Unsaturated Hydrogeologic Properties of Reclaimed Coal Strip Mines

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Abstract

Two nuclear methods were used to quantify hydrogeologic parameters in the unsaturated zone of a reclaimed and revegetated coal strip mine in Clarion, Pennsylvania. Am-Be (neutron) and Cs-137 (gamma-gamma) geophysical logging tools were used to quantify volumetric moisture content, bulk density, total porosity, and unsaturated hydraulic conductivity. An additional study at the same site used postsampling neutron activation analysis to determine concentrations of a bromide tracer in unsaturated zone water samples. Those additional data were used to independently calculate unsaturated hydraulic conductivity.

Geophysical logging of six boreholes at the site was conducted on seven different dates. Temporal variations in volumetric moisture content versus depth were observed to be short-lived, with the general shape of the volumetric moisture content profiles remaining spatially stable over the eight month period of investigation. Bulk density values ranged from less than 1.14 to 1.86 g/cm^3, corresponding to total porosities of greater than 57% to 30.1%. Large void spaces were encountered during past and present drilling and observed at a measurement point. Unsaturated hydraulic conductivities were calculated using draining profile volumetric moisture content data as input to an explicit numerical solution of the unsaturated flow equation. Calculated values ranged from 2.4×10^{-7} to 1.5×10^{-3} cm/s. Examination of all of the geophysical log data together showed sharp increases in volumetric moisture content spatially coincident with zones where bulk density increases (and porosity decreases). The bulk density contrast appears to be of more influence than the magnitude of the material property. Increased unsaturated hydraulic conductivity associated with increased volumetric moisture content was seen in several boreholes.

Bromide tracer-labeled waters were collected from pressure-suction lysimeters installed at depths of up to 18.1 m for a period of 16 months. Unsaturated hydraulic conductivities, calculated by interpreting concentration peaks as average arrival times of steadily infiltrating water through a uniformly porous media, ranged from 2.8×10^{-6} to 7.2×10^{-5} cm/s. However, a dual-permeability mechanism is suggested by the observed behavior of the tracer. Analysis of the data suggests that fluid flow in this hydrogeologic setting is dominantly transient. Ground-water recharge occurs in short-lived pulses. The periodicity of acid mine drainage formation and flushing to the water table is expected to correspond to infiltration and recharge events.

1.0 Introduction

Volumetric moisture content, bulk density, and total porosity were measured in situ in the unsaturated zone of a reclaimed and revegetated acid-producing coal strip mine using nuclear probes. These parameters are of use in characterizing ground-water flow in the unsaturated zone. In addition, transient unsaturated hydraulic conductivity was calculated using volumetric moisture content data from draining profiles of the same boreholes. These data and analytical results were previously unavailable in the literature. For comparison, unsaturated hydraulic conductivities were calculated using the observed concentration peaks from a long-term tracer study at the same site. Shallow, intermediate, and deep unsaturated zone water samples were analyzed for concentration of the bromide tracer using neutron activation analysis at the Breazeale Nuclear Reactor, The Pennsylvania State University. The tracer study calculation of unsaturated hydraulic conductivity, made in Lagrangian coordinates, yielded a travel-time and path averaged value.

The study area is located in Clarion County, Pennsylvania. The topography of the study area and surroundings, along with monitoring and sample collection locations, are shown in Figure 1. Like many other localities in western Pennsylvania and other coal-producing regions of the United States, strip mining of coal deposits here was preceded by the blasting of overburden sandstones and shales. The coals and associated sedimentary rocks often have high pyrite content, with total sulfur in excess of 1%. When these rocks are disaggregated in the absence of large sources of alkalinity (such as a limestone bed), acid mine drainage results. Its chemistry is characterized by extremely low pH, sometimes as low as 0, and high metals content. At the site, metals mobilized by this acid water include iron, aluminum,

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Received April 1990, revised April and July 1993, accepted August 1993.

magnesium, and manganese (Henke, 1985). In Pennsylvania, this phenomenon has resulted in severe environmental degradation (Appalachian Regional Commission, 1969). Increased permitting and operating costs as a consequence of acid mine drainage have caused economic hardships and even bankruptcies of coal strip mine operators.

Recognizing that the strip mine spoil in this topographic setting of relatively high relief is largely unsaturated (Figure 2), and that fluid flow rates control chemical transport from the acid-producing unsaturated zone, the nuclear logging investigation and the tracer study were designed to characterize both the behavior of unsaturated fluid flow and the medium in which it was occurring. These investigations are a part of a comprehensive program of acid mine drainage abatement research which has been ongoing since the early 1980s (Parizek and Guo, 1990; Williams et al., 1990; Diodato, 1989; Diodato and Parizek, 1988; Fielder and Parizek, 1988; Henke, 1985). The reclaimed and revegetated strip mine spoils have greater volume and porosity than the adjacent undisturbed bedrock. Drilling and blasting, which are a part of the mining operation, cause the spoil to bulk in volume when compared to the original undisturbed rock strata. As rock units of different lithologies are mixed during backfilling and grading, the spoil bank becomes highly heterogeneous.

At the site, the lithology of the spoil bank is dominated by an assemblage of blocky sandstones and finer grained shales. A cross section, schematic in part, of the hydrostratigraphy of the spoil pile and adjacent undisturbed strata is shown in Figure 2 (after Henke, 1985). These rocks are assigned to the Clarion Formation of the Allegheny Group (Williams et al., 1990; Henke, 1985). As suggested by Seaber (1992), each of the units in the hydrostratigraphic section can be distinguished on the basis of material properties influencing fluid flow. The lithologic sequence shown on the southern, unmined side of Figure 2, from bottom to top, is sandstone, underclay, coal, sandstone, shale, underclay, coal, shale, sandstone. On the northern, mined portion of the figure, the area which has been backfilled and reclaimed is a heterogeneous man-made deposit of disaggregated

