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Impacts on Ground-water Hydrology from Surface Coal Mining in Northern Appalachia

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ABSTRACT

Prediction of the hydrologic impacts caused by surface mining is a permitting prerequisite, directed by regulations stemming from the Surface Mining Control and Reclamation Act of 1977. Aquifer testing and monitoring at five reclaimed surface coal mines in western Pennsylvania and northern West Virginia illustrate that surface mining significantly impacts the hydraulic conductivity, transmissivity, and ground water levels in the disturbed strata. The estimated hydraulic conductivity of mine spoil aquifers (1.2×10^{-5} to 1.4×10^{-4} m/s) ranged from 0.83 to 2.65 orders of magnitude greater than adjacent unmined strata (3.8×10^{-8} to 4.1×10^{-6} m/s) with a geometric mean over 2 orders of magnitude higher. Similar trends were observed for transmissivity. Ground water levels in spoil wells were 44 to 71 percent lower than structurally and topographically similar wells in adjacent unmined strata. The contrast in hydrologic properties between mined and unmined areas are primarily porosity and permeability increases related to the greatly increased interconnected voids created by the physical breakup of the overburden during mining. These hydrologic differences are also affected by the lithology of the spoil material, the influences of unit lithology and thickness on the degree of stress-relief fracturing in the unmined strata, and the age of the spoil aquifer.

Key Words: surface mine spoil, hydraulic conductivity, ground water.

INTRODUCTION

Surface coal mining in the northern Appalachian coalfields has a significant impact on the ground water hydrologic system. Regulations promulgated from the Surface Mining Control and Reclamation Act of 1977 require prediction of the probable hydrologic consequences (PHC) of mining as part of the surface mining permit application. The PHC include but are not limited to prediction of ground water levels, quality, direction of flow, recharge and discharge rates, and the probable impacts of mining on the hydrologic system. However, until recently, there has been little empirical data to form the basis of PHCs.

Additionally, mine drainage pollution prevention measures commonly require prediction of the post-mining hydrologic regime. Many pollution prevention measures entail selective handling of spoil materials with respect to the projected position of the post-mining water table and ground water flow paths. Frequently, the post-mining water table re-establishes well above the predicted level and the acid-forming spoil material is partially saturated or is within the water table fluctuation zone. This situation may actually promote or accentuate the acid mine drainage production. There are two opposing theories of how to selectively handle the acid-forming materials with respect to the post-mining water table. The first method places the acidic spoil in discrete pods or layers above the highest projected level of the post-mining water table in the backfill ("high and dry") to minimize ground water contact. The second method places the acidic spoil below the lowest projected level of the post-mining water table ("dark and deep"). There are conflicting opinions as to which method is more effective. However, proponents of both agree the worst possible scenario is to position the acidic spoil within the zone of water table fluctuation. Secondarily, alkaline material (e.g., limestone, calcareous shales, alkaline residual and waste products) are placed in the backfill to maximize contact with ground water in saturated and unsaturated zones. This practice promotes the formation of highly alkaline ground water in the backfill that may neutralize AMD or inhibit AMD production. Unfortunately, an inadequate understanding of the post-mining hydrologic regime makes effective special handling of acidic and alkaline material highly problematic. To this end, an improved understanding and a predictive model of the hydrologic impacts of surface mining are needed.

Background

Hydrologic data from five surface coal mines located in West Virginia and Pennsylvania were collected to quantify the hydrologic impacts of surface mining (figure 1). Water levels were recorded and aquifer tests (slug injection and/or withdrawal tests) were performed on monitoring wells in unmined strata and the reclaimed spoil aquifers. Wells used for the comparison were located in adjacent unmined and spoil areas. Test wells were selected that exhibited similar topographic and geologic (structural) conditions to facilitate the direct comparison. Where more than one spoil and/or unmined area monitoring well existed that satisfied this criteria, the data from the wells were averaged. Table 1 lists the number of each type of monitoring wells used for each site.

TABLE 1. Background data summary.

