

Pennsylvania requires both ground water and surface water quality data. Groundwater data can be from either onsite or nearby residential wells (within 1000 feet) that, in addition, must be sampled during mining as a permit requirement. Groundwater analyses must include pH, alkalinity, acidity, iron, manganese, sulfate, specific conductance, and suspended solids. Results of the analyses are compared with NP values for consistency. Surface water quality requirements include a background sampling program of 2 samples of any surface flows or seeps. Monitoring points are then chosen from among these background sampling points to be sampled monthly for 6 months, including at least 1 month of low flow in July, August, or September. Analysis is the same as for ground water, with the addition of aluminum for high quality streams.

Tennessee requires a minimum of 6 months of monthly sampling for surface water, and may request 1 year of baseline data for areas that are considered at risk for AMD production. They also request well samples that are representative of undisturbed ground water quality.

Virginia requires at least 6 months of monthly sampling for both surface and groundwater quality. Stream sampling must also include data from both upstream and downstream of the permit area.

West Virginia requires the applicant to establish a seasonal baseline of water quality and flow for all existing surface water of at least 6 months with 1 sample per month. West Virginia also requires well level determinations (if landowners will allow access), and sampling and analysis of ground and surface waters according to OSMRE methods. Together with mathematical models, these data will predict the probable hydrologic consequences of the proposed operation.

GROUNDWATER CHEMISTRY FROM ADJACENT PREVIOUSLY MINED AREAS AS A PREDICTION TOOL

Water quality from prior mining has been used as a prediction tool since at least the early part of the twentieth century. More recently, Brady and Hornberger (1990) and Brady (1998b) discussed the use of post-mining water quality from adjacent sites as a prediction tool for surface mines. The assumption is that if the same coal and overburden are being mined and the mining conditions are similar, hydrogeologic conditions will be sufficiently alike so that the groundwater quality from the proposed mine will approximate that of the previously mined area. Frequently, this is the case. Groundwater chemistry from previous mining, when available and used properly, can be the best prediction tool in the tool kit. In fact, as subsequently discussed, there are times when the requirement for acid-base accounting (ABA) is waived in some states because water quality from previous mining has demonstrated that mining can occur without pollution.

The major advantage of looking at the quality of pre-existing mine drainage is that it is the result of a full-scale weathering (leaching) test, which has incorporated into it climatic, mining and other variables. Climatic variables include site-specific precipitation and field temperatures, including any seasonal variations. Field conditions also include infiltration and runoff factors. The mining variables include the strata (lithologies) encountered by mining, including its variability within the site, and the redistribution of these rocks in the spoil. Other variables include spoil pore gas chemistry, including vertical variations, and real world scale (i.e., rock particle size, ratios of rock volume to water volume). These are factors that are only approximately simulated, if at all, in laboratory leaching tests. Studies of previous mining also provide information on actual concentrations of mine drainage constituents, including pH, alkalinity, acidity, Fe, Mn, Al, and sulfate. Interpretation, however, requires an understanding of the limitations of this method.

The most confident predictions of post-mining water quality will always be those made using a variety of prediction tools, especially if each tool points toward the same conclusion. Adjacent mining is often given precedence when prediction tools are conflicting. Much more often than not (although there are exceptions), if post-mining water quality at adjacent mines is good, the ABA will likewise show calcareous overburden and pre-mining water quality will be alkaline.

However, certain factors must be considered when interpreting water quality from previously mined areas: whether the proposed mining is on different coals and overburden, whether mining is on the same seam(s) but with significant differences in stratigraphy or in amount of area disturbed, and whether potential hydrologic complications or differences in mining practices exist. Each of these, if not properly taken into account, can lead to improper predictions of water quality for the proposed surface mine.

Proper Correlation of Sedimentary Units

Predictions of water quality based on what has occurred at nearby mines can only be valid if the same coal seam(s) and strata are being considered. Accurate geologic maps that show coal croplines and structure are an extremely helpful aid in assuring correct correlations of coal seams. Numerous excellent studies by the state geological surveys have helped resolve stratigraphic correlation problems. Local geologic reports also show stratigraphic correlations, locations of coal outcrops, and structure. However, site specific and nearby permit drilling information should always be used to confirm correlations.

Some examples will illustrate the importance of knowing which coal seams were mined. The first example involves the Clarion and lower Kittanning (LK) coals in Redbank Township, Clarion County, Pennsylvania. Water quality associated with the LK seam is typically acidic, and is consistent with results of ABA, which shows up to 30 ft (10 m) of strata with % S frequently being 0.5 to 7.5%.

The marine Vanport limestone occurs stratigraphically between the Clarion and the LK coals. Although no ABA was performed on the Vanport in this vicinity, it typically has greater than 80% calcium carbonate. The limestone is about 6 ft (2 m) thick in the area of the mine site. Where the spoil is predominately Clarion coal overburden, the drainage is net-alkaline. Mine discharges predominantly associated with the LK coal are net-acidic. Discharges that are a mixture of Clarion and LK spoil range from net-alkaline to net-acidic. The mixed spoil, even when acidic, is less acidic than water from areas where just the LK coal was mined. Thus, the overburden from the two coals produces different water qualities.