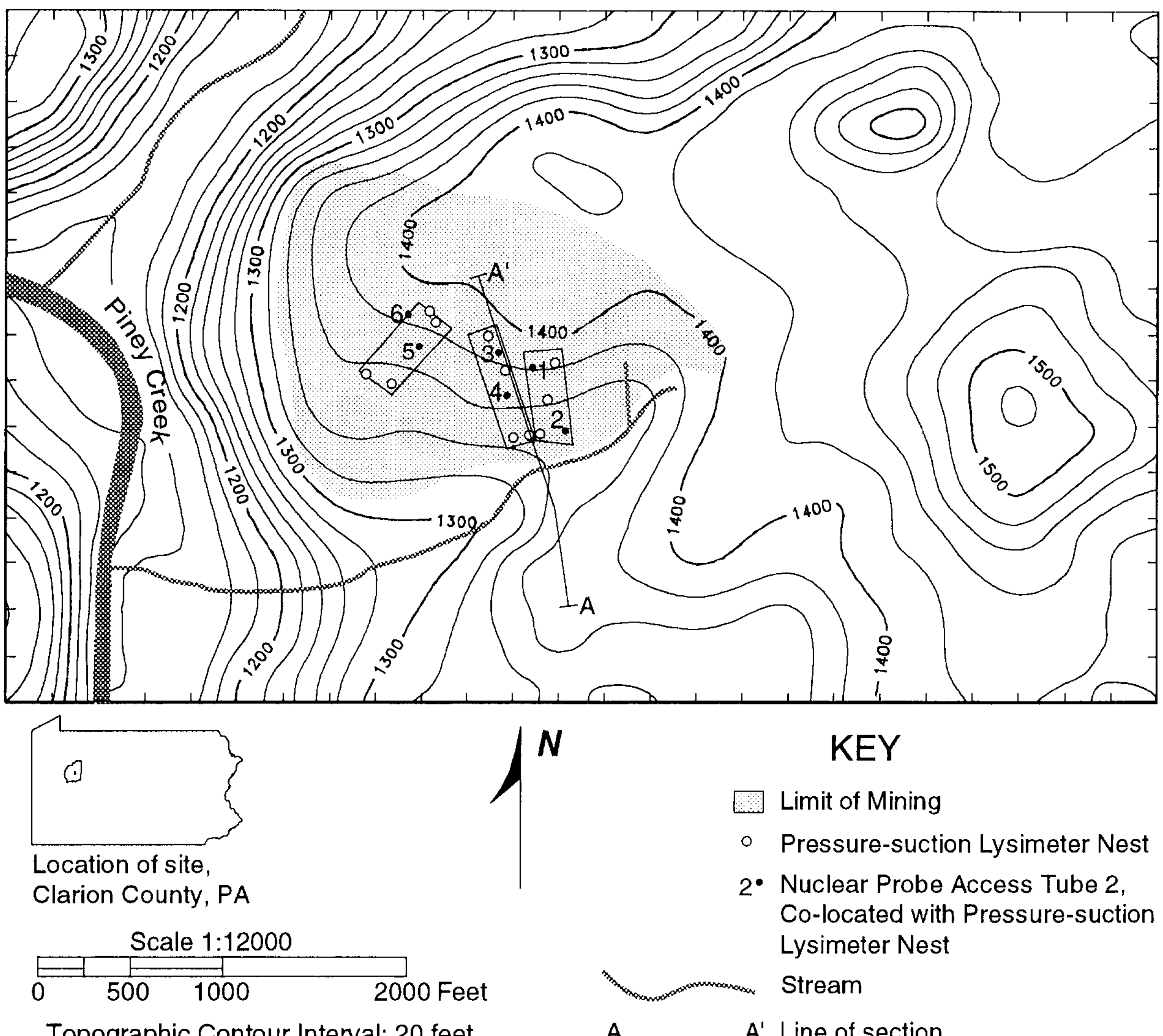

Fig. 1. Topography of the reclaimed and revegetated strip mine and surrounding area, Clarion County, Pennsylvania. Symbols indicate locations of access tubes and pressure-suction lysimeter nests used to collect data for the nuclear logging and tracer studies, respectively.

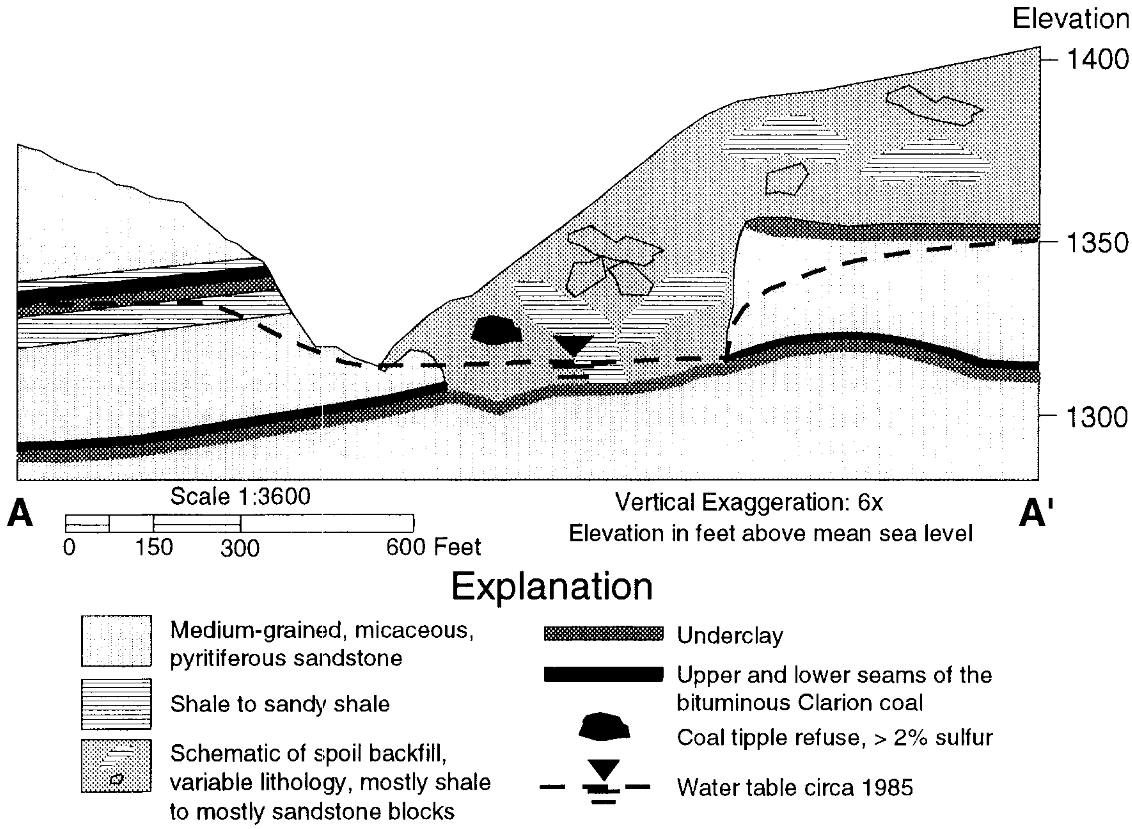

Fig. 2. Cross section through unmined and mined area (after Henke, 1985). The reclaimed mine spoil pile, partly schematic here, is composed of a heterogeneous mixture of mostly unsaturated sandstone and shale spoil.

sandstones and shales. Logs of the boreholes in which the pressure-suction lysimeters were installed show both sandstone and shale spoil. However, they frequently show "no return" or "poor return" and 15 cm bit drops (occurring repeatedly in some of the holes). The shale beneath the upper underclay has apparently pinched out on the mined side of the valley. The water table is indicated by the dashed line. A pod of buried coal tipple refuse (> 2% sulfur) occurs above the water table near the center of the figure. The behavior of fluid flow in this setting is understandably complex. The purpose of this paper is to characterize this flow and the parameters which affect it.

2.0 Methodology

2.1 Nuclear Logging

Nuclear logging was conducted to determine volumetric moisture content, bulk density, porosity, and unsaturated hydraulic conductivity values in the mine spoil pile. Six 6.4 m long seamless aluminum nuclear logging access tubes were installed at the site. These were installed in boreholes within several meters of the lysimeter nests which were sampled during the tracer experiment. The thin-walled nuclear logging access tubes accommodated the nuclear probes within a very close tolerance. For each installation, a tube was placed to one side of a borehole, which was backfilled with cuttings returned during drilling or with sand and gravel. Figure 1 shows the location of nuclear logging access tubes and pressure-suction lysimeter nests. The six localities of access tubes and lysimeter nests used in these studies are labeled 1 through 6. The access tube in borehole 3 structurally failed and was removed from the study.

