Shallow Ground Water Flow in Unmined Regions of the Northern Appalachian Plateau: Part 1. Physical Characteristics[1]

by

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Abstract. At a Pennsylvania study site, ground-water flow and aquifer properties in undisturbed strata are controlled by fracture frequency and aperture development. Analysis of images from a borehole video camera illustrate that the frequency of horizontal and vertical fractures decreases non-linearly with increasing depth. A highly transmissive fractured zone extends from 0 to roughly 15 meters in the strata underlying hilltops and hillsides. This zone exhibited hydraulic conductivities over 100 times higher than strata lying 8 meters or more deeper. These extreme hydraulic conductivity changes permit a temporary perched water table to arise from rainfall events. Surface water quickly enters near-surface fractures and flows rapidly downward and laterally through the shallow fractured zone. Well hydrographs illustrate that the residence time for much of this water is relatively short-- a few days up to a week. Most of this shallow ground-water flow emanates at cropline springs, while most of the remainder continues as shallow ground-water flow and a small portion of the ground water enters the deeper flow system. In the deeper system, the flow rate is substantially slower with a much longer residence time than the shallow zone. This is caused by a low hydraulic conductivity (*i.e.* geometric mean of 1.1×10^{-6} m/s). The longer residence time allows the deep-flowing ground water more time to react with the minerals in the strata, increasing conductance and dissolved solids concentrations, relative to the shallow ground water. Specific conductivity profiles in the uncased boreholes illustrate that the conductance of the ground water increases with depth. The increases in conductance observed in some cases were gradual, while in other cases conductance increases were very discrete, corresponding to major fractures intersected by the borehole.

Additional Key Words: Appalachian Plateau, shallow ground-water flow, fracture frequency.

Introduction

The development of stress-relief fractures in undisturbed strata in the Appalachian Plateau has been widely reported (Ferguson, 1967; Ferguson and Hamel, 1981; Wyrick and Borchers, 1981; Wright 1987; Merin, 1989). Stress-relief fractures are created by the removal of rock mass by natural erosional processes. Stress-relief fractures that form in the valley walls are vertical or near-vertical and commonly parallel the valley orientation. Bedding-plane separations and small thrust faults form in the valley bottoms from the compressional stresses.

The frequency and depth extent of stress-relief fractures are directly related to the rock types, degree of induration, rock-layer thickness, and depth. Well indurated units in the valley walls such as thick sandstones and limestones tend to have a lower fracture frequency than less competent shales and claystones (Ferguson, 1967). A study of sandstones revealed a logarithmic increase in distance between fractures and increasing rock-layer thickness (Rats, 1964). Fracture

[1]Paper presented at the 1996 Annual Meeting of the American Society for Surface Mining and Reclamation, Knoxville, TN, May 18-23, 1996.

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Proceedings America Society of Mining and Reclamation, 1996 pp 42-51

DOI: 10.21000/JASMR96010042

https://doi.org/10.21000/JASMR96010042

spacing in Appalachia was observed at a fraction of a meter near the surface, increasing to over ten meters at depths up to 90 m (Trainer, 1983). Merin (1989) noted that bedding-plane fracture spacing increased non-linearly with depth, with spacing between fractures ranging from 1.3 cm to over 11 m. He saw no relationship between frequency and increasing depth for most vertical joint sets. Ferguson and Hamel (1981) observed that fractures in competent units tend to terminate at bedding contacts in softer units and that fracturing frequency decreases with increasing distance into the valley walls in the Appalachian Plateau. Borchers and Wyrick (1981), working in southern West Virginia, observed that stress-relief fractures "are a near-surface phenomenon" and that they decrease with depth. They doubted whether these fractures extend below 30 to 60 m. Kipp and Dinger (1987) noted that most fractures were within 46 m of the surface in eastern Kentucky. They reported that highly fractured rock units near the surface were relatively unfractured when more deeply buried beneath ridges. Wright (1987) also observed a significant reduction in fracture frequency and development with increasing depth in southwestern Virginia.