Site	Wells in Unmined Strata	Spoil Wells	Date Tested	Spoil Lithology %Ss	Spoil Lithology %Sh	Strata Lithology %Ss	Strata Lithology %Sh	Strata Lithology %Cl
1	1	3	03/28/94	56	44	26	45	29
2	1	1	05/25/94	30	70	18	70	12
3	1	3	11/28/89	51	49	0	69	31
4	6	3	10/31/91	86	14	43	19	38
5	1	4	06/23/92	25	75	7	82	11

Ss = sandstone, Sh = shale, and Cl = coal.

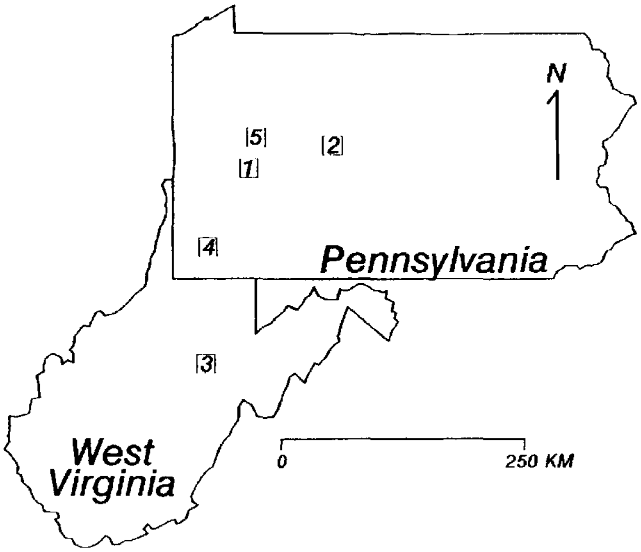

FIGURE 1. Mine site location map.

The test sites are all located on the northern Appalachian Plateau, which is lithologically characterized by interbedded coals, shales, siltstones, sandstones, claystones, and some limestones. These units commonly occur in cyclic sequences (cyclothems) starting with shale at the base followed by sandstone, claystone, and coal. This pattern is commonly repeated throughout the Carboniferous sequence. Topographic relief exceeding 100 meters is common in the Appalachian Plateau. The erosion-created relief in this region often permits the hillside exposure of several series of cyclothems.

Researchers have observed in the Appalachian region that ground water flow in bedrock is mainly through fractures (secondary permeability) and that intergranular (primary permeability) flow is insignificant (Wyrick and Borchers, 1981). Brown and Parizek (1971) observed that hydraulic conductivity may be increased by as much as three orders of magnitude because of fracturing. These fractures were mainly created by stress-relief as rock mass was removed by erosional processes. However, some fractures may have been formed by tectonic forces. Regardless of the genesis of the fractures, ground water has been shown to flow primarily through bedding plane separations in the rocks underlying the valleys and through vertical or near vertical fractures in the strata of the adjacent hillsides. The hillside fractures related to stress-relief were observed to parallel the valley orientation (Ferguson, 1967; Borchers and Wyrick, 1981).

Ferguson (1967) observed that the frequency of stress-relief fracturing was related to the competency and thickness of the rock. Thin shales tend to have closely spaced (a few centimeters apart) joints, whereas joints in massive sandstones and limestones were up to 3 meters apart. Brown and Parizek (1971) observed that fractured sandstone and coal units at two mine sites in central Pennsylvania yielded the highest amounts of water. Borchers and Wyrick (1981) noted that the fracturing frequency due to stress-relief decreases with depth and that they most likely do not exist below 60 meters. Ferguson and Hamel (1981) observed that vertical fracturing is not continuous from competent into weaker incompetent units and that fracture frequency decreases laterally into the valley side walls.