2.1.1 Volumetric Moisture Content

Volumetric moisture content determinations were made using a dual-source Americium-Beryllium (Am-Be) probe with a BF_3 detector. This probe uses a back-scattering or thermalization technique to measure fast neutron moderation. The Am-Be is a source of fast neutrons and produces gamma radiation with an energy of about 60 KeV (Troxler, 1974). The theory of the measurement technique is discussed in the literature (Keys, 1988; Troxler, 1974). In brief, the number of thermalized neutrons detected is strongly a function of hydrogen content of the surrounding environment, and thus is correlated with water content.

The volume of mine spoil investigated (zone of measurement) of the neutron logging technique is dependent on a number of factors (Keys, 1988). Aside from borehole effects, these include the initial energy of the neutron, the presence and quantity of neutron poisons, the amount of water in the zone of measurement, and the bulk density of the zone of measurement. In general, an increase in initial energy increases the volume of investigation, while increases in the other parameters decreases it.

The Am-Be probe is supplied with a shield which is a volumetric moisture content standard. Before lowering the probe into the hole, a standard count of 30 seconds duration was taken. After the logging of the hole was completed, the probe was withdrawn back into its protective shield and another standard count was taken. The standard count used in calculations was the arithmetic mean of the two standard counts. Thirty second counts were taken down the hole in 15.2 cm increments, beginning 30-60 cm below land surface, until the complete hole had been logged.

Count ratios, the number of counts measured divided by the standard count, were calculated for each of the measurements. The use of a count ratio helps to mitigate effects due to decreasing source strength because measured counts and standard counts decrease proportionately. Volumetric moisture content was determined from a regression equation relating count ratio to volumetric moisture content (Troxler, 1974).

2.1.2 Depth-Density Measurement

The depth-density (gamma-gamma) probe uses Cs-137 as a source of gamma radiation and measures attenuated gamma radiation. The measurements are proportional to the wet mass bulk density of the surrounding environment. Compton scattering is the primary attenuation process for density logging (Keys, 1988). The sphere of influence of the density probe has a radius of about 13 cm (Troxler, 1974). Assuming that the geologic medium is not deforming over time, repeat measurements of bulk density are not required. The field methodology for the density logging was similar to the moisture-content logging. Using the count ratios calculated from the field measurements, bulk density values were determined from a calibration table (Troxler, 1974).

2.1.3 Total Porosity

Total porosity was calculated from

$$n = 1 - \frac{\rho_b}{\rho_p} \qquad (1)$$

where n is total porosity, ρ_b is dry mass bulk density, and ρ_p is particle density. Dry mass bulk density was calculated from wet mass bulk density and volumetric water content data. A particle density of 2.65 g/cm^3 was used. This value is a reasonable approximation for rocks and soils of dominantly silicate mineralogy.

2.1.4 Unsaturated Hydraulic Conductivity

Two volumetric moisture content profiles of the same space at a different time represent the left-hand side of the unsaturated flow continuity equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial h}{\partial z}\right] \qquad (2)$$

where θ is volumetric moisture content, t is time, z is depth, h is hydraulic head, and $K(\theta)$ is unsaturated hydraulic conductivity. This form of the continuity equation implies flow in the Z-direction only, which we take to be vertical. We desire to solve (2) for $K(\theta)$. Integrating over the depths $Z = z_0$ to $Z = z_1$, after Nielsen et al. (1973), which leads to

$$\int_{z_0}^{z_1} \frac{\partial \theta}{\partial t}\,\partial z = K(\theta)\frac{\partial h}{\partial z}\bigg|_{z_1} - K(\theta)\frac{\partial h}{\partial z}\bigg|_{z_0} \qquad (3)$$

If infiltration across the surface of the ground does not occur, then $K(\theta)[\partial h/\partial z]|_{z_0} = 0$, and (3) reduces to

$$\int_{z_0}^{z_1} \frac{\partial \theta}{\partial t}\,\partial z = K(\theta)\frac{\partial h}{\partial z}\bigg|_{z_1} \qquad (4)$$

Expanding the hydraulic head term

$$h = \Psi_m + Z \qquad (5)$$

where Ψ_m is matric head, and Z is elevation head, so that

$$\frac{\partial h}{\partial z} = \frac{\partial \Psi_m}{\partial z} + 1 \qquad (6)$$

If we make the assumption that matric potential gradient effects are much smaller than elevation gradient effects ($[\partial \Psi_m/\partial z] \ll 1$), then substituting (6) into (4) leads to

$$K(\theta)|_{z_1} = \int_{z_0}^{z_1} \frac{\partial \theta}{\partial t}\,\partial z \qquad (7)$$

Moisture content versus depth profiles taken immediately following the cessation of a rainfall event and a day later were used. Total area between the two curves was evaluated at the measurement points (z_1) using a trapezoidal approximation for each of the curves and then subtracting the area of the later curve from the area of the earlier curve. Conceptually, this approach means that the flux through any given depth is equal to the total area bordered by the two volumetric moisture content curves, depth 0 (z_0), and the depth in question (z_1). Therefore, even at depths where there is no change in volumetric moisture content with time, the flow through the depth interval is proportional to the area between the curves above it. Because of the earlier assumption of no-flow across the top of the profile, the method presented here is only valid for draining studies.

2.2 Tracer Experiment

A tracer experiment was conducted to determine unsaturated hydraulic conductivity values in the mine spoil. The chosen tracer was the nonradioactive, neutron activatable bromide-79. The advantages of bromide-79 as a tracer are outlined in the literature (Jester et al., 1977; Schmotzer et al., 1973). Butters et al. (1989), and Butters and Jury (1989) used an application of NaBr in an undisturbed soil zone (shallow) hydrogeologic setting to evaluate unsaturated zone transport models. The quantification of unsaturated hydraulic conductivity in this study is accomplished by measurement of bromide contents of infiltrating waters through time. Bromide concentration peaks are inferred to represent average transport times (Brasino and Hoopes, 1985; Raupach et al., 1983; Jester et al., 1977; Schmotzer et al., 1973). If we can assume that bromide is a conservative tracer, then, given a sampling schedule of sufficient frequency to define concentration peaks, arrival times of concentration peaks are proportional to average travel times of tracer bearing waters. To calculate unsaturated hydraulic conductivity, it is necessary to assume that fluid flows in the shortest path from the land surface to the buried pressure-suction lysimeter and that fluid flow occurs in a continuous, rather than discrete or pulsed, manner. These two assumptions concerning the behavior of fluid flow will tend to skew the values obtained for unsaturated hydraulic conductivity downwards.