Ground-water flow in strata of the Appalachian Plateau is mainly controlled by the permeability created by stress-relief fractures. Brown and Parizek (1971) observed that sandstones and coals were the highest-yielding aquifers at two sites in central Pennsylvania. Sandstones, coals, and well indurated-units are more transmissive because they are self supporting and can hold fractures open. Softer units (*e.g.*, shales and claystones) are less permeable, because the fracture apertures are narrower (Peffer, 1991). These units are somewhat plastic and self healing; when fractures are created they have relatively small apertures or they tend to close up (Hawkins, 1995).

In a ground-water model developed by Kipp and others (1983), precipitation infiltrates into near-surface open fractures and percolates down until a confining unit is reached. The water then flows horizontally toward the outcrop, where it intersects fractures in the confining unit that allow downward flow, or where it emanates as a cropline spring. The remainder of the ground water continues in a stairstep fashion downward and toward the valley floor. Brown and Parizek (1971) observed a similar flow pattern. They divided the ground-water flow system into three components: 1) an "upper flow system" encompassing topographic highs down to the underground coal mines, 2) a "middle flow system" which discharges laterally and towards the stream valley, and 3) a "lower flow system" that represents the regional ground water system discharging to major river systems. Abate (1993) developed a conceptual ground-water model entailing a series of perched systems above each coal seam at the study site. In this paper, the conceptual ground-water system of this site is expanded and modified using additional testing techniques and data. Previous research and work by the authors at numerous other sites in the Appalachian Plateau indicate that the model developed has widespread applicability.

Site Background

The study site, the Kauffman mine, is located in Boggs Township, Clearfield County, Pennsylvania, midway between the towns of Clearfield and Houtzdale. A map of the site is located in the second part of this paper (Brady and others, 1996). The site is located between Camp Hope Run to the north and Sanbourn Run to the south, within 300 m of the regional drainage system, Clearfield Creek. The site is in a broad upland setting dissected by northwest-flowing tributaries. Topography is fairly steep, with a relief exceeding 200 m above drainage. The soil is relatively thin, sandy, well drained, and rocky. The predominant vegetation are hardwood trees with an undergrowth of ferns and mountain laurel.

Strata of the site and adjacent areas range from Mississippian sandstones at the level of Clearfield Creek to Pennsylvanian siltstones and sandstones forming the hilltops. Mining affects the Middle and Lower Kittanning formations, with the Lower Kittanning No. 2 and No. 3 coals being the target seams. These seams are usually separated by a carbonaceous claystone about 0.5 m thick. Above the No. 3 coal are dark gray to black shales and siltstones. Overlying the dark shales are gray, thick cross-bedded channel sandstones. In places, these sandstones rest directly on top of the No. 3 seam. About 7.5 m above the No. 3 coal is a thin rider seam, that may be the Lower Kittanning No. 4 coal. Above the rider seam, the strata are predominantly sandstones and siltstones with minor occurrences of clay, shales, and coals. In the western portion of the site, some of the strata within the Lower Kittanning overburden are alkaline. The strata dip slightly (< 2°) toward the west-northwest. Ground water moves primarily through fractures in the rock and cleat in the coal.

At several locations across the site, piezometer nests were installed at 3 or 4 discrete levels. The "A" wells were completed with the 1.5 m screened interval open to the Lower Kittanning coal and enclosing strata. The "B" wells were installed with a 1.5 m screened interval enclosing the Clarion No. 2 coal beneath the Lower Kittanning coal. The "C" wells were completed with a 3 m open interval accessing strata beneath the Clarion coal seam. The "D" wells were left as open uncased boreholes extending down to units slightly below the Lower Kittanning coal with only 3 m of casing extending from the surface through the soil horizon. A few well nests had "E" wells installed in sandstones open at a 1.5 m interval located between the "A" and "B" wells.