Initially, individuals working with mine spoil commonly assumed that ground water flow was a porous medium system similar to flow through unconsolidated sediments. However, Caruccio and others (1984) observed pseudokarst aquifer characteristics in a surface mine backfill. Subsequent work by Hawkins and Aljoe (1990) illustrated that spoil exhibits characteristics of both systems. On a large scale and under steady-state conditions, spoil exhibits porous media characteristics. When the spoil aquifer is subjected to stress (e.g., aquifer tests) or transient conditions, pseudokarst characteristics become more prominent (Hawkins and Aljoe, 1991). Large voids and conduits within the backfill strongly influence the ground water flow regime; however, ground water velocity and overall site hydraulic properties are ultimately controlled by the lower hydraulic conductivity zones within the spoil. The lowest hydraulic conductivity values in the spoil exist between discrete voids or conduits. In these areas between voids, true porous media flow occurs and the lower hydraulic conductivity controls ground water through the backfill.

Spoil material is comprised of clay (<0.002 mm) to very large boulder (>2048 mm) sized particles. Spoil ranges from very to extremely poorly sorted with sorting classification values commonly similar to that of glacio-fluvial sediments (Folk, 1974; Jones and Anderson, 1994). Hawkins and Aljoe (1991) also observed that spoil and glacial sediments exhibit similar hydrologic properties. During backfilling, spoil material is indiscriminately pushed into the open pit and regraded. Some minor sorting may occur as a consequence of this process. Larger fragments tend to roll to the base of spoil ridges, while the bulk of the medium-sized and smaller fragments tend to remain on the sideslopes and the ridge tops (Rehm and others, 1980; Hawkins, 1993). This action appears to create highly transmissive linear zones toward the base of the backfill that are oriented parallel to the spoil ridges.

Methods

Aquifer testing and data collection at the mine sites were performed as part of and in conjunction with a more comprehensive study of spoil aquifer transmissive properties. The aquifer tests and water level measurements were conducted on a one-time basis. No effort was made in this study to determine seasonal average ground water levels or the impact of ground water level on aquifer transmissive properties. The spoil and bedrock wells of each site were tested within 5 days of each other.

Comparison wells for each site were selected that were similar in terms of elevation, proximity, and geologic structure. The elevation of wells in unmined areas averaged 7.3 meters above the spoil wells. The distance separating the different types of wells ranged from 67 to 305 meters. The majority of the wells were separated by less than 160 meters. The strata at all sites were nearly horizontal. Structural dip, based on the base of the respective coal seams, ranged from 0.4 to 2.0%. The base of the spoil and unmined rock aquifers were in all cases the bottom of the lowest coal seam mined. The stratum underlying the coal (e.g., seat clay) is usually an effective aquitard in this region. Geologic and hydrologic data as well as the aquifer testing indicated that unconfined (water table) conditions exist for the spoil and unmined strata aquifers at all sites.

Slug tests were performed on the wells using pressure transducers and data loggers to record the water level displacement recovery. The slug test water level displacement was achieved by injecting 19 or 38 liters of water into the well and/or inserting or withdrawing a solid cylinder of known volume. The estimated hydraulic conductivities were determined using a method developed by Bouwer and Rice (1976) and expanded by Bouwer (1989). Static water levels were measured using an electronic water level indicator. Well depths were determined from well logs or direct measurement using a weighted tape.

Volumetric calculations for the lithology of the spoil and the unmined strata aquifers were performed for each site based on monitoring well and premining drill hole logs. The lithologic content of the spoil aquifer was calculated from all the material disturbed during mining minus the coal. The lithologic content of the unmined aquifer is based on the lithology of the saturated units. The lithology of spoil aquifers ranged from 25 to 86% sandstone and 14 to 75% shale. The undisturbed aquifers ranged from 0 to 43% sandstone, 19 to 82% shale, and 11 to 38% coal (table 1).