At the site there are 62 pressure-suction lysimeters buried in the mine spoil in 17 drill holes at approximately 2.1 m depth intervals. The porous ceramic tip of each pressure-suction lysimeter was installed within a layer of super-sil. Sand backfill was placed in the borehole above the lysimeter body, and capped with a layer of bentonite pellets. Cuttings were then used to fill the borehole to the next pressure-suction lysimeter installation location. Two sets of background samples were collected from 57 of the pressure-suction lysimeters. Subsequently a 4,080 mg/l aqueous bromide solution was applied around 16 of the lysimeter nests in a diffuse pattern. Six 7.62 m long lines, arranged at 60° intervals around each lysimeter nest, received 18.9 l of solution each, poured from spouted jugs. Care was taken to avoid application immediately on the lysimeter nest, to ensure against the possibility of piping or channeling through backfill sediments in the borehole. Soil and meteorological conditions at the time of the application were ideal. The land surface was dry and rapid infiltration occurred with no runoff observed. Coincident with the completion of the application, a very gentle rain began to fall. This drizzle gradually increased in intensity over the next 6 to 12 hours, ensuring infiltration of the tracer. During the course of the experiment, all transport of the tracer was driven by naturally occurring rainfall.

Unsaturated zone water samples were collected from the pressure-suction lysimeters installed at the site. The sampling schedule sought to capture concentration peaks associated with both high and low average unsaturated hydraulic conductivity. Twenty-one sampling events occurred during the 493-day data acquisition period: 10 in the first four months, 9 in the next nine months, and 2 in the last four months. A careful sampling procedure ensured that the integrity of the samples was maintained during collection.

Five ml portions of the samples were placed in 2 dr poly vials and irradiated with gamma radiation. Neutron activation produced a number of short-lived isotopes of bromide-79. For this study, the bromide-82 isotope was used. A Ge(Li) detector and a pulse height analyzer monitored the disintegrations from a wide range of isotopes. Because each isotope has a unique spectrum of escape energies, isotopes were readily identified. Sample concentrations were calculated by comparing the magnitude of peaks of a particular escape energy with the magnitude of peaks of the same escape energy produced by a standard of known concentration.

Twenty-three pressure-suction lysimeters buried at successive depths in six lysimeter nests were identified as representative of the range of lithologies in the unsaturated zone at the site. Drillers' logs of the zones where these were installed indicated that 6 were in dominantly sandstone spoil, 9 were in mixed sandstone and siltstone to shale spoil, and 8 were in intervals where there was no return or very poor return and frequent bit drops. The depth of burial of the lysimeters ranged from 2 to 16 m. A total of 257 neutron activation analyses were completed on water samples collected from these devices. Some sample activations were duplicated to verify the reproducibility of the results. Bromide concentrations in background samples were below the detection limit of 20 ppb.

Transport of the bromide tracer was conceptualized as one-dimensional advection of an instantaneous solute pulse in a steady-state incompressible flow field. To simplify the analysis, diffusion and dispersion processes were neglected and the medium was assumed to be homogeneous. The advective transport equation describing this can be written as

$$\frac{dC}{dt} = -\frac{q}{\theta}\frac{dC}{dz} \tag{8}$$

where C is concentration, q is specific flux (L/T), and θ is volumetric moisture content. The ground-water velocity is described by

$$v = \frac{q}{\theta} = -\frac{K(\theta)}{\theta}\frac{dh}{dz} \tag{9}$$

The solution in a Lagrangian coordinate system is

$$\begin{aligned} t \neq \tau;\ C(x, t) &= 0 \\ t = \tau;\ C(x, t) &= C_0 \end{aligned} \tag{10}$$

where $\tau = (x/v)$ is a travel-time coordinate, and C_0 is the initial concentration of the tracer.

Time-series plots for each sampling point were used to identify the time of the tracer concentration peak. For example, Figure 3 is a bromide concentration versus time plot for a 198 cm deep pressure-suction lysimeter from nest 6. In this device, the concentration peak occurs after 49 days.

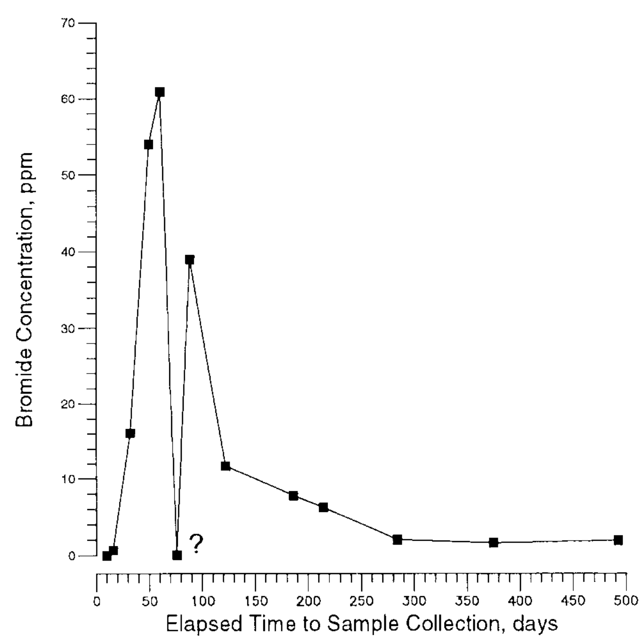

Fig. 3. Bromide concentration versus time from a 198 cm deep pressure-suction lysimeter. The concentration peak occurs 49 days after the application of the tracer. Also note the long die-off tail.

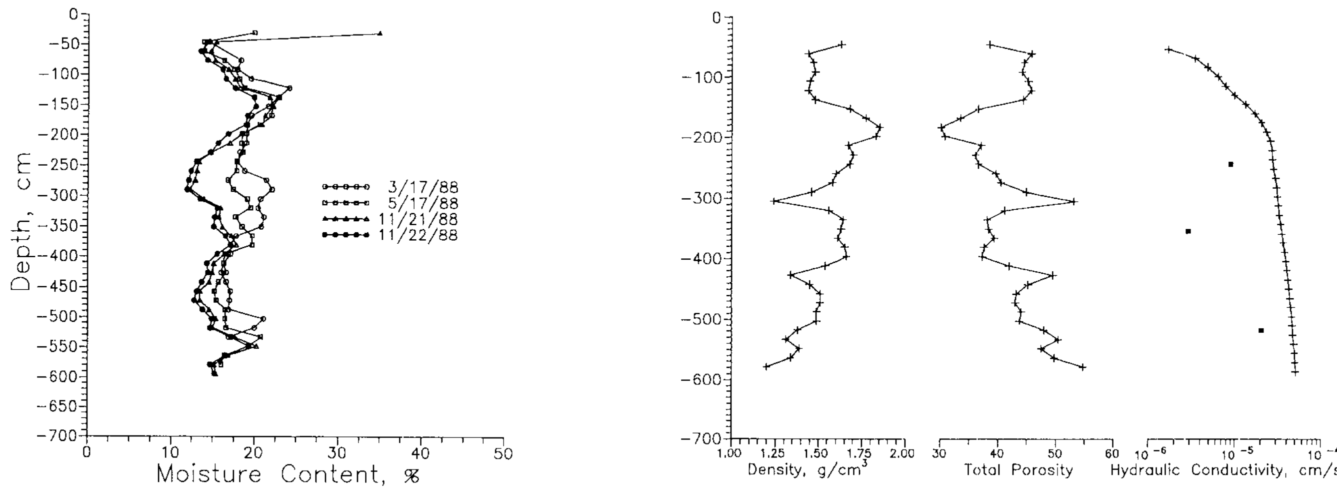

Fig. 4. A) Volumetric moisture content data from nuclear access tube 1. B) Bulk density, total porosity, and unsaturated hydraulic conductivity of nuclear access tube 1 and unsaturated hydraulic conductivity from the nearby lysimeter nest.

