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STRESS-RELIEF FRACTURE CONTROL OF GROUND-WATER MOVEMENT IN THE APPALACHIAN PLATEAUS

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ABSTRACT

The Kentucky Geological Survey has been conducting studies in the Eastern Kentucky Coal Field since 1980 to determine the various hydrogeologic conditions that exist in the region. One of the most important segments of the project is the documentation of ground-water conditions in a drainage basin before, during, and after mining. The goals of this research are to develop a conceptual model of ground-water flow for small basins and to determine the effects of mining and reclamation on local ground-water flow conditions and water quality.

A portion of the project is being conducted in the Wolfpen Branch area in northwestern Knott County, Kentucky. Before mining commenced, the study area contained a first-order stream draining approximately 185 acres of relatively undisturbed second-growth timber. Three coals were mined in the early 1980's by contour methods, and a hollow fill was constructed in the valley. Shortly before mining began, 13 observation wells were installed at four sites within the basin. The wells monitor ground water in that part of the geologic section extending from immediately below the lowest coal being mined to about 300 feet below drainage. The well sites were located so that two or three wells could be completed into each water-bearing zone from different topographic positions within the basin, and such that the wells would monitor the same stratigraphic units in the valley bottom, valley walls, and the core of the ridge. Monthly water-level measurements were taken in all wells after their construction, and continuous recorders were in operation between 1982 and 1984 on six of the wells.

Ground-water 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 more 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 bottom, and controls much of the shallow ground-water flow in the basin. This shallow ground water represents the principal portion of the active ground-water flow system.

INTRODUCTION

In Kentucky, mining companies and regulatory agencies trying to formulate and review pre-mine plans and permit applications are currently hindered by a lack of baseline ground-water information. Previous groundwater investigations in the Eastern Kentucky Coal Field were primarily of a regional and reconnaissance nature, relying mainly on relatively shallow, privately owned wells (Price and others, 1961 a, 1961 b, 1962, and Kilburn and others, 1961). As a result, information about well construction and yield was often determined solely from the reports of well owners. While some general information can be obtained from these studies, there is not enough detailed information available to form a conceptual model of ground-water conditions for small watersheds within the coal field. The development of such models could lead to a better understanding of the effects of mining on the ground-water system, and facilitate ground-water monitoring and development for future use.

In response to this need, the Kentucky Geological Survey initiated a study in 1980 to determine hydrogeologic conditions in the Eastern Kentucky Coal Field, and to assess the effects of surface mining on ground-water quality and quantity. An important segment of the project was to document the influence of mining activity on hydrologic conditions in a small watershed. This portion of the study was conducted in the Wolfpen Branch Basin in northwestern Knott County, Kentucky (Fig. 1). This paper is an expansion of the preliminary results reported by Kipp and others (1983).

SETTING

Nearly all of the Eastern Kentucky Coal Field is in the Appalachian Plateaus physiographic province, which extends from the state of New York to Alabama (Fig. 2). The coal field is a large, intricately dissected upland characterized by narrow, crooked valleys and narrow, irregular, steep-sided ridges. Most of the smaller creeks have no valley floors, while larger streams have floodplains of moderate width. Local relief increases from 300 feet in the north near the Ohio River, to about 2,500 feet in the south along Pine Mountain, near the Tennessee-Kentucky border (Price and others, 1962).

The Pennsylvanian-age rocks in eastern Kentucky have been divided into three major units. The Lee Formation is in the lower part of the sequence and is commonly at the base. It is characterized by pebbly quartzarenite. The Breathitt Formation overlies and inter-tongues with the Lee Formation. It generally consists of subgraywacke, gray siltstones and shale, and coal beds. The Conemaugh and Monongahela Formations are at the top of the section and occur only in northeastern Kentucky (Rice, 1981).