Discussion

Hydraulic conductivity values of the mine spoil were from 0.83 to 2.65 orders of magnitude larger than that of the adjacent unmined strata (table 2). The geometric mean of the hydraulic conductivity of the spoil aquifers (3.75×10^{-5} m/s) from the five sites was over 2 orders of magnitude greater than that of the unmined aquifers (3.69×10^{-7} m/s). As expected, transmissivity values exhibit similar results. Transmissivity of the spoil ranged 0.55 to 2.38 orders of magnitude above that of undisturbed aquifers with a mean 1.6 orders of magnitude higher. The high hydraulic conductivity and transmissivity values exhibited by the spoil material are caused by the high degree of rock fragmentation from mining and reclamation processes.

Site 2 exhibited the least difference in hydraulic properties (less than half the next closest site) between the unmined strata and the spoil. This may be related to the short elapsed time since regrading. The age of the backfill for this site was less than 9 months at the time the aquifer test was conducted. Aljoe and Hawkins (1992) observed significant increases in hydraulic conductivity with increasing spoil age. Future retesting of this site is planned, which will determine if the spoil hydraulic conductivity will change with time, thereby changing the transmissive difference between the spoil and unmined aquifer for site 2.

The unmined strata exhibited a wider hydraulic conductivity range (about 2 orders of magnitude) between sites than the spoil aquifers (approximately 1 order of magnitude). A similar relationship is exhibited by comparison of the transmissivity values. The wider range of hydraulic properties of the unmined strata appears to be related to whether or not a monitoring well intersected a fracture and to some extent the lithology of the saturated units. Monitoring wells that fail to intersect fractures or fractures with large enough apertures to permit significant ground water movement will yield relatively low estimated hydraulic conductivity values. In the valley walls, the fractures are usually vertical or nearly vertical (Ferguson and Hamel, 1981). Therefore, it is not unexpected that some monitoring wells will not intersect transmissive fractures. Monitoring wells that intersect highly transmissive fractures will exhibit elevated hydraulic conductivity values.

TABLE 2. Summary of hydrologic data.

	Site				
	1	2	3	4	5
Spoil Hydraulic Conductivity	1.4×10^{-4}	2.8×10^{-5}	1.2×10^{-5}	1.2×10^{-4}	1.3×10^{-5}
Strata Hydraulic Conductivity	3.1×10^{-7}	4.1×10^{-6}	7.1×10^{-8}	2.0×10^{-6}	3.8×10^{-8}
Spoil Transmissivity	5.9×10^{-4}	1.1×10^{-4}	3.1×10^{-5}	1.2×10^{-4}	7.8×10^{-6}
Strata Transmissivity	2.5×10^{-6}	3.2×10^{-5}	4.6×10^{-7}	9.3×10^{-6}	4.9×10^{-8}
Spoil Saturated Thickness	4.35	4.03	1.88	1.53	0.72
Strata Saturated Thickness	7.86	7.75	6.49	4.78	1.28

Hydraulic conductivity values are in m/s.
Transmissivity values are in m^2/s.
Saturated thicknesses are in meters.

Aquifer lithology has an indirect impact on the hydraulic properties of the unmined strata in terms of fracture density and aperture size. Ferguson (1967) noted that sandstones tend to have widely spaced (>3 m) fractures and joints. Peffer (1991) observed that brittle, well indurated units, such as sandstones, form aquifers because they tend to hold joints open. Joints in shales and claystones have narrower apertures because these units are more plastic and less rigid than sandstone. None of the unmined aquifers tested during this study were monolithic; therefore, it was difficult to ascertain the direct impact of individual lithologic units. However, figure 2 illustrates that with increasing sandstone content in the unmined aquifers, hydraulic conductivity increases. The two lowest hydraulic conductivity levels measured (sites 3 and 5) in the unmined units occur where sandstone content in the aquifer was the least (0 and 7%, respectively). Site 4 had the highest percentage of sandstone (43%) along with the second highest hydraulic conductivity. However, the difference in the hydraulic conductivity of site 4 (2.0×10^{-6}) and site 2, which had the highest hydraulic conductivity (4.1×10^{-6}), is insignificant. Site 2 is somewhat anomalous, because the sandstone content (18%) was less than half that of site 4. The coal and shale content in the saturated portion of the aquifers exhibited little relationship with hydraulic conductivity.