Fracture Frequency Analysis

A borehole video camera was used in the uncased boreholes to record and analyze characteristics of the fractures intersected. Fracture frequency, distribution, orientation, and ground-water-yielding fractures were determined from these borehole surveys. Previous research has shown that fracture density decreases with depth (Ferguson and Hamel, 1981; Borchers and Wyrick, 1981; Kipp and Dinger, 1987; Wright, 1987). Studies on the rate of fracturing decrease or fracture orientation are rare. Merin (1989) recorded decreasing bedding-plane fracture frequency and a decrease in hydraulic conductivity with depth in a hard siltstone. Decreasing fracture frequency was reflected by decreases in permeability and significant water-quality differences.

Video tapes of the uncased boreholes were reviewed to determine the fracture orientation and the fracture frequency. The fracture counts were grouped in 10 foot intervals and normalized into fractures per unit length.[1] The first interval started at 10 feet below the surface because casing was installed for hole stability. Fractures were categorized by orientation: 1) vertical/near vertical (90°+/-10°), 2) horizontal/near horizontal, mainly bedding plane separations (0°+/-10°), and 3) oblique, all fractures between vertical/near vertical and horizontal/near horizontal.

The highest fracture frequency intersected by the borehole was observed for horizontal fractures. The relatively high number of horizontal fractures was somewhat unexpected, based on previous research by Ferguson and Hamel (1981) that indicated that bedding-plane separations were more common to the valley bottoms than the ridge tops. Trainer (1983) observed that "bedding-surface openings" are common in horizontally bedded rocks in West Virginia, Maryland, Virginia, and Tennessee. The frequency of horizontal fractures (fig. 1) decreases substantially with depth. The average number of horizontal fractures intersected by the borehole decreases from 0.7 and 0.93 fractures per foot for the 10-20' and 20-30' intervals, respectively, to less than 0.1 fractures per foot at the 100-110' level.

Vertical fractures exhibited the second highest frequency of the three types (see fig. 2). However, given the mode of frequency determination, the number of vertical fractures are probably under-represented spatially in the ridge top. The fractures and boreholes are parallel or nearly so. Therefore, it is anticipated that the number of vertical fractures observed is less than the actual frequency in the strata. Measurements at freshly-exposed highwalls indicate that this assessment is correct. Vertical fractures

[1] As an artifact of the borehole videography, the fracture frequency analysis will be reported in english units to maintain consistancy with figures 1 and 2.

frequency significantly decreased at increasing depth. The average number of vertical fractures ranged from 0.77 fractures per foot at the 10-20' interval to none being recorded at the 100-110' interval. Although no fractures were encountered at the 100-110' interval, measurements of hydraulic properties indicate that fracturing extends beyond 100'.

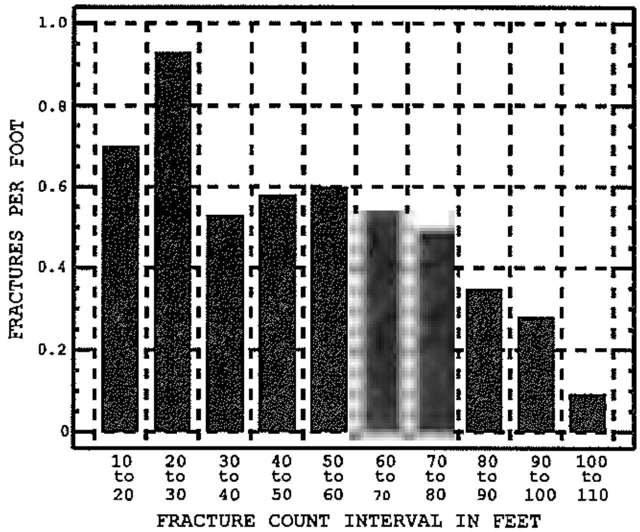

Figure 1. Frequency of horizontal fractures.