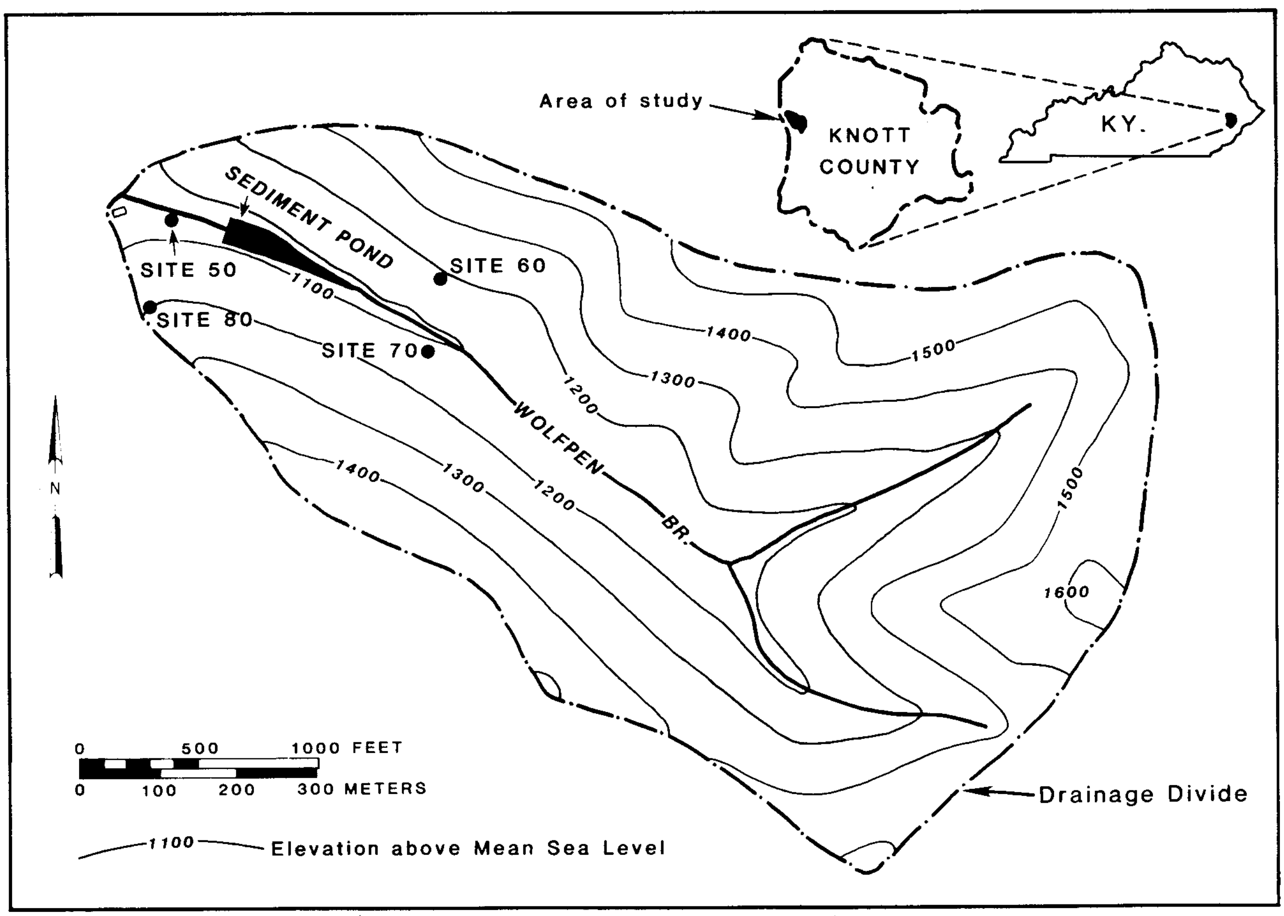

Figure 1. Location of Wolfpen Branch study area.

Before mining commenced, Wolfpen Branch Basin contained a first-order stream draining approximately 185 acres of relatively undisturbed second-growth timber *(see* Fig. 1). Local relief was about 500 feet. Rocks encountered during the investigation include the portion of the Breathitt Formation extending from the Magoffin Member below drainage up to the Francis coal (Fig. 3). From 1981 through 1984, three coals (both splits of the Hazard No. 7 coal and the Francis coal) were mined by contour cuts, and a hollow fill was constructed in the valley.

Figure 2. Location of Appalachian Plateaus Province.

WELL INSTALLATION

Thirteen observation wells were installed at four sites within the basin before mining began *(see* Fig. 1, sites 50, 60, 70, and 80). The well sites were located so that two or three wells could be completed into each water-bearing zone from different topographic positions within the basin *(see* Fig. 3, sites 50,60,70,80). Three of the sites were located on the hillsides (sites 60, 70, and 80), as close as possible to future mine cuts. A fourth site was placed in an undisturbed area in the valley bottom near the mouth of the basin *(see* Figs. 1 and 3, site 50). Continuous cores were drilled at each of the four well sites to provide information on potential aquifers and to aid in the interpretation of the stratigraphy of the area. Geophysical logging of the test holes provided additional stratigraphic and hydrologic information. Geologic data collected during coring and geophysical logging were then used to select zones to be monitored by observation wells.

GROUND-WATER OCCURRENCE

Monitoring efforts have provided several insights into the occurrence and movement of ground water in the Wolfpen Branch Basin. Monthly water-level measurements indicate that ground water occurs in hydrostratigraphic

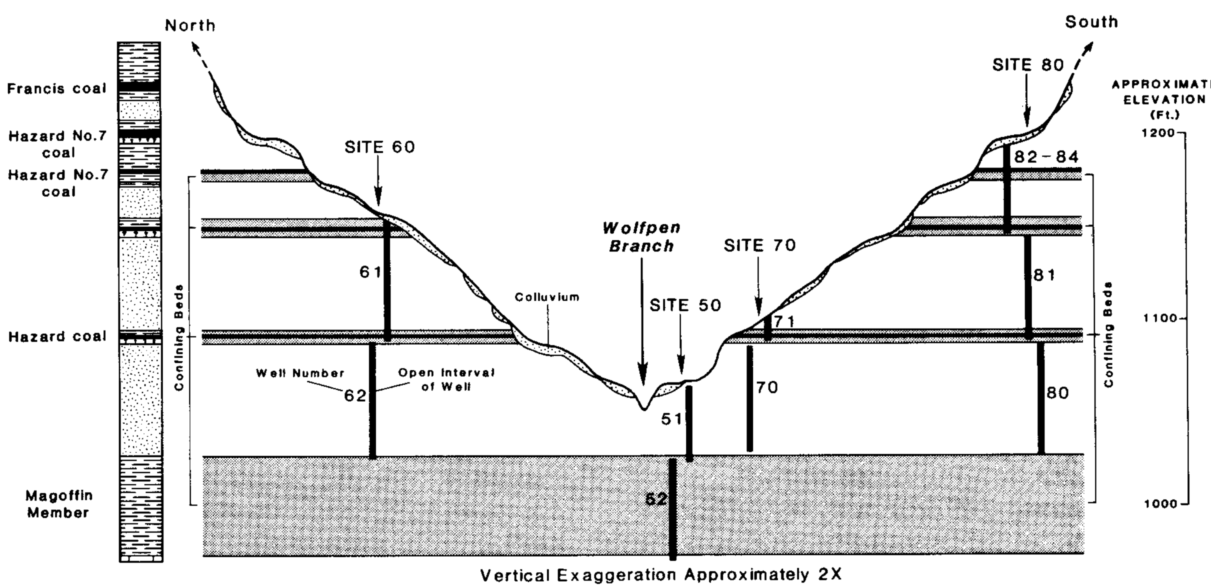

Figure 3. Schematic cross section showing monitoring well placement and open-well interval.

units consisting of sandstone, which are separated by claystone or argillaceous siltstone units acting as confining beds. These confining units are commonly associated with the major coals in the section *(see* Fig. 3). Discontinuous perched conditions exist in the hillsides near the valley walls. In two cases (wells 61 and 83) water cascades into wells that breach confining beds and allow perched water to drain to a lower unit. Further back within the cores of the hills, however, the hydrostratigraphic units became completely saturated and are often slightly artesian.