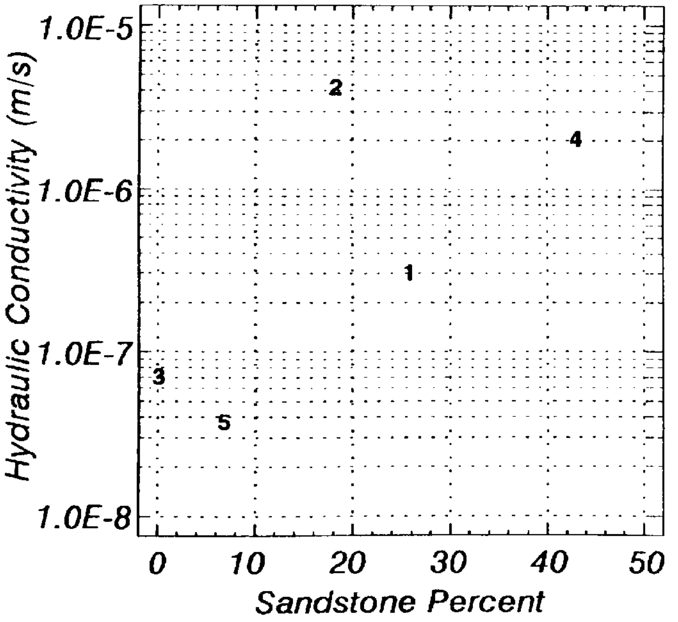

FIGURE 2. Relationship of hydraulic conductivity to sandstone content of the unmined strata aquifer.

The relatively narrow range of hydraulic conductivity in spoil is unexpected and is most likely caused by the limited number of spoil wells analyzed. Furthermore, except for site 2, the spoil hydraulic conductivity was based on the geometric average of three or more wells, which tends to attenuate the effect of extreme values. Analyses of spoil hydraulic conductivity, performed by the author, from over 100 wells representing 15 surface mines illustrated an extremely broad range (1.5×10^{-8} to in excess of 2.5×10^{-1} m/s). An in-depth analysis of these hydrologic data will be the focus of future work. Lithologic content of the spoil aquifer directly impacts the hydraulic properties. The highest spoil aquifer hydraulic conductivity values were yielded by the sites (1 and 4) that had the highest percentage of sandstone (figure 3). Similar trends were observed by Aljoe and Hawkins (1992). Well indurated sandstones generally tend to break into large blocky fragments. When randomly spoiled, large sandstone fragments promote the formation of large interstitial voids. Shales, on the other hand, tend to break into smaller particle sizes than the sandstone, and thus create smaller voids. Secondarily, shales, which are highly susceptible to weathering, break down and form low-permeability clays. Clay formation and interstices filling further decreases the hydraulic properties of spoil.

The higher transmissive qualities of spoil are directly related to the greatly increased interconnected void space (effective porosity), regardless of lithology, compared to the undisturbed aquifers. The volume increase (swell) of the spoil shortly after reclamation can be up to 25% greater than the natural undisturbed strata (Van Voast, 1974). This volumetric increase of the disturbed strata is mainly in the form of increased porosity. Furthermore, permeability is greatly increased because the voids in the spoil are better interconnected than discrete fractures in the unmined strata.