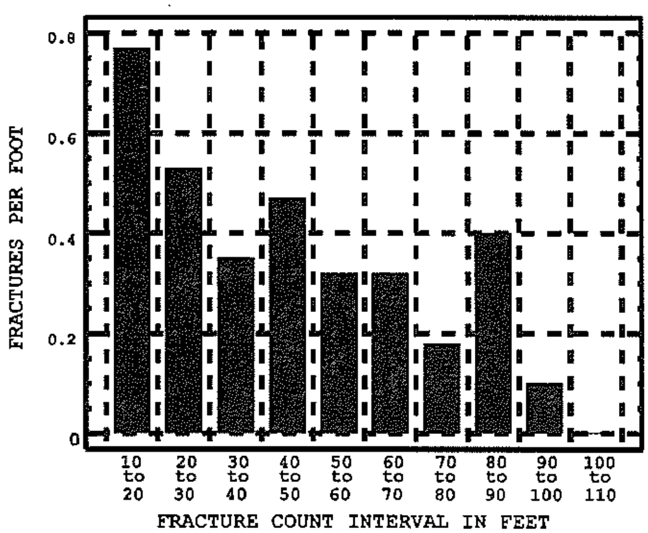

Figure 2. Frequency of vertical fractures.

Oblique fractures exhibited the lowest frequency of the three types. No trends with regard to depth were noted. The lack of frequency changes with depth may be related to the genesis of oblique fractures. The stress-relief origins of most of the horizontal and vertical fractures in the ridge-top wells are directly related to tensile stresses from rock mass removal. Oblique fracture orientation is consistent with those created by compressional forces from past tectonic activity. Compression generated fractures are usually less than 90° and generally 30° on either side of the direction of the compressive force (Billings, 1972). Given the relatively shallow nature of the strata studied (<35 m) and the forces creating oblique fractures, a change in frequency with depth was not expected because tectonic forces are not limited to shallow depths.

Aquifer Properties

Decreasing stress-relief fractures with increasing depth is reflected by lower hydraulic conductivities recorded in the uncased boreholes as the water level decreased. The hydraulic conductivity of several of the uncased boreholes was determined using slug injection tests. The wells were retested several times with differing water levels (saturated thicknesses). The uncased boreholes exhibited a wide range in water levels with fluctuations commonly exceeding 10 m.

Changes in hydraulic conductivity that spanned two orders of magnitude were recorded with water-level fluctuations.[2] With a water-level drop (saturated thickness decrease) of 8 m, from 16.8 m to 24.8 m below the surface, well W6D exhibited a hydraulic conductivity decrease from 3.6×10^{-6} to 3.3×10^{-8} m/s. A similar change was observed in that borehole with a 7.5 m reduction of water level. Well W5D exhibited a decrease in hydraulic conductivity of nearly two orders of magnitude, from 3.1×10^{-7} to 6.0×10^{-9} m/s, with a 8 m water-level drop, 10.8 m to 18.6 m. Well W22D exhibited a change in hydraulic conductivity from 4.6×10^{-6} to 1.3×10^{-7} m/s with a water level decrease of 3.8 m. Testing of well W7D showed a substantial and systematic reduction in hydraulic conductivity with minor water-level drops. With a water level of 21.55 m,

[2]Complete hydraulic conductivity and transmissivity data for this site are available upon request.

22.24 m, and 22.61 m below the surface in W7D, the estimated hydraulic conductivity was 2.3 X 10^{-7}, 1.3 x 10^{-8}, and 5.1 x 10^{-9} m/s, respectively. Merin (1989) observed similar hydraulic conductivity decreases with depth in a siltstone aquifer of the northern Appalachian Plateau.

The remaining uncased boreholes (W2D, W3D, and W4D) exhibited relatively small water-level changes (<3 m) when they were tested. Hydraulic conductivity changes for these wells and wells W5D, W6D and W22D, with minor water level changes, were small (<10X).

In contrast to the uncased boreholes, aquifer testing of the piezometers by both slug injection and constant discharge yielded no distinct trends with regard to increasing depth. The hydraulic conductivity ranged from 10^{-6} to 10^{-7} m/s. The lack of trends may be due to the relatively narrow open interval (1.5 m or 3 m). The piezometers access the deepest levels or below the levels of the uncased boreholes. Fractures at depth are of a hit-or-miss nature. Short intervals (<5 m) with very few or no visible fractures were commonly observed in the boreholes. This was especially true for the deeper rock units. Therefore, the hydraulic conductivity of the piezometers may exhibit large deviations from the average conductivity, mainly toward lower values.