Monthly water-level measurements were taken at monitoring wells after their completion, and continuous recorders (Stevenson, Type-F, windup clocks) were installed on six of the wells during the fall of 1982. In general, these recorders were in operation until late spring of 1984. Well hydrographs indicate that amplitude and frequency of water-level fluctuations, in response to precipitation, evapotranspiration, and mining activities such as blasting, pond construction, excavation, and reclamation, are dependent on well location and depth of completion.

Figure 4 shows the relation between precipitation, as measured at the U.S. Weather Service Off ice at Jackson, Kentucky, 15 miles northwest of the study area, and water level fluctuations for wells 51, 70, and 80 for portions of May and June 1983. These wells monitor the same stratigraphic interval but at different topographic positions *(see* Fig. 2). Well 51, monitoring the valley bottom, and well 70, monitoring the valley wall, respond quickly and distinctly to precipitation, whereas well 80, monitoring the same zone but further in toward the core of the ridge, does not respond to the individual precipitation events. Sharp, distinct variations of approximately 0. 1 to 0.2 foot occur in the valley bottom in response to recharge, and the peak duration is generally less than 1 day. Along the valley walls the peak amplitude is about the same magnitude as the valley bottom, but peak duration is generally drawn out to a full day or more and the hydrograph has a smoother profile. The quick response of shallow wells (wells 51 and 70) in the valley bottom and hillslope implies high hydraulic conductivity and direct connection to infiltration from the surface as compared to the core of the ridge (well 80).

Diurnal evapotranspiration effects can also be distinctly discerned in wells 51 and 70 (Fig. 5). Daily water-level fluctuations, as most easily measured in well 70, are approximately 0.05 foot, with highs being recorded through night-time periods and the lows during the daylight hours. In contrast, well 80, toward the center of the ridge, does not indicate any evapotranspiration effects. In addition, comparison of the sinuous and upward-trending hydrograph of well 80 to those of wells 51 and 70 indicates that well 80 is monitoring a ground-water regime not directly interconnected with the near surface.

EFFECTS OF MINING

Information concerning the occurrence and movement of ground water was obtained for only a few months before the basin was disturbed by mining. Varied response to mining can be seen in the water-level records. The first change was noted following the construction of a sediment retention pond near the mouth of the basin (Fig. 1). Water levels in well 51 rose approximately 4 feet following completion of the dam and filling of the impoundment with water (Fig. 6), and have remained at essentially the same level since that time. The increased head created by the pond a few hundred feet upstream of the well site apparently controls water levels in the valley bottom near the mouth of the basin. This artificial head is probably somewhat responsible for modifying the response of water levels in well 51 to precipitation and evapotranspiration when compared to well 70 *(see* Figs. 4 and 5).

Hydrograph response due to mining activities has also been noted in wells completed in the valley walls. On the north side of the basin *(see* Fig. 1), the water level in well 61 dropped 35 feet (Fig. 7) when the Hazard No. 7 coal and associated overburden were removed approximately 30 feet above and almost directly upslope from the well. Apparently, the ground-water flow path was disrupted when water discharging from the highwall and precipitation falling onto the pit were preferentially drained through temporary ditches constructed in the cut to transport potential mine drainage to sediment ponds outside of the Wolfpen Branch Basin (Fig. 8). The water level returned to approximately its pre-mining level in January 1983 *(see* Fig. 7) after the cut was filled during reclamation, and remained at that level throughout the ensuing year of monitoring. A deeper well (well 62) at the same location was unaffected by the mining disturbance *(see* Figs. 7 and 8).

Water levels in the valley walls on the south side of the basin *(see* Fig. 1) have also been affected by mining. The hydrographs have not, however, shown the same type of response as that at site 60 across the valley (Fig. 9). In this case, flow in the near-surface zone was enhanced or remained steady while a lower unit experienced declining head. The shallow well (well 82) exhibited increased water levels of about 5 feet following the opening of a contour cut on the hillside above in February 1983. This may be the result of increased infiltration into the shallow ground-water system from the open cut.