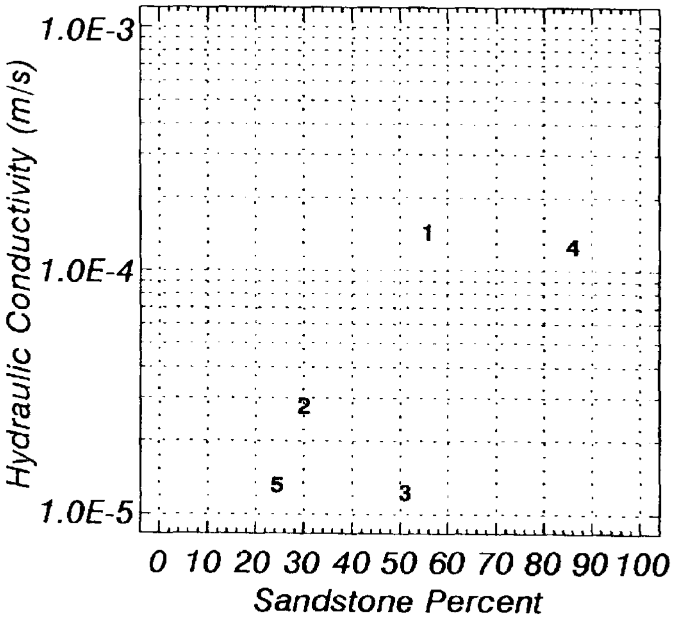

FIGURE 3. Relationship of hydraulic conductivity to sandstone content of the spoil aquifer.

Porosity values determined from aquifer testing (slug and tracer tests) of the mine spoil from site 3 ranged from 13.8 to 16.4%. These were similar to, although slightly lower, than the commonly-used swell factor. The lower-than-expected porosity values may be caused by piping, settling, and compaction that initiates shortly after backfilling. Physical changes occurring within the backfill are illustrated by significantly higher hydraulic conductivity in spoils over 30 months old compared to those under 30 months old (Aljoe and Hawkins 1992).

Porosity values for bedrock are considerably lower than those observed for spoils. Laboratory-measured porosity values in undisturbed coal-yielding strata ranged from 0.8 to 9.4% with a mean of 3.9% (Brown and Parizek, 1971). The laboratory-determined values are expected to be below actual field values because only primary (intergranular) porosity is measured in the laboratory. The addition of secondary porosity (fractures and joints) in this determination would increase the porosity values somewhat. However, MacKay and Cherry (1989) estimated the effective porosity of fractured-rock aquifers to range from 0.001 to 0.1%, which is considerably lower than the values determined by Brown and Parizek (1971).

Not unexpectedly, the measured water levels in spoil wells for all sites were lower than the water levels in wells completed in adjacent unmined strata. The water levels in the spoil wells ranged from 44 to 71% lower than in the undisturbed strata wells, with an arithmetic mean of 55%. For this comparison, the base of the mined coal seam at each site was used as datum. The seat clay (claystone, siltstone, or underclay) underlying the coal seam commonly acts as an aquitard in the Appalachian region. The lower water levels in the spoil aquifers are primarily caused by the higher hydraulic conductivity compared to the bedrock aquifers. Using Darcy's Law, assuming the flow rate and area of flow remain constant, increases in hydraulic conductivity will cause the water level (head) to be reduced. The lower water levels observed in the spoil are probably to some extent related to differences in elevation between the spoil wells and the unmined strata wells. However, the drop in the water table levels from the unmined strata to the spoil are significantly greater than can be attributed solely to topographic influences.

The actual mining-induced water level changes were probably greater than the recorded levels because the water levels were measured in the undisturbed strata after mining and reclamation had been completed. The depressed water levels exhibited by spoil commonly cause water levels in the adjacent unmined strata to be drawn down. Figure 4 is a representation of the water table from the unmined strata aquifer across the highwall into the spoil aquifer, based on data from site 1. The spoil aquifer behaves as a linear well zone, parallel to the highwall, with a constant pumping rate. This creates a monoclinal depression in the water table dipping toward the spoil and parallel to the final highwall. Because of the extreme heterogeneity and anisotropy of mine spoil, the water table in the backfilled section is probably more irregular than shown.