The importance of knowing which coals were mined in an area is also illustrated by a study near Luthersburg in Clearfield County, PA (David Bisko, DEP hydrogeologist, personal communication, 1991). The lower through upper Kittanning (UK) coals were mined. The lower and middle Kittanning (MK) coals, if surface mined by themselves, produce acidic drainage. If these coals are mined in conjunction with sufficient calcareous strata associated with the UK coal, the water quality is usually alkaline. Most mines in the area did multiple seam mining, although the combination of seams mined varied from site to site. Overburden above the LK and MK coals is high in sulfur (up to 2.7%), but low in NP. The highest NP's are associated with the Johnstown limestone, which occurs below the UK coal.

The point of the above examples is that mines having similar geology can be meaningfully compared but that mines involving different sections of strata should not be compared. Overburden chemistry above one seam should never be relied upon to represent a different seam. Water quality prediction requires knowing the stratigraphic relationships of the coal seams that were mined, and seam specific data is required.

It is also necessary to accurately correlate drill holes within a mine site. If drill logs are not accurately correlated, the interpretation is erroneous.

Effects of Variations in Stratigraphy, Weathering and Disturbed Area

Mining may be proposed on the same seam, but if there are significant stratigraphic changes between the previously mined area and the proposed area, comparisons may be inappropriate. The two most common factors related to stratigraphic changes are geologic facies differences from one mine to the next, and the mining of differing amounts of cover. Higher cover will encounter additional strata. An additional factor is the role that differing amounts of disturbed area can have on water chemistry.

Paleoenvironmental maps can help predict the distribution of facies; however, studies of this type are rare. Even if good paleoenvironmental maps exist, facies changes can be abrupt, and detailed drilling is typically necessary in areas of facies transition. Paleoenvironmental maps probably are best used as a tool for designing an overburden sampling plan.

An example of the role of facies changes can be illustrated by six mines studied in the Stony Fork watershed in Fayette County, Pennsylvania (Brady et al., 1988). All mined the UK coal seam. The mines developed in the area interpreted as a high-energy depositional environment have sandstone and siltstone overburden. The sandstone and siltstone units are not calcareous, whereas the low-energy deposits contain calcareous shale and freshwater limestones. Mines in the area containing the calcareous strata produce alkaline drainage. Mines with predominately sandstone overburden produce acidic drainage.

One mine is within both the high- and low-energy depositional environments. Inspection of the active highwall revealed an area where the limestone was eroded and replaced by a channel deposit. All the overburden drill holes were located within the low-energy portion of the mine, thus over-estimating the calcareous nature of this site. This permit was issued prior to an understanding of the lateral distribution of depositional facies. If the true nature of the site had been known, the permit would have been denied or the mining plan would have been modified to compensate for the acid potential of the sandstone overburden.

Different amounts of cover mined on the same coal seam can also result in different water quality. Because of equipment limitations, old pre-act mining from the 1940s and 1950s seldom exceeded 40 ft (12 m) of cover. Improvements in mining technology have allowed many of these sites to be remined to greater cover heights. Mining of additional cover can have both positive and negative influences. Figure 2.7 illustrates a situation where low cover mining ~40 ft (12 m) or less would encounter high sulfur strata, but no appreciable calcareous strata. A mine would not encounter calcareous strata until a highwall height of 40 ft (12 m) or more was reached, due to the stratigraphic position of the calcareous strata and the dissolution of carbonates by surface weathering. Shallow mining <40 ft (12 m) would probably result in acidic drainage, whereas mining to a cover height of 85 ft (26 m) should encounter enough calcareous rock to result in alkaline drainage.

An example of where mining more overburden resulted in a deterioration of water quality is illustrated in Brady (1998b). The original shallow-cover <30 ft (10 m) mining occurred in the 1950s, and only a few tens

of acres were affected. This site had some acid-producing strata located near the coal, and essentially no calcareous strata. The water quality in 1978 through 1981 had low concentrations of sulfate, acidity, manganese, and aluminum, and little variation in their concentrations. Specific conductance was also low (~100 µS/cm). Mining that occurred from Nov., 1980 - Sept., 1985 took a maximum of 80 ft (24 m) of overburden and affected approximately 175 acres (71 hectares). Acidity, manganese, sulfate, aluminum and specific conductivity all increased.

Hydrogeologic Complications

There are several hydrologic complications that can affect the use of water quality from adjacent mines as a prediction tool. The most obvious of these is the situation where there is no water discharging from the previously mined area. This can be falsely assumed to mean success, because there are no contaminated discharges. The absence of discharges does not mean that there is no associated water flowing from the mined area. In the humid climate of the northern Appalachian Basin, groundwater recharges the mine spoil and is undoubtedly flowing somewhere. It may not discharge as seeps or springs, but may be entering a deeper groundwater flow system and ultimately discharging as base flow to a stream or contributing to a discharge from a lower stratigraphic interval.