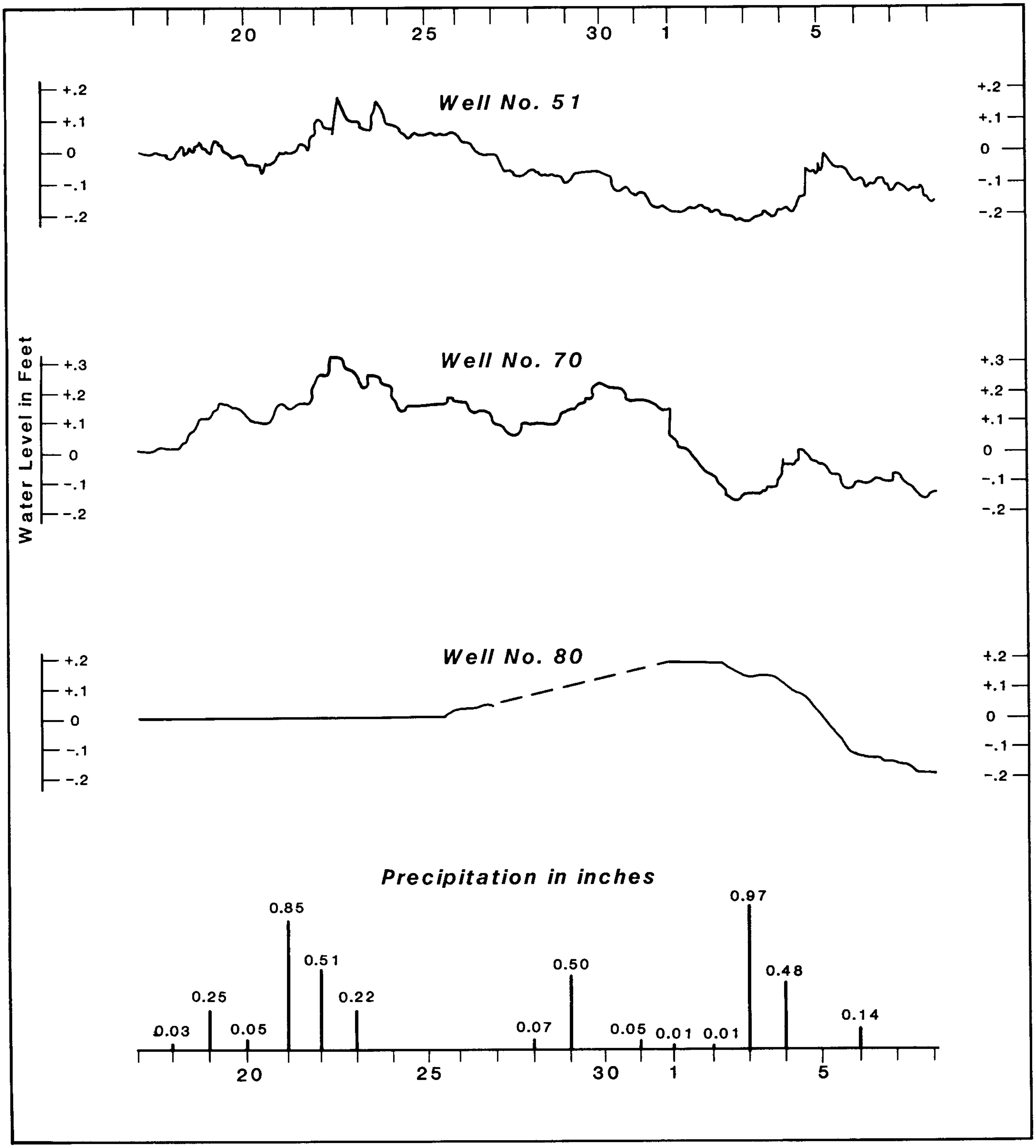

Figure 4. Hydrographs of wells 51, 70, and 80 showing the relationship between water levels and precipitation.

The well of intermediate depth (well 81), which is completed into the next lowest sandstone unit *(see* Fig. 3), showed slightly depressed water levels. Field observations indicated that the mining company did not experience problems with large quantities of mine drainage at this location and, therefore, had not established drainage ditches within the cut. The minimal mine drainage encountered may have been because site 80 is located on the nose of the ridge at the basin's entrance where minimum recharge occurs to the shallow ground-water system *(see* Fig. 1). Much of the shallow ground may have also been naturally intercepted and drained to the hollow fill constructed in Wolfpen Branch above the sediment pond as mining progressed from the north side of the valley around to and along the southern ridge *(see* Fig. 1).

The deep well (well 80) at the same location experienced a 30-foot decline in water level *(see* Figs. 3 and 9).

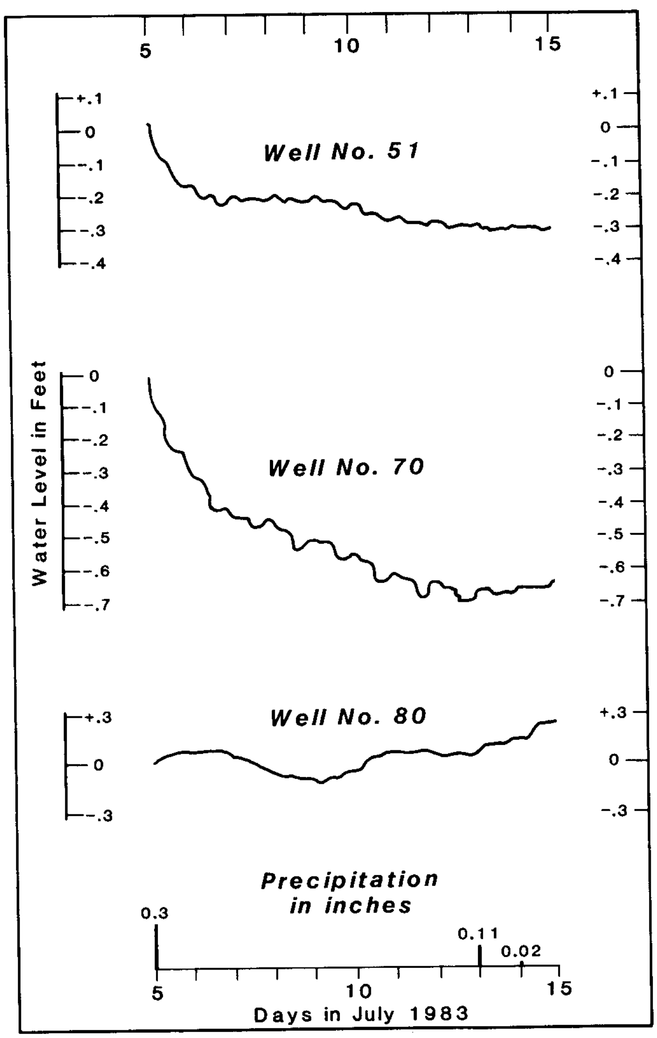

Figure 5. Hydrographs of wells 51, 70, and 80 indicating diurnal evapotranspiration effects.