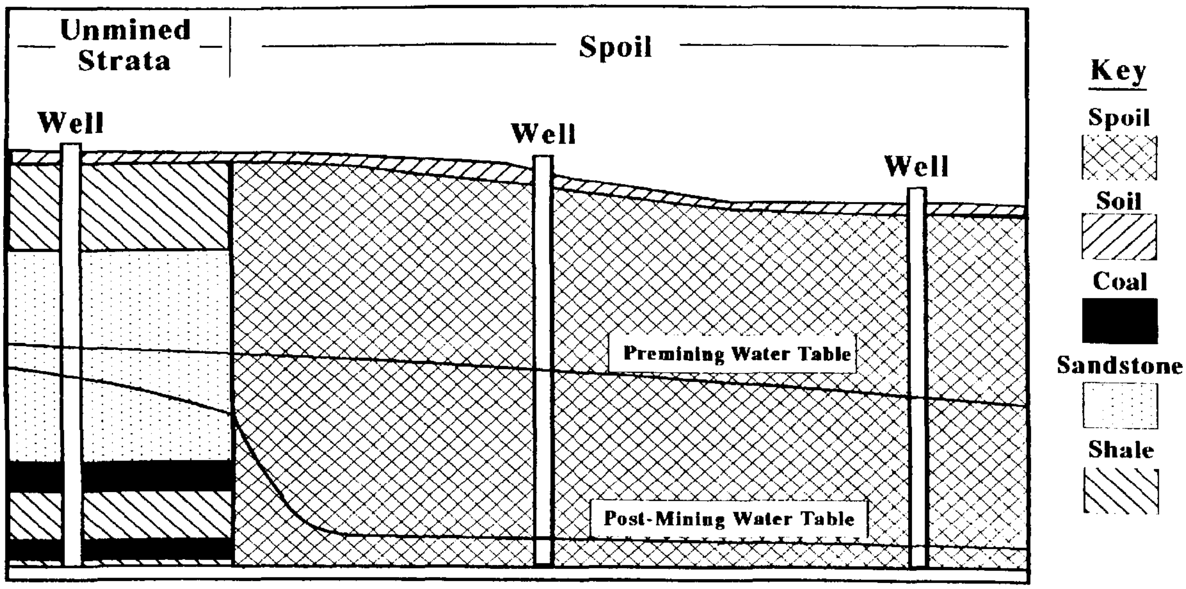

FIGURE 4. Schematic representation of the water table from the unmined aquifer into the spoil aquifer.

Summary

Analysis of the impacts of surface mining indicates that post-mining hydrologic conditions can be highly variable and difficult to predict. However, there are some general responses and trends that the ground water professional can use to better understand and predict the impacts caused by surface mining. An improved understanding of the post-mining hydrologic regime will in turn improve the accuracy of Probable Hydrologic Consequences. A clearer understanding of the post-mining ground water table is important for the development and implementation of mine drainage pollution prevention measures, such as selective spoil handling.

Wells in unmined strata exhibited a wider variation of hydraulic properties than the spoil wells. This wide variation appears to be related to the "hit or miss" nature of fractures that are the primary ground water flow path in the Appalachian Plateau.

Lithology appears to influence the hydraulic properties of the surface mine spoil and the unmined strata aquifers. Spoil aquifers with a high percentage of sandstone tend to exhibit higher hydraulic properties (hydraulic conductivity, transmissivity, porosity) than those with lower percentages. This is related to the blocky nature of spoiled sandstone, which creates large voids. The lowest hydraulic conductivity values observed in the unmined strata were exhibited by aquifers with the least amount of sandstone in the saturated zone. Shale- and claystone-rich bedrock aquifers are less permeable because the joints and fractures are tighter and more poorly developed than those in sandstone-rich aquifers.

The hydraulic conductivity of surface mine spoil is consistently higher than that of adjacent unmined strata. The spoil hydraulic conductivity averaged 2 orders of magnitude greater than the bedrock aquifers. Transmissivity exhibited trends similar to the hydraulic conductivity. This increase in hydraulic properties is mainly related to the high degree of rock fragmentation and associated large volume of voids created during overburden removal and subsequent spoil regrading. As a result, the spoil water levels averaged over 50% below that of the adjacent unmined strata. Greatly increased porosity values were also measured for mine spoil, which reflects the larger volume of voids in spoil aquifers.

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