Well Hydrographs

The substantial hydraulic-conductivity decreases observed with depth create a temporary shallow perched system following significant precipitation events. Hydrographs for the uncased boreholes and water-level measurements in the piezometers indicate that precipitation events create a bimodal flow system in the uppermost unconfined aquifer. A shallow perched flow system develops above the water table, causing water levels in the uncased boreholes to rapidly rise. The deeper water table continues to exist in the "core" of the hill above the underclay of the Lower Kittanning coal. The piezometers did not exhibit similar rapid water-level changes. Tighter strata within the deeper system cause ground-water flow to be much slower, with longer retention times than the shallow zone. Recharge to this lower zone has a longer lag time than the shallow zone.

With precipitation, water rapidly infiltrates into near-surface fractures. Ground water flows vertically for several meters (roughly 7 to 17 m) and then flows laterally toward the hillsides. Depth to which the water will percolate until it begins to flow laterally depends on the hydraulic conductivity, which is directly dependent on fracture aperture size and frequency. Aquifer testing illustrates that large changes in hydraulic conductivity (>100X) can occur within a short distance (8 m) vertically. This magnitude of hydraulic conductivity change is often defined as the distinction between an aquifer and an aquitard. These hydraulic conductivity changes with depth cause the formation of a temporary shallow perched water table. Water from this shallow system rapidly enters the uncased boreholes and fills them to the level of the upper saturated surface (see figs 3) and 4). The rate of inflowing water from shallow depths is greater than the rate the water is reintroduced into the lower and less permeable strata. The subsequent return of water levels to pre-rainfall levels are regulated by the hydraulic conductivity of the lower units and the low inflow rate that continues for several days to a few weeks after a precipitation event. Similar temporary perched ground-water systems have been observed at numerous other sites in the northern Appalachian Plateau (*e.g.*, Garrett Co., Maryland; Westmoreland Co., Pennsylvania) (Hawkins, unpublished data).

The boreholes exhibited water-level rises exceeding 12 meters from the onset of rain. Commonly, the initial water-level rise was observed 5 to 20 hours after the start of rain, whereas the peak usually occurred in less than 30 hours for well W5D and 48 hours for well W6D. This compares to 25 hours for the initial rise and 120 hours for peak rise for a cropline spring located on the site (Abate, 1993). The longer response time for cropline springs is caused by the longer vertical and lateral flow distance. Figures 3 and 4 are examples of water-level responses to rainfall events of 2.92 cm over 12.5 hour and 7.44 cm over 22 hour periods, respectively. These rapid water-level increases, if no additional rainfall occurs, are followed by a much slower return to pre-rainfall levels (Fig. 4). The protracted return to pre-rainfall levels is regulated by the permeability of the lower sections of the boreholes. Piezometers accessing the same units as the lower sections of the open boreholes do not exhibit the same rapid water-level rise as the boreholes. The water levels in the boreholes were over exceeding 15 meters above levels measured concurrently in comparable piezometers. A much longer time interval is required with recharge to this lower zone.

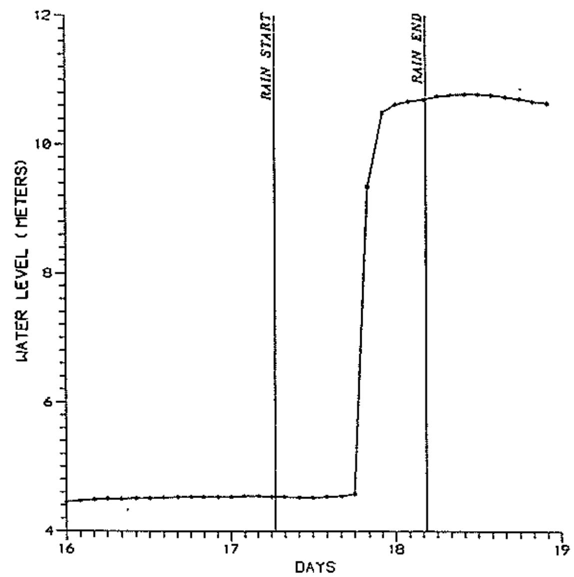

Figure 3. Hydrograph of well W6D from August 16 to 19, 1994.