Water in this well stood only 6 feet above that in well 51, completed in the same unit in the valley bottom, through July when it began to rebound. Intermittent measurements through April 1985 indicate that the water level has recovered to approximately elevation 1,083 feet. It may be that flow into this part of the deepest unit has been diverted by mining that occurred in its recharge area in another portion of the basin, most probably to the southeast *(see* Fig. 1).

"Blasting shadows" can also be seen in hydrographs for several of the wells on the southeast ridge. Figure 10

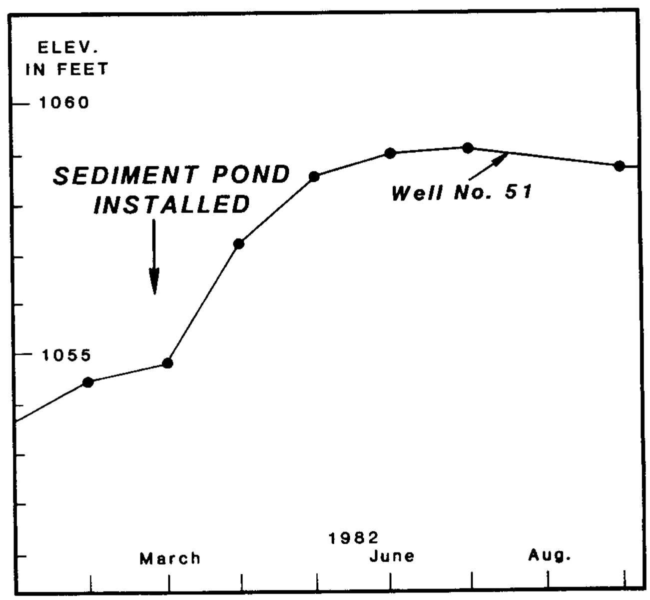

Figure 6. Response of water level in Well 51 to construction of sediment pond.

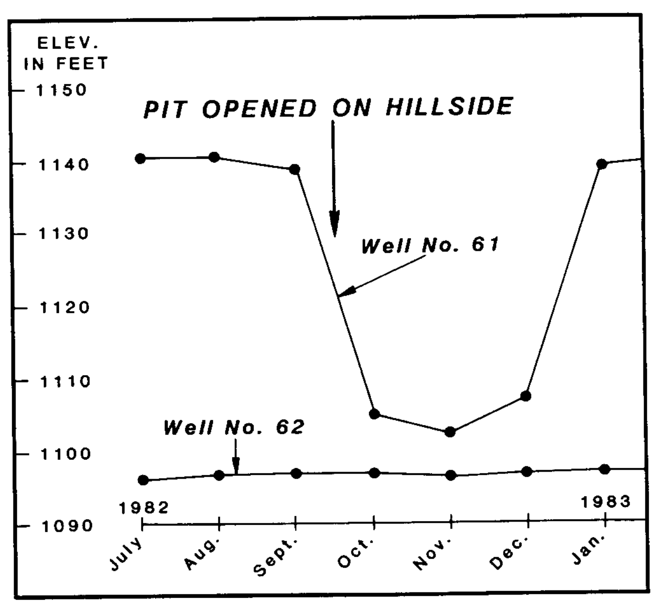

Figure 7. Water-level response in wells 61 and 62 during mining.

displays abrupt water-level changes in well 71 during June 1983, when recharge through precipitation was at a minimum. At this time, extensive mining was occurring

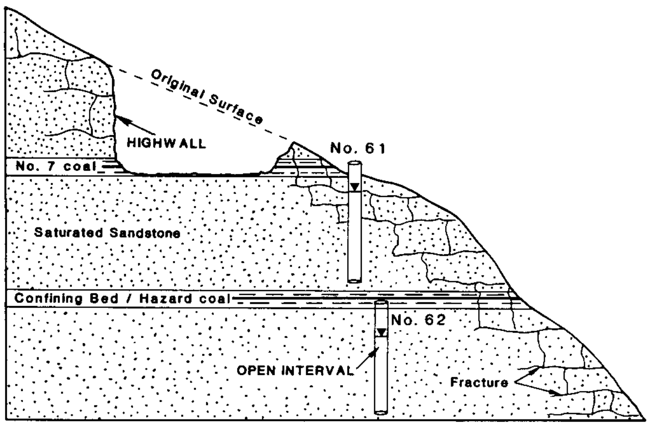

Figure 8. Schematic cross section indicating the position of wells 61 and 62 in relation to mining cut.