Adjacent mining as a prediction tool only works where there is representative groundwater (from springs or wells) that can be sampled and analyzed. If groundwater sampling points are inadequate, monitoring wells or piezometers can often be installed into previously mined spoil or into an underlying aquifer to ascertain the post-mining water quality. Groundwater chemistry is rarely uniform through time or through space.

When using water quality data as a prediction tool, it must be kept in mind that water quality, even at the same sample point, is not normally a constant, but will vary for a variety of climatic reasons such as seasonal influences and precipitation/infiltration events. In some instances, not only water quality, but also water quantity must be considered. Flow can affect concentration of water quality parameters.

Not all mines respond similarly. Smith (1988) and Hornberger et al. (1990), in discussing flow, concentration, and load, point to three types of discharges. Brady (1998b) describes a fourth type of discharge that is also discussed below. The four types of discharges are:

1. High flow - low concentration / low flow - high concentration response, where the flow rate varies inversely with concentration and variability is generally very great;
2. Steady or damped response discharges that exhibit relatively minor or delayed response in flow rate with minor changes in chemical characteristics;
3. “Slugger” response, where dramatic increases in discharge are accompanied by little change in concentrations, resulting in large increases in loading; and
4. “Slammer” response, where dramatic increases in discharge are accompanied by increases in concentration, resulting in extremely large increases in loading.

Since mine drainage discharges vary in response to climatic events, to accurately characterize mine discharge chemistry, it is necessary to have multiple samples that truly represent seasonal variation and

climatic events such as rainfall and snowmelt. The “slugs” and “slams” of sulfate and acidity following rain events at some sites are apparently due to soluble sulfate salts that build up during dry periods as a result of pyrite weathering in the unsaturated mine spoil. These salts are essentially stored mine drainage. Infiltrating waters from rainfall or snowmelt dissolve these salts, and flush them into the saturated groundwater zone (Brady, 1998b). If one fails to sample the site during such events, an important component of the site water chemistry may have been missed.

Another complication in interpreting mine site water quality is that water chemistry can vary within a mine, to the extent that some mines produce both alkaline and acidic water (Brady, 1998b). In addition, even at sites that produce either alkaline or acidic water, water quality trends may change over time. The point to be made here is that a single sample may not reflect the true character of water being produced by a mine.

Another thing that must be kept in mind about groundwater is that its chemistry can change along its flow path. Dissolution or precipitation of minerals can alter the original chemistry of the mine drainage. When conditions allow for oxidation of iron, spoil water within the subsurface may be high in iron, and have a higher pH, than a surface discharge from the “toe” of the spoil. As an acidic plume travels through calcareous rocks, some attenuation of the mine drainage quality should occur. Also, groundwater samples may be a mixture of water from mined and unmined (or mined on a different seam) sources.

Interference from other sources of contamination can also complicate interpretation. Mine drainage from coal mines, however, is typically distinct enough in chemistry that other sources can be readily identified. For example, mine drainage is notorious for containing elevated sulfate, but surface mines normally have low chloride concentrations. Gas and oil well brine waters, on the other hand, have low sulfate in comparison to the high chloride concentrations. The differences are so distinct that they should not be confused. However, sometimes water from the two can commingle, producing a mixed chemistry.

The bottom line is that caution must be exercised when interpreting groundwater chemistry from previously mined areas. Multiple samples from the same location and multiple sample locations, plus an understanding of the groundwater hydrology, are invaluable and will contribute to accurate interpretations of the data.

Surface water is more difficult to use as a prediction tool than groundwater. This is due to dilution of mine drainage by runoff, mixing of waters from tributaries that are not impacted by mining, groundwater baseflow from areas unaffected by mining, flow of ground or surface waters affected by mining on a different seam of coal, and alteration of water quality by oxidation and precipitation of metals (Brady, 1998b). Stream water quality can be useful, however, in presenting a “broad-brush” view of mining-related problems over a large area. It is most useful for relatively conservative parameters such as sulfate and manganese. Surface water quality studies such as Wetzel and Hoffman (1983, 1989) can show broad regional trends in water quality. However, unless more detailed information is available, such as what seams were mined, how much of the watershed was mined and what mining and reclamation practices were used, this information is not generally useful for predicting water quality for a proposed mine site.

Differences in Mining Practices

Differences in mining practices must be considered when water quality from previous mining is being used to make predictions. Recent advances in surface mining practices have the potential to favorably affect water quality, as compared to old pre-act surface mines. Examples are concurrent reclamation, alkaline addition, special handling, and engineering water movement through or around the backfill. A site that includes these pollution prevention measures may produce different quality water than sites that did not.

Mine sites that clearly employed adverse practices may be producing water of poorer quality than what a proposed mine site would produce employing favorable mining practices. Mining practices that could have adversely affected surface mine water quality include disposal of refuse from a coal processing plant, auger mining, improper handling of acidic strata, and non-concurrent reclamation. Other mining practices that may influence post-mining water quality are the type of mining equipment used (dragline vs. trucks and loaders vs. bulldozers), and the length of time a pit remains open and exposed to weathering.