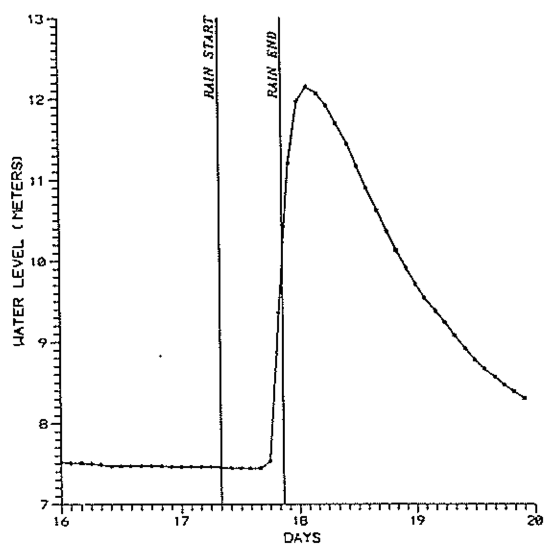

Figure 4. Hydrograph of well W5D from September 16 to 20, 1994.

Most of the ground water in the shallow perched zone, upon reaching the less fractured and unweathered zone, will rapidly flow laterally along a path nearly parallel to the surface. When a unit is encountered with poorly developed fractures, (*e.g.*, coal underclay), much of this water will emanate as a cropline spring. Figure 5 is a schematic cross-section, conceptually illustrating the shallow ground water flow. This water has a relatively short in-ground residence time and flows primarily through highly-leached strata. Therefore, the spring water exhibits a very low ionic strength, similar to rainwater. The chemical quality aspects of this water are discussed by Brady and others (1996).

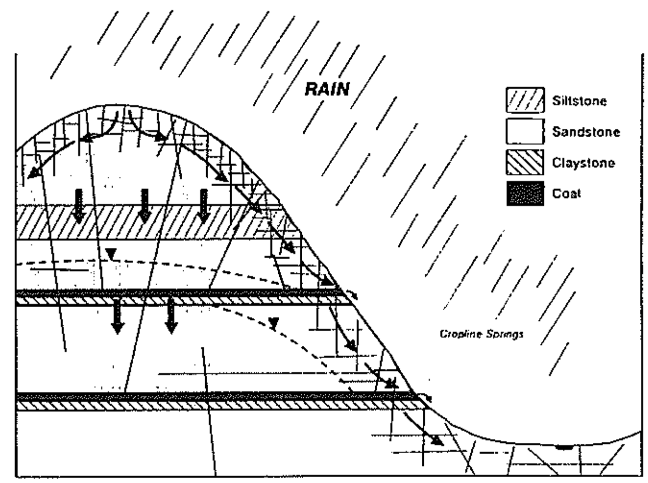

Figure 5. Schematic cross-section with conceptual ground-water flow paths.

The vertical hydraulic conductivity changes observed are not as abrupt as those associated with lithologic changes; they occur over a moderate distance. Therefore, a small amount of ground water flow continues in the shallow zone for several weeks after precipitation. A low-rate seepage was commonly observed into the open boreholes (at this site as well as several other sites in the northern Appalachian Plateau) several weeks following the last rainfall. This small amount of ground-water flow is what maintains the flow at the springs through dry periods. The gradual reduction of vertical and horizontal permeability in the shallow fractured zone permits continued ground-water flow long after the last rainfall event. Small aquitards or less permeable areas within the shallow fractured zone may also be a source of this slow-release water. Spring-water quality during dry periods indicates that the majority of the water originates in the shallow fractured zone, rather than in the deeper ground water system (Brady and others 1996).