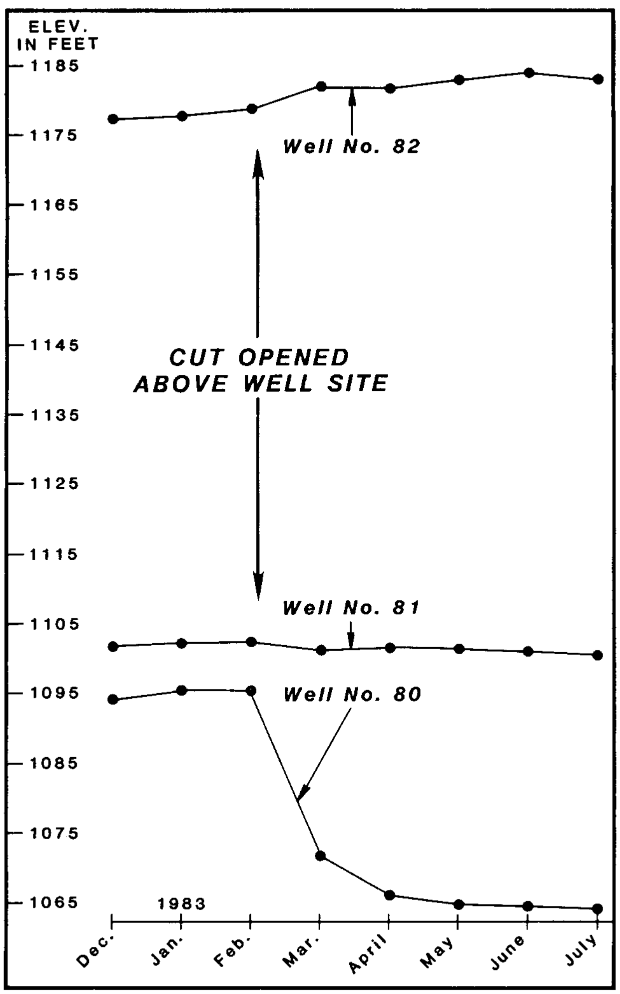

Figure 9. Effect of mining on water levels in wells 80, 81, and 82.

on both the Francis and Hazard No. 7 coal seams near these wells at the outermost limit of the southern ridge. In general, only one shot per day was detonated, usually in the late afternoon, during the entire 4-year mining operation at Wolfpen Branch. In some instances, several days passed between shots when overburden material was removed and the coal was mined. The hydrograph for well 70 shows blasting occurred on June 13,14, and 15 (Monday through Wednesday), skipped June 16, then concluded with shots on the 17th and 18th.

The hydrograph for well 80, the deep well, does not indicate the effects of blasting. The shots are extremely strong, and this non-response implies that the deep system is not in adequate hydraulic connection with the near-surface systems, as well as indicating that the deeper zone is not confined at this location. During this time period the water level was only 5 feet above the bottom of the well 80, and approximately 60 feet below the major confining unit beneath the Hazard coal seam (*see* Fig. 3).

CONCEPTUAL MODEL OF GROUND-WATER FLOW

Hydrographs show that shallow wells in the valley bottoms and valley walls respond quickly to surface activity when compared to the wells monitoring deeper zones. The quick and distinctive response of the shallow wells to precipitation, evapotranspiration, and mining activities indicates a zone of high hydraulic conductivity and direct connection to infiltration from the surface. Several lines of evidence indicate that secondary fracture permeability control these phenomena.

Drilling-fluid circulation was frequently lost in the first 20 to 30 feet during well installation. Fractures associated with iron oxide-stained zones were noted in all of the cores recovered (Fig. 11), and occasionally up to 3 feet of core was not recovered due to its fractured nature. Fracture orientation varied from vertical to horizontal (bedding plane), and fractures ranged in size from hairline to breaks that had weathered and eroded surfaces indicative of moving water. These fractures were normally concentrated within 50 feet of the land surface, but weathered fractures were present to depths of up to 80 feet in cores drilled on hillsides.

Laboratory permeability tests by several private engineering firms on the overburden material on and in the vicinity of the site indicate that the rock units have low hydraulic conductivity (approximately 10-6 ft./min.). Table 1 lists hydraulic conductivity values from several downhole injection tests done by a private contractor for the coal company for wells 50 and 81. In general, these values, as calculated by methods developed by the U.S.

Department of the Interior (1977), range from 10^{-5} to 10^{-6} feet/minute even in the upper 80 feet of the hole. One exception occurs in well 50 at the 35-40 feet zone (seeTable 1) where the hydraulic conductivity increases two orders of magnitude to 10^{-3}. This zone is characterized by a bedding-plane fracture less than 0.1 foot in width (as determined by core recovery) that "stole" all drilling fluid when the hole was initially core drilled.