Regulatory agency experience has shown that long-term interruptions in mining and reclamation on surface mine sites with low NP overburden can result in poor post-mining water quality. During the cessation, the acidic spoil is left exposed to the elements to weather and form acid products. When comparing mines on the same coal seam that were mined concurrently with mines that had long-term interruptions, the areas that were mined intermittently frequently had poorer water quality.

Water quality from underground mines may differ significantly from surface mine water quality on the same coal seam. As a general rule of thumb, if an underground mine on a particular coal seam is making alkaline drainage, a surface mine on that same seam will also produce alkaline drainage. The inverse, however, is not necessarily true. If an underground mine is discharging poor quality water, it should not be assumed that a surface mine on the same seam will also produce poor quality water. The reason for poorer water quality from underground mines relative to surface mines is that in underground operations, the strata with the maximum disturbance and exposure to weathering is the coal, roof rock and floor rock. This rock frequently has the greatest amount of pyrite in the overburden. Post-mining caving and collapse of the mine roof and crushing of coal pillars increases the surface area of these pyritic rocks. Water and air flowing through the mine will cause pyrite in the rock to oxidize. In contrast, at surface mines, almost all of the coal is extracted and removed, and stratigraphically higher overburden rock is disturbed. If this overburden rock is calcareous, alkalinity generation can neutralize acid and inhibit pyrite oxidation.

"Daylighting" (remining an underground mine by stripping) can thus dramatically improve water quality (Brady, 1998b; Skousen et al., 1997). For example, at a site mined in Allegheny County, Pennsylvania during the early 1900's, water samples collected in 1974 had a pH below 3 (Pennsylvania DER, 1976). Aloe Coal Company began daylighting the underground mine in the mid-1970's. They daylighted approximately 60 percent of the mine (John Davidson, mine inspector, personal communication in Brady, 1998b). Aloe mined up to 250 ft (87 m) of cover, which is not normally economical; however, this was a "cost-plus" operation (the coal buyer paid costs, plus a profit). There are several freshwater limestone units that were encountered by Aloe, the thickest being the Benwood, which is frequently 50 ft (15 m) thick.

After daylighting, the water had a pH above 7 (1995). Most daylighting will not encounter as much calcareous strata as in the above example and the water quality improvements may not be as spectacular; however, when calcareous materials are encountered during daylighting operations, water quality does generally improve.

State Practices

State practices for the evaluation of data from adjacent mining activities are outlined in Table 3.3.

Alabama permits reviewers look at adjacent permits and make those files available to the applicant. The applicant is required to prepare a 1:2000 scale site map with their hydrologic reclamation plan that includes surrounding mines, the new permit area, monitored streams, and ABA sampling locations. The applicant is also required to collect baseline water quality data on adjacent mines, including all discharges, seeps, and surface streams. The permit reviewer looks at adjacent mining ABA analysis and coal sulfur to compare for consistency with the submitted ABA results for the new permit. Special handling, alkaline addition, or mining practices that may have affected post-mining drainage quality on adjacent sites are also identified.

Illinois and Indiana do not require adjacent mine data, though an operator can include applicable information from adjacent operations. However, information is required for baseline data for wells and streams within 1000 feet (and sometimes more) of the permit area. Available information from adjacent sites is used during permit review. The states may use their own resources to determine the cause of any AMD on adjacent sites and may request the applicant to address the suspected cause. The permit reviewer will compare ABA and water quality analysis from the applicant with data from adjoining sites for consistency. Special attention is given to known acid-producing units to ensure that they are identified and accounted for.

Kentucky may require data from adjacent sites, if problems were previously identified there. Data required may include drainage water quality, overburden quality, and details of the mining history and any spoil handling practices.

Maryland requires 1 to 2 water quality samples from the applicant for every expression of surface water on adjacent mines. The reviewer compares the ABA analysis from the applicant with the ABA data from adjacent sites for consistency, and identifies any special handling, alkaline addition, or mining practices that may have affected post-mining drainage quality.

Ohio requires the applicant to analyze any existing water quality data from nearby permits and to present the data in the form of tables, graphs, or spreadsheets. The permit reviewers also examine geologic and hydrologic data from adjacent mines.

Pennsylvania considers data from adjacent, reclaimed mining to be the most important tool in pre-mining AMD prediction. As a result, only about 50% of new permit applicants are required to provide overburden analysis based on the post-mining discharge quality at adjacent sites. Applicants are required to do an exhaustive background sampling of all accessible discharges within 1000 feet of the new permit or any discharges that are considered hydrologically connected to the new permit. Pennsylvania also reviews all the available adjacent permit applications to check overburden analysis and geologic correlation for

Table 3.3. State requirements for data from adjacent mining activities.

