UNSATURATED FLUID FLOW IN MINE SPOIL: INVESTIGATIVE METHODS LEADING TO A QUANTITATIVE CHARACTERIZATION

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A tracer study using non-radioactive neutron activatable bromide-79 was employed as an investigative technique to determine *in situ* unsaturated hydraulic conductivities at a reclaimed and revegetated strip mine in Clarion, PA. This investigation is a part of an ongoing acid mine drainage abatement study using surficial lime plant flue dust and limestone quarry waste. Water samples were collected through time from 55 pressure-suction lysimeters installed at various depths at the field area. 23 were selected for study and neutron activation analysis was used to determine Br concentration. Interpretation of the concentration peaks as average arrival times of infiltrating rainwater yielded unsaturated hydraulic conductivities ranging from 0.0279 to 0.5313 ft/day with one value of 1.1625 ft/day. This high value is interpreted as an example of infiltrating water piping through the highly heterogeneous disturbed spoil pile. Excluding the high and low values, the mean and the median unsaturated hydraulic conductivities were found to be 0.1876 ft/day and 0.1582 ft/day, respectively. These values are in the range of 0.14 to 18.76 percent of saturated hydraulic conductivity of the various geologic materials at the site. Further refinement of the data may be yielded by geostatistical investigations, as the semivariogram of the concentration values at a sampling point through time may suggest alternative concentration peak dates. A second investigative technique, the use of neutron depth-density and depth-moisture probes, will be of use in the determination of soil bulk density and soil moisture content values. An increased understanding of the behavior of alkaline waters and the hydraulic conductivity in the unsaturated zone will help investigators to evaluate past abatement strategies and to plan future ones.

INTRODUCTION

The unsaturated hydraulic conductivities of a reclaimed and revegetated acid-producing strip mine are being investigated and quantified by means of a tracer experiment. This research is in conjunction with a large-scale acid mine drainage abatement experiment the C&K Coal Old Forty Strip Mine site, Clarion, PA. The latter seeks to quantify the effects of two surficial treatments, each using different application amounts of lime plant flue dust and limestone quarry waste, in abating the acid production of the strip mine. On a macroscopic level, the alkaline waters resulting from precipitation on the applications in the two treatment plots may have been expected to percolate down through the spoil pile as a relatively uniform front. However, inspection of chemical analyses of soil water samples from the site suggested that the downward flow of these waters was not uniform. A desire for an increased understanding of the nature of unsaturated fluid flow at the site was the motivation for the bromide tracer experiment.

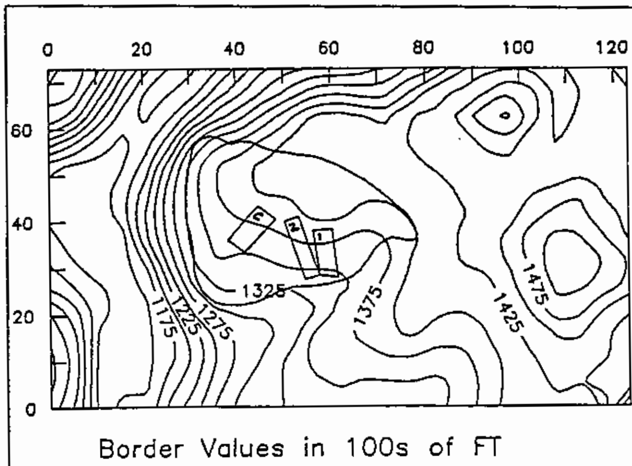

Figure 1. Site map showing limits of mining, treatment plots 1 and 2, and the control plot, C.

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At the site there are 17 drill holes that contain nests of pressure-suction lysimeters. These are buried at approximately 7-ft depth intervals. Figure one is a map of the site showing the treatment plots and lysimeter nest locations. The drill holes were backfilled preferentially using drill cuttings and other spoil materials readily available at the site. In some cases, it was necessary to use additional, exotic sand and gravel. But, in general, the use of materials found at the site helped to ensure that drill holes remained representative, both chemically and hydraulically, of the adjacent spoil pile.