Velocities were calculated from the assumed linear distance traveled (depth) to the pressure-suction lysimeter divided by the elapsed time to the concentration peak. Volumetric moisture content data came from the geophyical logging. The data used for a given pressure-suction lysimeter were the temporal average of all measurements taken from the adjacent nuclear access tube at the same depth. When the pressure-suction lysimeter was installed at depths greater than the bottom of the nuclear access tube, the average volumetric moisture content of the overlying sediments was used. Because nuclear probe access tube 3 was not usable, calculations for the adjacent lysimeter nest used the average of all volumetric moisture contents. Hydraulic gradients were assumed to be solely due to elevation. Finally, unsaturated hydraulic conductivity was determined from

$$K(\theta) = \theta v \tag{11}$$

The values determined from (11) are unsaturated hydraulic conductivities spatially and temporally averaged along the flow path to the sampling point, as characterized by the travel-time coordinate. The methodology applied resulted in approximations marginally better than order of magnitude of unsaturated hydraulic conductivity in reclaimed strip mine spoil.

3.0 Results

3.1 Nuclear Logging

The data and analytical results from all nuclear logging are summarized in Figures 4 through 8. For each borehole profiled, part A of the figure shows the volumetric moisture content within the borehole for as many as six different profiling dates. On a seventh date, profiling was stopped by rain because of an electrocution hazard. Part B of the figures shows dry mass bulk density, total porosity, and unsaturated hydraulic conductivity for each of the boreholes. Unsaturated hydraulic conductivities calculated from the bromide tracer experiment are plotted as squares on the latter curves. Tracer-derived unsaturated hydraulic conductivities from depths greater than 7 m are not shown.

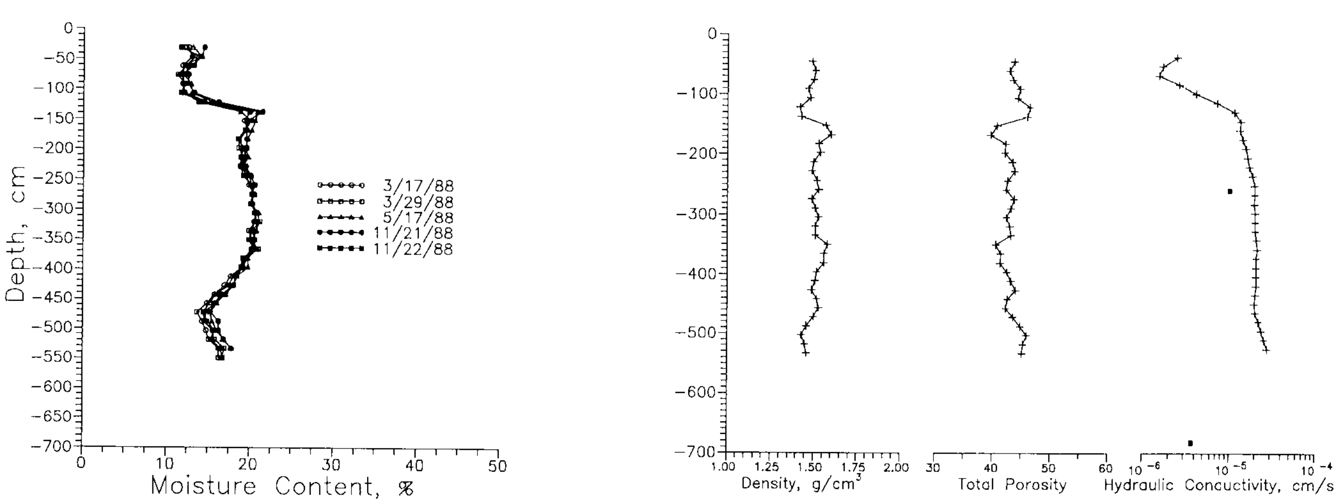

Fig. 5. A) Volumetric moisture content data from nuclear access tube 2. B) Bulk density, total porosity, and unsaturated hydraulic conductivity of nuclear access tube 2 and unsaturated hydraulic conductivity from the nearby lysimeter nest.

3.1.1 Volumetric Moisture Content

Moisture content values ranged from 8.5% to 46.2% over the study period. While some variation in volumetric moisture content may exist on a daily basis, there is a remarkable stability in the overall shape of the profile in any given borehole through time. A pervasive feature in Figures 4A through 8A is a shelf-like abrupt rise in volumetric moisture content within a very short depth interval. The sharp increase in volumetric moisture content is seen in all holes at varying depths, and occurs often more than once per borehole. This is believed to be the result of abrupt material property discontinuities. For example, this could occur on top of a layer of reduced porosity. If this postulate is correct, there should be spatially coincident abrupt changes in bulk density, total porosity, and unsaturated hydraulic conductivity. These features may be an artifact of man-made layering within the spoil bank and might result from the backfilling process itself. Dump bedding is created by gravity separation of different size rock fragments deposited by drag lines. Thus dump bedding is a type of man-made stratification where layers are parallel to the angle of repose of the material. Strip mine spoil material would most likely be dumped and graded in intervals of approximately 1.5 m of lift at a time. Heavy equipment operating on top of the most recently deposited lift layer would serve to compact it, increasing bulk density and decreasing total porosity at the top of the layer. Repetition of this process would create a cyclic pattern. (We have observed similar "depositional sequences" in municipal landfills.) Although the appearance of zones of increased volumetric moisture content may resemble perched water, the measured volumetric moisture contents are less than the porosities, so the zones are not water-saturated.

3.1.2 Bulk Density

Figures 4B through 8B show curves of dry mass bulk density, which is calculated from the measured wet mass bulk density and the measured volumetric moisture content. The values shown here were measured on a single date, although depth-density logging was conducted twice to