State	Requirements	Comments
AL	A hydrologic reclamation plan with a 1:2000 scale site map. Baseline data on adjacent mines should include seeps, discharges, and streams.	Files from adjacent permits are available. Reviewers compare adjacent mining ABA analysis for consistency with the ABA submitted with the new application. Special practices on adjacent sites are also identified.
IL, IN	Not required.	Data from adjacent sites, if available, is used internally. Agency may use own resources to determine cause of any AMD, and then require the applicant to address the issue. Reviewers compare adjacent mining ABA analysis and water quality analysis for consistency with the ABA submitted with the new application.
KY		May require data from adjacent sites if problems were previously identified there, including drainage water quality, overburden quality, and details of the mining and spoil handling practices.
MD	1 to 2 water quality samples for every expression of surface water on adjacent mining.	Reviewer compares ABA analysis from the applicant with ABA data from adjacent sites, and identifies any special practices that may have affected post-mining drainage quality.
OH	Must present any existing water quality data from nearby sites.	Reviewers also look at geologic and hydrologic data from adjacent mines.
PA	Exhaustive background sampling of accessible discharges within 1000 feet of the new permit or any discharges considered to be hydrologically connected to the new permit.	Data from adjacent, reclaimed mines considered the most important tool in pre-mining AMD prediction. Only about 50% of new applicants are required to provide overburden analysis, based on adjacent site post-mining discharge. All adjacent permit applications are reviewed for consistency, and to identify any special practices that may have affected water quality.
TN	Site surveys on adjacent mines for surface discharges, seeps, and streams. At least 1 water sample for any identified surface water sources.	Reviewers compare ABA analyses from the applicant with ABA from adjacent sites for consistency, and identifies any special practices that may have affected post-mining drainage quality.
VA	No mandatory requirement to submit adjacent mining data.	Data from adjacent mining is used internally. If an adjacent mine has AMD, VA may determine the cause and request the applicant to address it in the application. Reviewers compare ABA analyses for consistency. Special attention is given to known acid-producing units.
WV	No mandatory requirement to submit adjacent mining data.	Data from adjacent mines is used internally. ABA analyses are compared for consistency, and to identify any special practices that may have affected post-mining drainage quality. Emphasis placed on field inspectors' knowledge, their experience with AMD production on nearby permits, and the willingness and ability of operators to follow special handling and mining requirements.

consistency, and to identify any special handling, alkaline addition, or coal or coal preparation waste disposal provisions that may have affected final discharge water quality. Reviewers pay particular attention to inspection reports on adjacent sites for problems or violations, for example, citations for not abiding by

special handling provisions, unauthorized addition of alkaline or acidic material, and violating concurrent reclamation requirements.

Tennessee requires site surveys on adjacent mines for surface discharges, seeps, and streams. At least 1 water quality sample must be submitted from the applicant for any identified surface water sources. The permit reviewer compares the ABA analysis from the applicant with the ABA from adjacent sites for consistency, and identifies any special handling, alkaline addition, or mining practices that may have affected post-mining drainage quality.

Virginia uses data from adjacent mines internally during the permit review process, but does not have any mandatory requirement that permit applicants submit such data. If an adjacent site has any AMD discharges, the reviewing agency may use its own resources to determine the cause and then request the applicant to address the suspected cause in the permit application. The reviewer also compares the ABA analysis from the applicant with any ABA data that is available from adjacent sites for consistency. Special attention is given to known acid-producing units in the permit area to ensure that they are identified and accounted for by the applicant.

West Virginia also uses data from adjacent mines internally during the permit review process without any mandatory data requirement of the permit applicants. The reviewer compares the ABA analysis from the applicant with the ABA from adjacent sites for consistency, and identifies any special handling, alkaline addition, or mining practices that may have affected post-mining drainage quality. Permit reviewers place special emphasis on the knowledge of field inspectors, discussing with them their experiences with AMD production on any nearby permits, and the willingness and ability of those operators to follow any special handling and mining requirements that may have been in place.

HYDROLOGIC CONTROLS

The installation of hydrologic controls, such as highwall drains, floor drains, and surface diversions, can impact post-mining water quality by influencing what materials are encountered by the ground water and the final discharge rate. Hydrologic controls can either enhance drainage, deter it to cause permanent inundation, or be used in conjunction with special handling in an attempt to prevent acid formation. State practices for hydrologic controls are outlined in Table 3.4.

Illinois and Indiana do not require surface infiltration controls except for special situations, such as coal processing waste disposal areas. Ohio requires that all surface drainage be directed to a properly designed sediment control structure, but will grant exemptions for small areas if suitable alternative measures are implemented. The applicant must also describe how the pre-mining recharge capacity will be restored. All of the other states except Kentucky identified the active use of surface infiltration controls, mostly in the form of diversion ditches or french-type drains, to limit the amount and exposure of water to potentially acid materials in the backfill. Maryland, Pennsylvania, Tennessee, Virginia, and West Virginia also note the use of spoil sub-drains and highwall drains in conjunction with selective spoil handling to control post-mining water levels and maintain a *high and dry* isolation environment for acid-producing material. West Virginia also allows encapsulation.