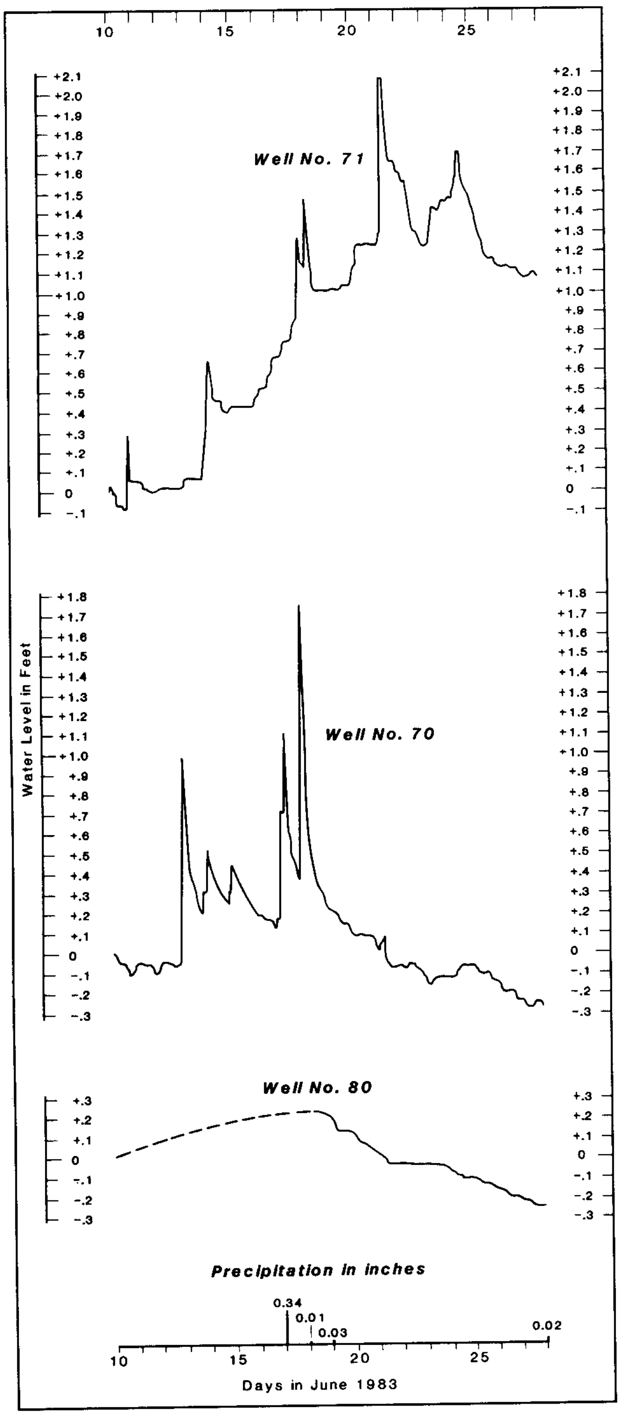

Figure 10. Hydrographs of wells 70, 71, and 80 showing the effects of blasting.

Rough estimates of well yield made from information obtained during initial well development also provide insight to the hydrogeology at the study area (Table 2). Several of the deep wells produced little water, and drawdown was very rapid. The yields from these wells were determined from the rate of recovery after pumping was terminated. The yield estimates for wells that were capable of more sustained pumping were made following correction for production from storage within the open hole. These tests indicate that wells completed in the valley floor and valley walls yield more water than wells completed into the same unit in the core of the ridge (see Table 1). This implies that rock units are fractured near land surf ace in the valley bottom and hillsides. The same units are not intensely fractured where they are deeply buried beneath the ridges.

Additional field data from the region demonstrate that a fractured zone of rock mantles the valley sidewalls. In general, entrances to deep mines require extensive cribbing to approximately 150 feet into the mine due to unstable roof conditions. A primary cause of rockfalls near mine entrances is the presence of fractures and associated weathered zones. In the interior of the mine these features are less prevalent, and rock strength becomes much greater.

Roadcuts; throughout the area indicate the presence of an intensely fractured zone of rock along the valley walls (Fig. 12). This fracture system is distinct from the

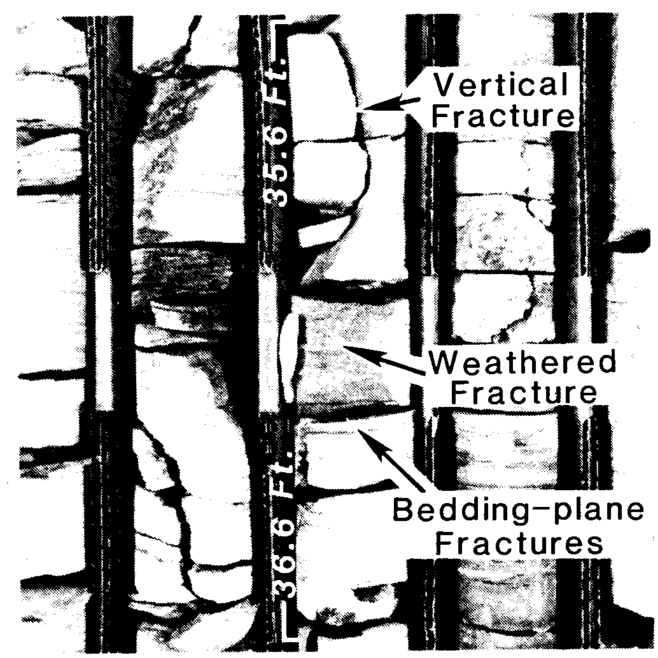

Figure 11. Photograph of fractures in core.

regional sets of joints that can be seen toward the core of the hills. It is evident from the excessive weathering features that there is preferential movement of water within the valley walls as opposed to the ridge core. Road contractors proclaim that the fractures are present before blasting commences and that their presence results in the failure of shots to move appropriate amounts of rock material. The presence of excessive weathering within valley walls, as seen upon initial removal of rock at new roadcuts, also demonstrates that water has been moving through the fractured zone for an extended period of time before road construction.

Table 1.—Hydraulic Conductivity Values for 5–Foot Intervals in Wells 50 and 81.

Tested Zone (ft.)	Lithology	K (ft./min.)*
WELL 50		
15–20	Sandstone with shale streaks	6.2×10^{-6}
25–30	Sandstone, fractured from 26.3–27.1	3.0×10^{-5}
35–40	Sandstone, fractured at 37.2 (lost circulation when drilling)	4.3×10^{-3}
50–55	Dark–gray shale with sandstone streaks	3.2×10^{-6}
70–75	Dark–gray shale with sandstone streaks	1.1×10^{-5}
95–100	Shale with 0.3–foot–thick coal	1.2×10^{-5}
WELL 81		
60–65	Sandstone with thin coal bands, iron–stained	3.5×10^{-6}
70–75	Sandstone with minor thin coal bands and shale streaks	4.0×10^{-7}
85–90	Massive sandstone with minor coal streaks	8.7×10^{-7}

* Hydraulic conductivity (K) was calculated by using the U.S. Department of the Interior, Bureau of Reclamation procedures (1977).