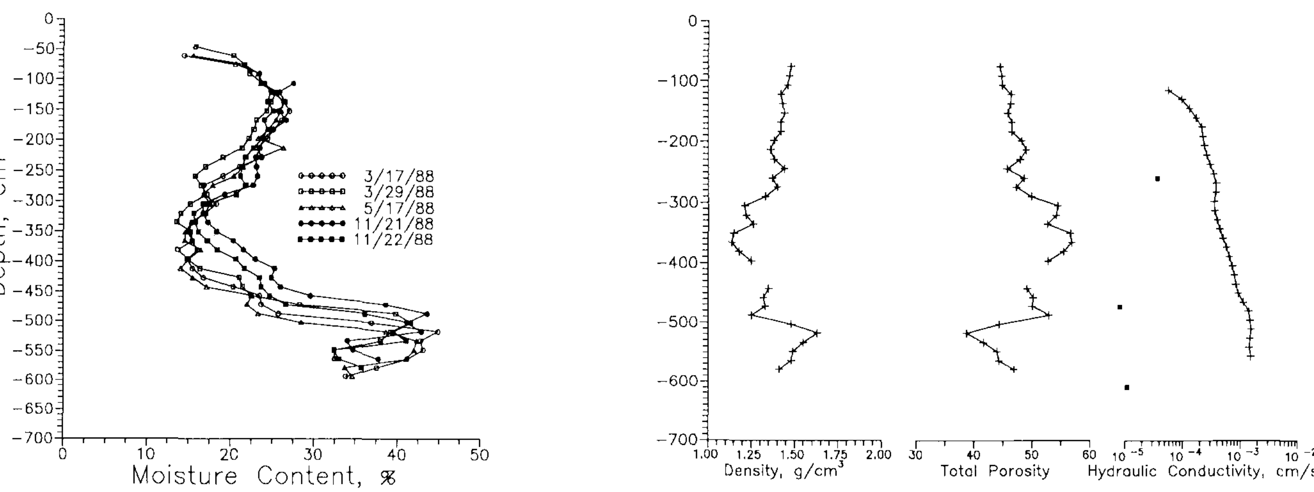

Fig. 6. A) Volumetric moisture content data from nuclear access tube 4. B) Bulk density, total porosity, and unsaturated hydraulic conductivity of nuclear access tube 4 and unsaturated hydraulic conductivity from the nearby lysimeter nest.

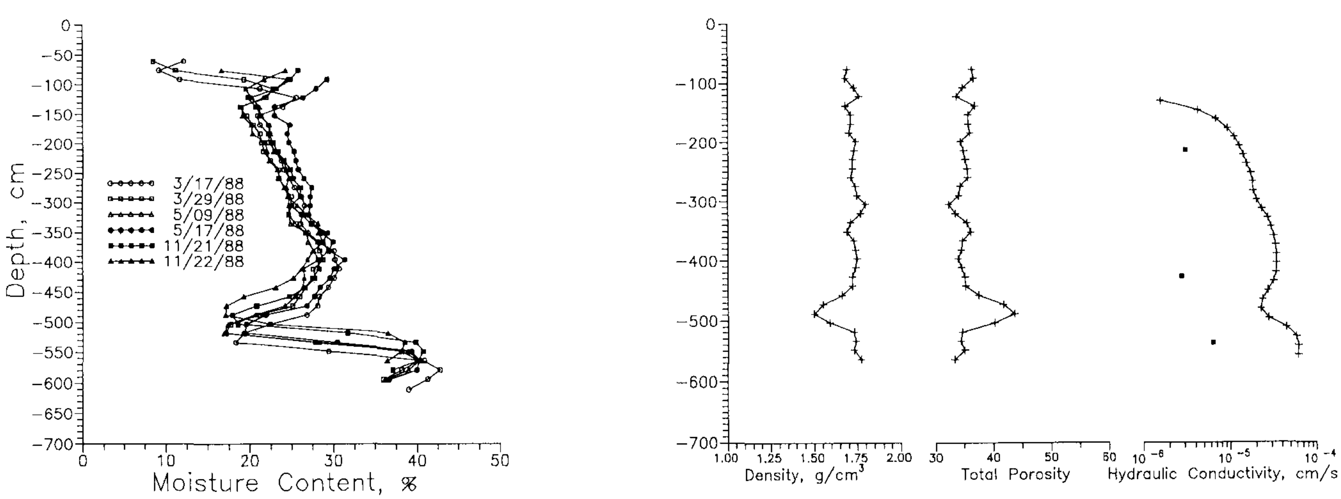

Fig. 7. A) Volumetric moisture content data from nuclear access tube 5. B) Bulk density, total porosity, and unsaturated hydraulic conductivity of nuclear access tube 5 and unsaturated hydraulic conductivity from the nearby lysimeter nest.

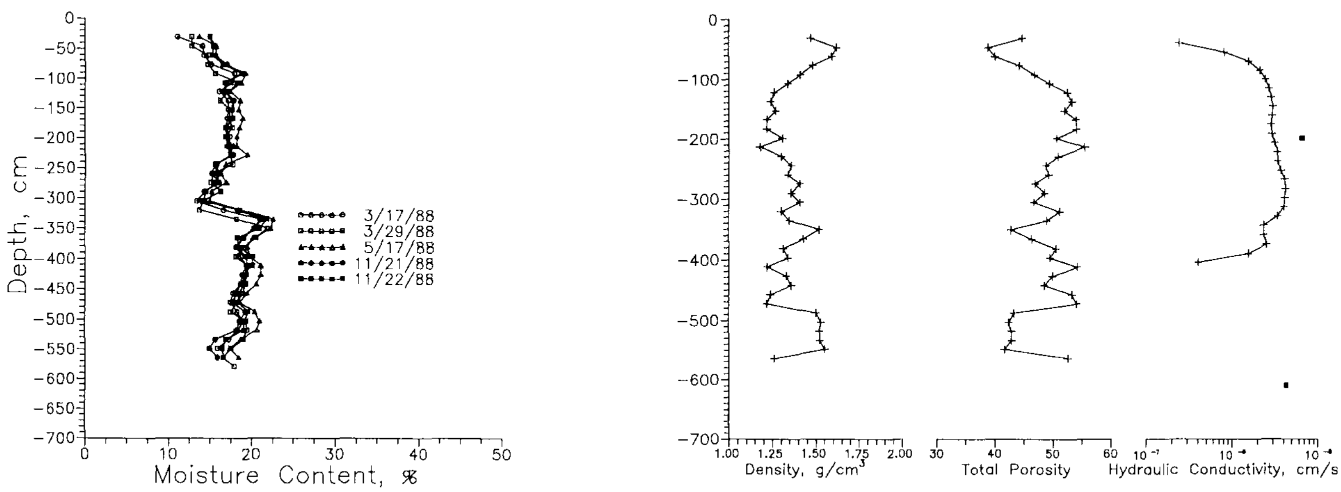

Fig. 8. A) Volumetric moisture content data from nuclear access tube 6. B) Bulk density, total porosity, and unsaturated hydraulic conductivity of nuclear access tube 6 and unsaturated hydraulic conductivity from the nearby lysimeter nest.

increase confidence in the reproducibility of the measurements. Data plots are clipped where bulk density was below calibration curve values. Approximately coincident with the shelf-like increases in volumetric moisture content in each of the holes are increases in bulk density. For example, in Figure 5 at about 150 cm; in Figure 6 at about 500 cm; in Figure 7 at about 500 cm; and in Figure 8 at about 300 cm. The magnitude of the bulk density itself does not seem to control the occurrence of increased volumetric moisture content; rather it is the occurrence of a sharp bulk density contrast that appears to cause this effect.

The bulk densities exhibit a wide range of values from less than 1.14 to 1.86 g/cm^3. The distribution of the bulk density values is normal with the mean, median, and mode closely coinciding at 1.5 g/cm^3, 1.49 g/cm^3, and 1.52 g/cm^3, respectively. In comparison, Pedersen et al. (1978) found mean mine soil (shallow) bulk densities to be 1.70 g/cm^3. Mine spoil bulk density values are considerably less than those of equivalent undisturbed lithologies.