Table 3.4. State practices for hydrologic controls

State	Hydrologic Control Practices
AL	Surface infiltration controls actively used, mostly in the form of diversion ditches or french-type drains, to limit the amount and exposure of water to potentially acid materials in the backfill.
IL, IN	Not actively required except for special situations, such as for coal refuse.
KY	Did not identify any surface infiltration controls.
OH	All surface drainage must be directed to a properly designed sediment control structure. Exemptions may be granted for small areas if suitable alternative measures are implemented. Applicant must also describe how the pre-mining recharge capacity will be restored.
MD, PA, TN, VA	Surface infiltration controls actively used to limit the amount and exposure of water to potentially acid materials in the backfill. Spoil sub-drains and highwall drains are also used, in conjunction with selective spoil handling to control post-mining water levels and maintain a *high and dry* isolation environment for acid-producing material.
WV	Surface infiltration controls actively used to limit the amount and exposure of water to potentially acid materials in the backfill. Spoil sub-drains and highwall drains are also used, in conjunction with selective spoil handling to control post-mining water levels and maintain a *high and dry* isolation environment for acid-producing material. Also allows encapsulation.

REFERENCES

Arndt, H.H. and P. Averitt, 1968. Mineral Resources of the Appalachian Region – Coal, USGS Professional Paper 580, U.S. Department of the Interior.

Back, W., J. S. Rosenhein, and P.R. Seaber, 1988. The Geology of North America, Hydrogeology, Geologic Society of America, Volume O-2.

Becher, A. E., 1978. Ground Water in Pennsylvania, PA Geological Survey, Educational Series #3, PA Department of Conservation and Natural Resources, Harrisburg, Pa.

Brady, K.B.C, A.W. Rose, J.W. Hawkins, and M.R. DiMatteo, 1996. Shallow groundwater flow in unmined regions of the northern Appalachian Plateau: Part 2. Geochemical characteristics. In: Proc. of the 13th Annual Meeting, American Society for Surface Mining and Reclamation.

Brady, K.B.C., 1998a. Groundwater Chemistry from Previously Mined Areas as a Mine Drainage Prediction Tool. In: Brady, K.B.C., M.W. Smith and J. Schueck (Eds.), Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania. PA DEP, p. 9-1 – 9-21.

Brady, K.B.C., 1998b. Natural groundwater quality from unmined areas as a mine drainage quality prediction tool. In: Brady, K.B.C., M.W. Smith and J. Schueck (Eds.), Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania. PA DEP, Harrisburg, PA, p. 10.1-10.11.

Brady, K.B.C., J.R. Shaulis, and V.W. Skema, 1988. A study of mine drainage quality and prediction using overburden analysis and paleoenvironmental reconstructions, Fayette Co., Pennsylvania. In: Mine Drainage and Surface Mine Reclamation, Vol. 1, 19-21 April, 1988. USBM IC 9183, Pittsburgh, PA, p. 33-43.

Brady, K.B.C. and R.J. Hornberger, 1990. The prediction of mine drainage quality in Pennsylvania. Water Pollution Control Assoc. of PA Magazine, 23(5): 8-14.

Brown, R.L. and R.R. Parizek, 1971. Shallow Ground Water Flow Systems Beneath Strip and Deep Coal Mines at Two Sites, Clearfield County, Pennsylvania, CR-66, PSU, University Park, PA.

Burwell, E.B. and B.C. Moneymaker, 1950. Geology in dam construction, Application of Geology to Engineering (Berkley volume). GSA.

Callaghan,T., G.M. Fleeger, S. Barnes, and A. Dalberto, 1998. Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania, Chapter 2-Groundwater Flow on the Appalachian Plateau of Pennsylvania, PA DEP, pub. # DEP2256, 425 p.

Carver, L, and H.W. Rauch, 1994. Hydrogeologic Effects of Subsidence at a Longwall Mine in the Pittsburgh Coal Mine, In: Proc., 13th Conf. on Ground Control in Mining, Syd S. Peng (Ed.), WVU.

Causey, L.V., 1961. Ground Water Resources of Etowah County, Alabama, Geological Survey of Alabama, Information Series 25.

Cifelli, R.C. and H.W. Rauch, 1986. Dewatering Effects from Selected Underground Coal Mines in North-central West Virginia, In: Proc., 2nd Workshop on Surface Subsidence Due to Underground Mining, WVU, Morgantown, W.Va., p. 249-263.

Davies, W.E., 1968. Mineral Resources of the Appalachian Region – Physiography, USGS Professional Paper 580, U.S. Department of the Interior.

Dixon, D.Y. and H.W. Rauch, 1988. Study of Quantitative Impacts to Ground Water Associated with Longwall Coal Mining at Three Mine Sites in the Northern West Virginia Area, 7th Conf. on Ground Control in Mining, August 3-5, 1988.

Fenneman, N.M., 1938. Physiography of Eastern United States, McGraw-Hill, NY, 714 p.

Ferguson, H.F., 1967. Valley stress relief in the Allegheny Plateau, Association of Engineering Geologists Bulletin, 5: 63-68.