Conductivity Logs

The short residence time of the shallow perched system and the longer residence time of the deeper unconfined system is reflected in the water quality observed in the uncased boreholes. Logging recorded increases in specific conductance with increasing depth in the uncased boreholes.

Some of the boreholes or portions of boreholes exhibited a relatively gradual increase with increasing depth. Figure 6 illustrates a gradual specific-conductance increase from 11 to 18 m and 19 to 30 m below the surface. Other boreholes exhibited substantial conductivity rises in a short distance (0.3-1.0 m). Figure 6 exhibits one of these rapid rises between the 18 and 19 m levels. A series of these conductivity jumps are exhibited by figure 7 at 20, 28, 31, and 32 m below the surface. The video logs show that these conductivity increases correspond to the locations of prominent fractures intersected by the borehole.

Not all fractures observed in the boreholes caused conductivity increases. There were numerous prominent fractures intersected by the boreholes that did not correspond to conductivity increases. However, the conductivity increases were always associated with fractured zones. This indicates that not all fractures contribute to the ground-water flow system. Booth (1988) observed that individual fractures may represent discrete aquifer zones that may have a distinctly different piezometric surfaces. Rasmuson and Neretnieks (1986) estimated that 5-20 percent of the fracture plane carries 90 percent of the water. Ground water flows through "channels" within fracture planes. Where fractures do not have corresponding conductance increases, ground water in these fractures may be of similar quality to water in fractures located above, or this may be where water from the borehole re-enters the aquifer. The latter is especially true in the lower portions of the hole, but may also occur in higher fractures during substantial recharge periods. When the head in the borehole exceeds the pressure head of a fracture, inflow from the borehole to the aquifer will occur.

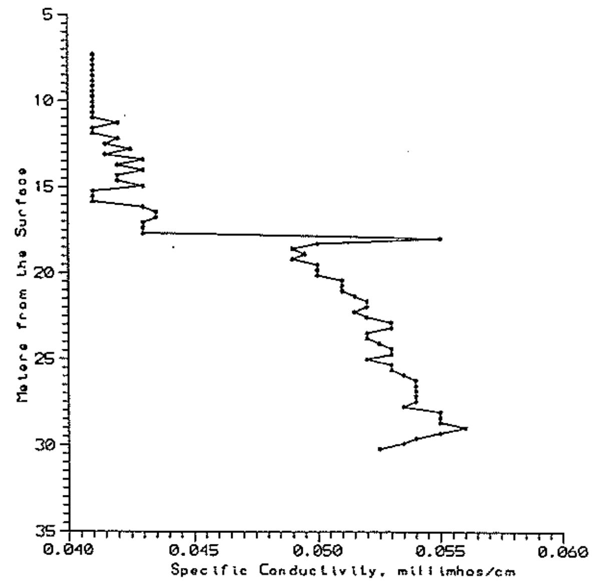

Figure 6. Specific conductance log for well W4D.

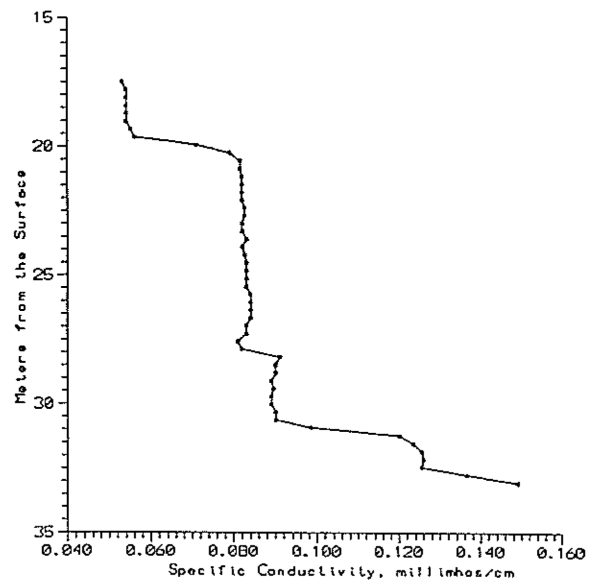

Figure 7. Specific conductance log for well W6D.