3.1.3 Total Porosity

General trends of reduced porosity at the ground surface, and increasing or cyclically changing porosity with depth can be seen in Figures 4B through 8B. As is expected from equation (1), total porosity is inversely related to dry mass bulk density. Large voids may be inferred at depth on some of the plots. In one instance, the values obtained for wet mass bulk density at 411 and 427 cm, shown as missing on Figure 5, exceeded the lower range of the calibration provided, which had a lower limit of 1.14 g/cm^3. These values correspond to a total porosity in excess of 57%. This is consistent with field observations, which showed a strong flow of air emanated from this hole when an air rotary rig was drilling another hole about 6 m away. After casing was installed in that hole, the air flow stopped. This evidence of large interconnected voids is not isolated. Inordinate amounts of backfill material were required for some boreholes, as backfill material apparently migrated into large void spaces created by haphazardly stacked blocks of sandstone spoil. Two pickup truck loads of sand were required to raise the bottom of one 15.2 cm borehole just 3 m.

Voids of this size present significant pathways for flow and contaminant transport. The type of flow depends on the saturation state of the void. In a water-saturated void, all flow would be in the water phase. Alternatively, in an air-saturated void, all flow would be in the air phase. In any case, where saturation of a phase is less than 100%, multiphase flow will occur. Miscible to slightly miscible contaminants, for example, the metals and acid compounds of acid mine drainage, will be transported in the water phase. Volatile organic compounds, if present, will generally be transported in both phases.

Total porosity values from deep in the spoil pile were high relative to porosities of surface mine soils. Pedersen et al. (1978) found two surface mine soils to have 34% and 39% porosity. These values closely correspond to the shallow values seen in Figure 4. Total porosity was normally distributed with nearly coinciding mean, median, and modal values of 43.5%, 43.7%, and about 45%, respectively.

3.1.4 Unsaturated Hydraulic Conductivity

Unsaturated hydraulic conductivity from draining profile volumetric moisture content data was calculated using equation (7). Draining profiles of the boreholes were logged both immediately after 2.87 cm of rain had fallen and again approximately one day later. The total elapsed time between the two profilings for any given borehole ranged from 24.8 to 26.0 hours. Calculated unsaturated hydraulic conductivity values ranged from 2.4×10^{-7} to 1.5×10^{-3} cm/s, with a geometric mean of 1.3×10^{-4} cm/s. The general trends shown in Figures 4B through 8B are of increasing unsaturated hydraulic conductivity with depth. While linear relations between unsaturated hydraulic conductivity and the other variables plotted in Figures 4 through 8 are not expected, correlations exist between unsaturated hydraulic conductivity and intrinsic permeability and volumetric moisture content (Domenico and Schwartz, 1990). To the extent that porosity is indicative of intrinsic permeability in

Table 1. Comparison of Unsaturated and Saturated Hydraulic Conductivity Values from Various Studies at the Site, Clarion, Pennsylvania

	Hydraulic Conductivity, cm/s		
STUDY	Minimum	Maximum	Mean
Bromide Tracer (23 values)	2.8×10^{-6}	7.2×10^{-5}	1.5×10^{-5}
Drainage Profile (153 values)	2.4×10^{-7}	1.5×10^{-3}	1.3×10^{-4}
Saturated Zone Pump Tests[a]			
Sandstone spoil (4 values)	1.94×10^{-2}	3.88×10^{-2}	2.87×10^{-2}
Siltstone and Shale spoil			2.82×10^{-3}
Tipple waste with 50% clay- and silt-sized particles			3.53×10^{-4}

[a] Henke, 1985.

unconsolidated sediments (Chilingar, 1963; Freeze and Cherry, 1979), some correlation can be seen in the trends. In addition, increases in calculated unsaturated hydraulic conductivity appear to correlate roughly with zones of increased volumetric moisture content. This is seen, for example, in Figure 4 at about 150 cm; in Figure 5 at about 100 cm; and in Figure 7 at about 500 cm. Data plots are clipped where calculated unsaturated hydraulic conductivity was negative. This condition occurred in the top 46 cm of Figure 7B, and in the bottom 152 cm of Figure 8B. This is believed to be the result of lateral water flow, a violation of the assumption of vertical drainage.

Table 1 is a summary of saturated and unsaturated hydraulic conductivity values at the site. The values from the tracer study fall within the range of those from the volumetric moisture content drainage profile study. Saturated zone pump tests from the site are distributed over two orders of magnitude. Hydraulic conductivity in the unsaturated and saturated zones at the site varies over five orders of magnitude. The generally lower values of the tracer study (squares in Figures 4B through 8B) are a consequence of space-time averaging. The draining profile study suggests that fluid flows relatively quickly over short distances during short time intervals. This flow would be associated with elevated volumetric moisture content in the spoil media as a result of precipitation, infiltration, and recharge, accompanied by increased unsaturated hydraulic conductivity in response to increased volumetric moisture content. As volumetric moisture content decreased back toward field capacity, fluid flow would slow significantly. It would then remain slow for extended periods of time until the next recharge event. The space-time averaging of the tracer study includes both short periods of rapid transport and extended periods of negligible transport. Note that this interpretation suggests that the assumption of steady flow used in the tracer study is inappropriate.

3.2 Tracer Study

Bromide concentration of waters collected from lysimeters in the unsaturated zone was measured by neutron activation analysis. Unsaturated hydraulic conductivity was calculated using these data and the volumetric moisture content data as described in section 2.2. The unsaturated hydraulic conductivities previously presented in Table 1, calculated based on the sampling date which yielded the highest concentration of bromide, range from 2.8×10^{-6} cm/s to 7.2×10^{-5} cm/s, with a geometric mean of 1.5×10^{-5} cm/s.

Figure 9 is a cumulative frequency plot of the 23 values from the tracer study and the 153 values from the nuclear logging study, with the standard lognormal distribution superimposed. The distribution of the data were normalized by the following transformation (Haan, 1977):

$$z = \frac{(x - \bar{X})}{s_x} \tag{12}$$

where x is the natural logarithm of the unsaturated hydraulic conductivity, and $\bar{X}$ and s_x are the sample mean and standard deviation, respectively, of the natural logarithm of the sample X. While the data make some excursions from the theoretical curve, they appear to follow a lognormal distribution, as is characteristic of this hydrogeologic parameter (Nielsen et al., 1973; Wilson, 1980).