Ferguson, H.F., 1974. Geological observations and geotechnical effects of valley stress relief in the Allegheny Plateau, American Society of Civil Engineers, Water Resources Engineering Meeting, Los Angeles, CA, pp. 1-31.

Feguson, H.F. and J.V. Hamel, 1981. Valley stress relief in flat-lying sedimentary rocks, In: Proc., International Symp.on Weak Rock.

Gold, D. P., 1980. Applications of remote sensing techniques to geologic problems, In: Remote Sensing in Geology, B. S. Seigal and A. R. Gillespie (eds.), John Wiley and Sons, Inc., pp. 419-503.

Harlow, G.E. and G.D. LeCain, 1993. Hydraulic Characteristics of, and Ground-Water Flow in, Coal-Bearing Rocks of Southwestern Virginia, USGS Water Supply Paper 2388, 36 p.

Hasenfus, G.J., K.L. Johnson, and D.W.H. Su, 1988. A hydrogeomechanical study of overburden aquifer response to longwall mining, 7th Conf. on Ground Control in Mining, WVU, Morgantown, WV.

Hawkins, J.W., K.B.C. Brady, S. Barnes, and A.W. Rose, 1996. Shallow ground water flow in unmined regions of the northern Appalachian Plateau: Part 1. Physical characteristics. In: Proc., Annual Meeting of the American Society for Surface Mining and Reclamation, Knoxville, TN, May 18-23, 1996, p. 42-51.

Hobba, W.A., 1991. Relation of Fracture Systems to Transmissivity of Coal and Overburden Aquifers in Preston County, West Virginia, USGS Water-Resources Investigations Report 89-4137.

Hobba, W.A., 1993. Effects of Underground Mining and Mine Collapse on the Hydrology of Selected Basins in West Virginia, U.S.G.S. Water Supply Paper 2384.

Hornberger, R.J, M.W. Smith, A.E. Friedrich, and H.L. Lovell, 1990. Acid mine drainage from active and abandoned coal mines in Pennsylvania. In: S.K. Majumdar et al. (Eds.), Water Resources in Pennsylvania: Availability, Quality and Management, PA Acad. Sci., Philadelphia, PA, p. 432-451.

Jones, A.L., 1988. Geologic Setting and Water Quality of Selected Basins in the Active Coal Mining Areas of Ohio, USGS Water-Resources Investigations Report 88-4084, Columbus, OH.

Kendorski, F.S., 1993. Effect of High-Extraction Coal Mining on Surface and Ground Waters, 12th Conference on Ground Control in Mining, WVU.

Kipp, J.A. and J.S. Dinger, 1987. Stress-relief control of ground-water movement in the Appalachian Plateaus, National Water Well Association, Focus Conference on Eastern Regional Ground-Water Issues, Burlington, VT, 16 p.

Miller, R.L., J.B. Hadley, and D.P. Cox, 1968. General Geology. In: Mineral Resources of the Appalachian Region. USGS and USBM, USGS Professional Paper 580, p. 55-80.

Minns, S.A., 1993. Conceptual model of local and regional groundwater flow in the Easter Kentucky coal field, Thesis Series 6, KY Geological survey, 194 p.

Moore, J.D., 1990. Water in Alabama, AL Geological Survey, Water Resources Div., Circular 122G.

Nace, R.L. and P.P. Bieber, 1958. Groundwater Resources of Harrison County, WV, Bulletin 14, WV Geological and Economic Survey, Morgantown, WV, 55 p.

Parizek, R. R., 1971. Prevention of coal mine drainage formation by well dewatering, Special Research Project SR-82, The Pennsylvania State University.

Parizek, R.R., 1978. User's Manual for Pre-mining Planning of Eastern Surface Coal Mining, Vol. 4 – Hydrology, U.S. EPA, Industrial Env. Research Laboratory, Cincinnati, OH.

Pennsylvania Department of Environmental Resources, 1976. Raccoon Creek Mine Drainage Pollution Abatement Survey. Operation Scarlift SL 130-7, Commonwealth of PA, 290 p.

Piper, A.M., 1933. Groundwater in Southwestern Pennsylvania, Water Resource Report W1, PA Topographic and Geologic Survey, 4th Series, Harrisburg, PA.

Poth, C. W., 1963. Geology and Hydrology of the Mercer Quadrangle, Mercer, Lawrence, and Butler Counties, PA Water Resource Report 16, PA Topographic and Geological Survey, 4th Series.

Powell, J.D. and J.P. Larson, 1985. Relation between groundwater and mineralogy in the coal-producing Norton Formation of Buchanan County, Virginia. USGS Water-Supply Paper 2274, 30p.

Rauch, H.W., 1985. A Summary of the Effects of Underground Coal Mines on Quantity of Ground Water and Streamflow in the North-Central Appalachians, Eastern Mineral Law Foundation, Sheraton Hotel at Station Square, Pittsburgh, Pa.

Robison, T., 1964. Occurrence and Availability of Ground Water in Ohio County, West Virginia, Bulletin 27, WV Geological and Economic Survey, Morgantown, WV, 57 p.