Piezometer Data

Head levels measured in the piezometers indicate that there is a downward flow component for ground water across the site. Head potential decreases between piezometers within a nest ranged from 0.23 to 1.0 m for each meter of increasing depth. Decreasing water levels indicate that the ridge top is a recharge area. The water levels measured in the "D" wells represent a composite of the different head levels of the rock units accessed.

Water levels exhibited by the piezometers indicate that a series of confined or semi-confined aquifers exist below the unconfined aquifer above the Lower Kittanning coal. Piezometric surfaces exhibited by "C" wells were above the level accessed by the "B" wells, but below their piezometric level. Abate (1993) suggested that "non-uniform pressure distribution" and substantial vertical head reduction below coal underclay units indicated that a series of perched aquifers exist near the outcrop. These aquifers above the regional aquifer probably exhibit both confined and unconfined conditions depending on the location monitored within the site (*e.g.*, unconfined near the outcrop). Specific portions of an aquifer may also exhibit confined and unconfined conditions at different time periods.

Discussion and Conclusions

Based on the data and information presented, a refined conceptual ground-water model has been created. An extensive review of the published literature indicates that this model is applicable for fractured sedimentary strata throughout most of the Appalachian Plateau. Minor modifications may be required in some regions.

A highly fractured and weathered zone up to 20 meters thick blankets the hilltops and hillsides in the Appalachian Plateau. This zone is highly transmissive and is underlain by progressively less transmissive fractured units. This less transmissive zone facilitates a temporary perched system from rainfall events. Rainwater quickly infiltrates into near-surface fractures flowing vertically for a several meters and then flows laterally toward the hillsides. This water has a short residence time in this shallow, highly transmissive zone. Much of the laterally flowing near-surface ground water emanates at cropline springs. These springs occur at the level of the coal seams. Fractures in the coal underclay tend to be poorly transmissive. Some shallow flowing water passes through the underclay and continues down slope in the weathered/highly fractured zone. Some of this shallow-flowing ground water recharges underlying aquifers via deeper fractures and emanates from coal seams at lower elevations. This conceptual ground-water flow system is illustrated by figure 5.

The short residence time (days to a week) for most of the shallow-flowing ground water is reflected by the low ionic strength of water at cropline springs. Ground-water quality is reported in detail in the second part of this study (Brady and others, 1996).

Data collected from the piezometers indicates that a series of confined or semi-confined aquifers exist beneath the water-table aquifer underlying a coal underclay. Decreasing head levels with depth indicate that there is a downward ground-water flow component. Aquifer tests performed on piezometers in the deeper confined aquifers illustrate that they have low transmissive properties and moderate head pressure; therefore, ground water movement into them and through them is slow. Decreases in the fracture frequency with depth account for the reduction in hydraulic conductivity with depth in the unconfined aquifer and the low hydraulic conductivity of the underlying confined units.

Determination of ground-water flow in the Appalachian Plateau is complex. Changes in transmissive properties caused by decreasing fracture development with increasing depth must be considered when designing a monitoring and water-quality characterization plan. Water quality at cropline springs is representative of ground water flowing through a near-surface, highly fractured and weathered zone. Monitoring wells installed into the core of the hill access ground water that reflects the deeper and slower moving aquifer systems. Deep ground-water quality is indicative of the geochemical quality of the deeper strata. Below the unconfined zone, a series of confined aquifers exist with a continued downward ground water flow component.

A comprehensive literature review and the widespread experience of the authors indicate that the conceptual ground-water model developed in this paper is applicable to fractured strata aquifers throughout the Appalachian Plateau. However, in certain regions, minor adjustments may be required to completely characterize the system.

Acknowledgments

The authors wish to acknowledge Christopher Abate for the initial research that was conducted on this site. We want to thank all the personnel of Al Hamilton Contracting that aided with the project and have tolerated our frequent occupation of the operation. The authors also wish to thank the reviewers. This research was conducted and funded by the U.S. Bureau of Mines.

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