The mean of the tracer-derived data is an order of magnitude smaller than the mean of the draining profile-derived data. In addition, the former data set is much more narrowly distributed than the latter. Which set of values would be appropriately used in a modeling study? The distribution of the tracer-derived data is a result of the temporal and spatial averaging inherent in the calculation. It represents the average unsaturated hydraulic conductivities that would be found in a reclaimed strip mine month after month. On the other hand, the draining profile-derived data represent elevated unsaturated hydraulic conductivities during a short time period of higher volumetric moisture content. Fundamentally, the answer to the question posed is dependent on the goals of the modeling study. Steady-state unsaturated zone flow models, usually employed to describe long-period physical processes, might yield better results

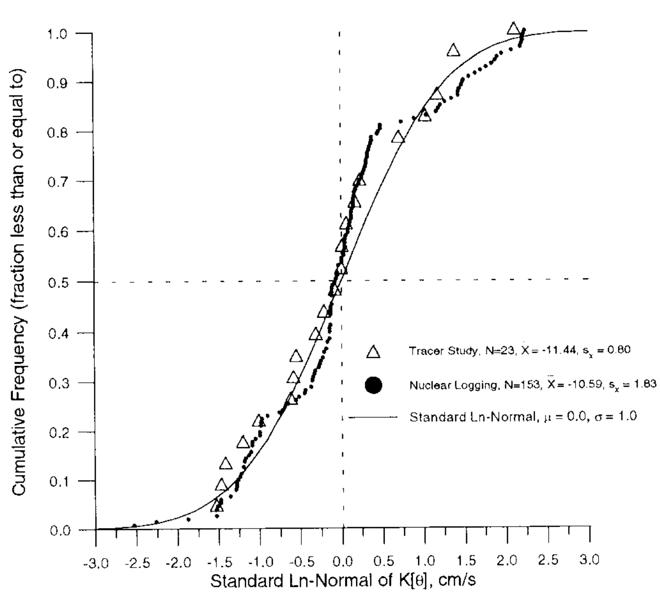

Fig. 9. Cumulative frequency distribution of the normalized logarithm of unsaturated hydraulic conductivity values determined from the tracer and nuclear logging studies. The solid line is the standard lognormal distribution.

with the tracer-derived data. Alternatively, short-term transient unsaturated zone flow models would be better off using values of saturated hydraulic conductivity scaled with relative permeability or other analytic relations.

The long die-off curve seen in Figure 3 suggests that storage capacities of the medium are significant. In one lysimeter, two concentration peaks of similar magnitude were separated by a period of six months (Figure 10). This may be an artifact of a dual-permeability type mechanism. Here, fluid flow (and associated chemical transport) might occur on a variety of scales: interblock flow in voids between blocks of sandstones and in voids in shaly zones, flow in finer grained matrix materials, and intrablock flow in the pores of the rocks themselves. As large voids became saturated during a wetting event, they would conduct most of the flow. Later, as drainage progressed, large voids would drain first while the remaining moisture was stored in the finer grained matrix materials under capillary (tensional) pressure. Finally, as the fine-grained rocks became increasingly unsaturated, fluid stored in large blocks of saturated rock could be drawn out into the fine-grained matrix. If this model is correct, then it would be possible for a pressure-suction lysimeter to collect waters conducted through macropores very rapidly and through micropores much later. In that case, the late concentration peak in Figure 10 may be representative of water which had been held in storage for a longer period of time. These drainage differences may have important implications when monitoring unsaturated spoil for the purpose of evaluating the effectiveness of acid mine drainage abatement measures.

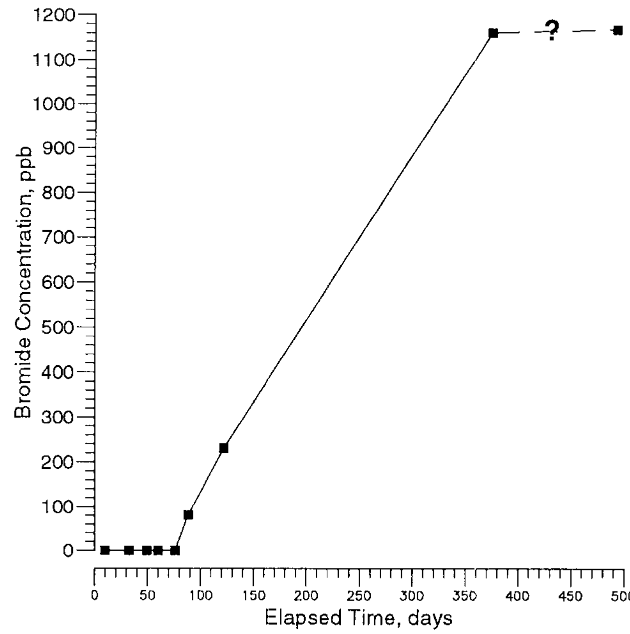

Fig. 10. Two bromide concentration peaks of similar magnitude in the same lysimeter, separated by a long period of time. This may be evidence of dual-permeability flow.

4.0 Conclusions

An in situ assessment of the physical properties affecting fluid flow in the unsaturated zone of a reclaimed and revegetated strip mine spoil pile was conducted. The nuclear probing methodology enabled rapid and repeated measurements to depths greater than 6 m. The highly heterogeneous nature of the spoil pile was clearly seen in the bulk density and porosity measurements. Evidence of possible impacts of the heterogeneities on volumetric moisture content distribution was seen in the volumetric moisture content profiles. Probable man-made compacted zones created during the backfilling operation were seen in the depth profiles. Water flow through the unsaturated zone, as inferred from volumetric moisture content measurements, occurs in relatively short-lived, rapid pulses. Because unsaturated hydraulic conductivity is strongly a function of volumetric moisture content, unsaturated hydraulic conductivity can be expected to increase orders of magnitude during these short time intervals, and later decrease as drainage progresses. From repeated measurements of the same borehole during a draining event, in situ transient unsaturated hydraulic conductivity was calculated. The observed infiltration behavior suggests that the assumption of steady flow used in the tracer study calculations is inappropriate.

The tracer study provided an independent means of determining unsaturated hydraulic conductivities spatially and temporally averaged along the flow path. Hydraulic conductivity data from this study were on average an order of magnitude lower and were more narrowly distributed than that from the draining profile study. The long die-off curves of tracer concentration suggest that the strip mine spoil pile material has a large fluid storage capacity. One postulate is that tracer-labeled water is retained during dry periods in the interstices of finer grained sediments, and is released when volumetric moisture content rises in the medium. Two tracer concentration peaks of similar magnitude, but widely separated in time, observed in the same lysimeter suggest that dual-permeability flow may be occurring.

From these studies we infer that acid mine drainage will flow from the spoil pile out into local stream discharges and aquifer systems in pulses in response to recharge events. During times of low flow, acid salts will continue to be produced in the interstices of the porous media. Thus, an effective abatement technique must inhibit acid production in situ during times of low water flow as well as during rapid recharge and discharge events. Assessment of the effectiveness of this and other environmental remediation efforts in similar disturbed settings should incorporate consideration of unsaturated fluid flow and chemical transport phenomena which vary less as the volume of space and the length of time of observation is increased. The actual benefits being achieved by acid abatement efforts may require monitoring of both early channeled waters as well as waters drained late in an infiltration and through-flow event.

5.0 Acknowledgments

The assistance of several members of the faculty and staff of the Pennsylvania State University in these endeavors was greatly appreciated. In particular, the authors thank C. Duffy, D. Fritton, W. Jester, J. Lynch, D. Raupach, and

W. White for their valuable criticisms and helpful insights. In addition, we would like to thank the following agencies for their support: The Pennsylvania State University, Pennsylvania's Ben Franklin Partnership Program, the Pennsylvania Department of Environmental Resources, the United States Geological Survey, and the C&K Coal Company. Support was also gratefully received from a U.S. Department of the Interior, Bureau of Mines grant #G1125132-4261, R. R. Parizek, Principal Investigator, through the Mining and Mineral Resources Research Institute, University of Nevada, J. Hendrix, Director. The constructive suggestions and comments of three anonymous reviewers were greatly appreciated.

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