Rose, A.W. and P.E. Dresel, 1990. Deep brines in Pennsylvania, In: Water Resources in Pennsylvania: Availability, Quality and Management (Chapter 31), The PA Academy of Science.

Sames, G.P. and N.N. Moebs, 1989. Hillseam Geology and Roof Instability Near Outcrop in Eastern Kentucky Drift Mines, U.S.B.M. # 611-012/00, 116 p.

Schmidt, J. J., 1959. McMahon Creek, Captina Creek, and Sunfish Creek basins underground water resources, Ohio Department of Natural Resources, Division of Water

Schneider, W.J., 1965. Water Resources of the Appalachian Region, Pennsylvania to Alabama, USGS Hydrologic Investigations Atlas HA-198.

Schubert, J.P., 1978. Hydrogeologic and Numerical Simulation Feasibility Study of Connector Well Dewatering of Underground Coal Mines, Madera, Pennsylvania, MS Thesis, PSU, University Park, PA.

Schubert, J. P., 1980. Fracture flow of groundwater in coal-bearing strata, Symposium on Surface Mining Hydrology, University of Kentucky.

Sgambat, J.P., E.A. Labella, and S. Roebuck, 1980. Effects of Underground Coal Mining on Groundwater in the Eastern United States, EPA Interagency Energy/Environmental Research and Development Program Report, EPA-600/7-80-120, 182 p.

Singh, R.N. W.E. Grube, Jr., R.M. Smith, and R.F. Keefer, 1982. Relation of pyritic sandstone weathering to soil and minesoil properties. In: Acid Sulfate Weathering. Soil Science Society of America, p. 193-208.

Skousen, J., R. Hedin, and B. Faulkner, 1997. Water quality changes and costs of remining in Pennsylvania and West Virginia. In: Proc. 18th Annual WV Surface Mine Drainage Task Force Symposium, 13 p.

Smith, M.W., 1988. Establishing baseline pollution load from preexisting pollutional discharges for remining in Pennsylvania. Mine Drainage and Surface Mine Reclamation-Volume II Mine Reclamation, Abandoned Mine Lands and Policy Issues, p. 311-318.

Stoner, J. D., D. R. Williams, T. F. Buckwalter, J. K. Felbinger, and K. L. Pattison, 1987. Water Resources and the Effects of Coal Mining, Greene County, Pennsylvania, Water Resources Report 63, PA Geological Survey, 4th Series.

Tieman, G.E. and H.W. Rauch, 1986. Study of Dewatering Effects at an Underground Longwall Mine Site in the Pittsburgh Seam of the Northern Appalachian Coalfield, USBM I.C. 9137.

U.S. Environmental Protection Agency, 1977. Elkins Mine Drainage Pollution Control Demonstration Project, Industrial Env. Research Laboratory, Cincinnati, OH, EPA-600/7-77-090.

Wahl, K.D, W.F. Harris, and P.O. Jefferson, 1971. Water Resources and Geology of Winston County, Alabama, Geological Survey of Alabama, Division of Water Resources, Bulletin 97.

Walker, A.C., 1962. Stillwater Creek Basin, underwater water resources, Ohio DNR, Columbus, OH.

Weeks, R.A., R.D. Zahnizer and L.L. Chute, 1968. Geography. In: Mineral Resources of the Appalachian Region. USGS Professional Paper 580, p. 27-30.

Wetzel, K.L. and S.A. Hoffman, 1983. Summary of surface-water-quality data, Eastern Coal Province, October 1978 to September 1982, USGS Open-File Report 83-940, 67 p.

Wetzel, K.L. and S.A. Hoffman, 1989. Distribution of water-quality characteristics that may indicate the presence of acid mine drainage in the Eastern Coal Province of the United States, USGS Hydrologic Investigations Atlas HA-705.

Williams, D.R., J.K. Felbinger, and P.J. Squillace, 1993. Water Resources and the Hydrologic Effects of Coal Mining in Washington County, Pennsylvania, USGS Open-File Report 89-620.

Williams, D.R. and T.A. McElroy, 1991. Water Resources Data for Indiana County, Pennsylvania, USGS Open File Report 90-384.

Williams, E.G., A.W. Rose, R.R. Parizek, and S.A. Walters, 1982. Factors Controlling the Generation of Acid Mine Drainage, USBM Final Report—G5105086.

Winters, W.R., C.C. Capo, M.A. Wolinky, and T.J. Weaver, 1999. Geochemical and hydrogeologic evolution of alkaline discharges from abandoned coal mines. Preprint, Pgh Coal Conference, 36 p.

Wunsch, D.R., 1993. Ground-water geochemistry and its relationship to the flow system at an unmined site in the eastern Kentucky coal field, Thesis Series 5, KY Geol. Survey, Series XI, 128p.

Wyrick, G.G. and J.W. Borchers, 1981. Hydrologic effects of stress-relief fracturing in an Appalachian valley, USGS Water-Supply Paper 2177, 51 p.