Figure 13 is a conceptual model of ground-waterflow at Wolfpen Branch developed by interpretation of these regional conditions and the site-specific hydrogeologic information previously presented. Within the interior of the ridges, water is stored and transmitted in intergranular pore spaces of the predominantly sandstone bedrock. These rock units are saturated but well yields are low. Lithology and water levels indicate that the saturated sandstone zones are confined (semi-confined) by relatively impermeable claystone or argillaceous siltstones associated with the major coal seams, which limit the vertical movement of water.

Table 2.—Well Yields for the Sandstone Unit Below the Hazard Coal Strata.

Well	Setting	Approx. Yield (gpm)	Draw–down (ft.)	Specific Capacity (gpm/ft.)	Length of Test (min.)
51	valley bottom	10	2.1	4.76	52
70	valley side	10	12.8	0.78	62
80	hill core	<<1	(recovery test)		days

The confining layers cause lateral flow toward the hillsides where ground water may discharge as springs or seeps. However, lithologic logs and hydraulic testing of monitoring wells; well-hydrograph response to precipitation, evapotranspiration, and mining activities such as excavation and pond construction; and observational data from deep mines and roadcuts in the region indicate the presence of a fracture system along valley walls that actively transmits ground water vertically downward through the confining units.

Major recharge to the hillside aquifers occurs when precipitation soaks through the thin soil and colluvium covering the ridges and hillslopes, or when runoff is directly intercepted by open fissures in rocks exposed at the surface. Water percolates down through the fractured sandstone units until a confining bed is reached. The perched water then flows horizontally out toward the hillsides along bedding planes until it can move vertically downward where fractures penetrate the confining bed. Wet-weather springs form on the hillside where the confining bed is relatively unfractured and can force ground water to the surface. This results in a stairstep pattern of ground-water movement from the ridgetops to the valley bottom (see Fig. 13).

Rocks within the centers of the ridges are saturated, but because they are not highly fractured, water must move by diffuse flow and is probably released only during extended dry periods. Little if any flow occurs between valleys because of the low permeability that is characteristic of the ridge cores.

Ground-water flow conditions in Wolfpen Branch are similar to those described by Borchers and Wyrick (1981) and Wyrick and Borchers (1981) foravalley inthe Appalachian Plateaus in West Virginia and those described by Larson and Powell (1986) in Virginia. Wyrick and Borchers (1981) attributed the abundance of near-surface fractures to "de-stressing" of rocks during downcutting of streams and the formation of the steep and narrow valleys characteristic of the Plateaus region.

This stress-relief type of fracturing can also be seen in roadcuts, dam sites, and highwalls throughout much of eastern Kentucky. Therefore, it is possible that the model is representative of many valleys in similar stratigraphic settings in the region. Additional studies need to be conducted in areas with different lithologies, topographic relief, and slope steepness.

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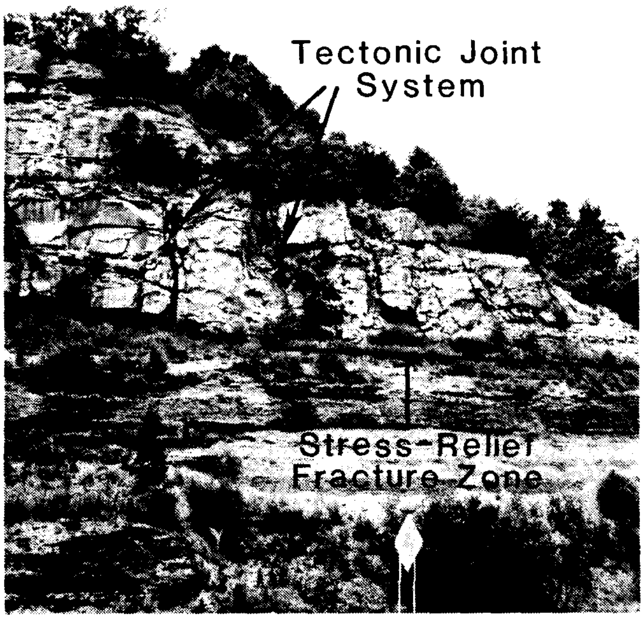

Figure 12. Photograph of roadcut showing near-surface fracture zone and regional joint sets.

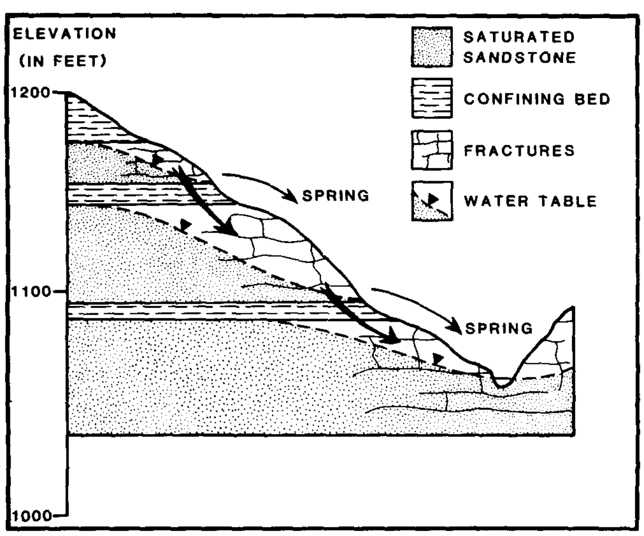

Figure 13. Conceptual model of ground-water flow in the Wolfpen Branch area.

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BIOGRAPHICAL SKETCHES

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