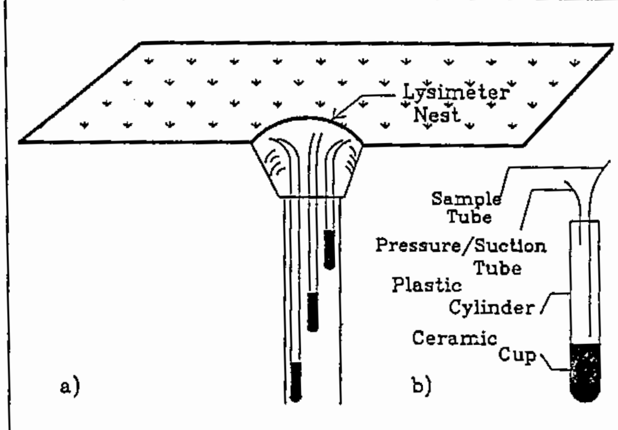

Figure 2. a) Schematic pressure-suction lysimeter nest installation. b) Cut-away view of a pressure-suction lysimeter.

Figure two is a schematic of a lysimeter nest installation. Soil water samples have been collected from these devices on a bi-weekly to monthly basis since 1984. What has been observed in some of these nests is an increased alkalinity at shallow depths, more acidic conditions at intermediate depths, and increased alkalinity at greater depths. This anomalous result immediately suggests three hypotheses. One hypothesis is that these lower alkalinity and pH samples could be produced by isolated hot spots in the spoil pile. If this is the case, then optimal remedial efforts should center on the identification and treatment of these hot spots, which may be responsible for the bulk of acid production. Alternatively, these low alkalinity zones could reflect decreased circulation of alkaline charged waters resulting from the treatment. This might result if these zones were more shaly, the disaggregated shale having a lower hydraulic conductivity than adjacent disaggregated blocky sandstone. Finally, this finding could be a result of a combination of the two previously mentioned factors, with the shaly zones containing the bulk of the pyritic material. The second hypothesis may be evaluated by determining the *in situ* unsaturated hydraulic conductivity of many zones in the spoil pile. In addition, knowledge of representative unsaturated hydraulic conductivity values will be of use to workers in this field.

THEORETICAL BACKGROUND

A tracer experiment is underway which aims to map hydraulic conductivities through the spoil pile. The chosen tracer was the non-radioactive, neutron activatable bromide-79. The advantages of bromide-79 as a tracer are outlined in the literature Schmotzer *et al.* (1973) and Jester *et al.* (1977). Briefly, they are as follows. Background bromide typically exists in natural aqueous systems at very low levels (40 to 300 ppb) in geologic association with evaporitic brine and marine shale sequences. Neutron activation analyses of background samples from the site showed no detectable bromide. It is not toxic to humans below 0.5 to 1.0 mg/mL of blood. Bromide is conservative in that it does not readily adsorb, absorb, or precipitate to a significant degree on natural surfaces. Bromide is unaffected by the actions of microbial biota. Further, the sensitivity of detectors allows resolution of background bromide to as low as 20 ppb. In addition to this, analysis and initial purchase cost of bromide are relatively inexpensive (Schmotzer *et al.* 1973). 25 pounds of potassium bromide were purchased for this experiment for less than two hundred dollars. Ammonia bromide is even less expensive, but potassium bromide was chosen to eliminate any slight nitrification of ground waters which may otherwise have occurred.

The quantification of unsaturated hydraulic conductivity in this study is accomplished by direct measurement of *in situ* bromide contents of infiltrating waters through time, the peaks of which are inferred to represent average transport times. This inference is not without precedent (Schmotzer *et al.* 1973, Jester *et al.* 1977, Brasino and Hoopes 1985, Raupach *et al.* 1983).

Saturated Hydraulic Conductivity

Hydraulic conductivity is a parameter of the D'Arcy fluid flow relation which describes the capacity of a given medium to transmit a given fluid. It is expressed in the units of a velocity, length per time. Hydraulic conductivity is a function of the characteristics of both the medium and the fluid moving through it. This is well illustrated by the relation

$$K = (\kappa \rho g)/\mu \qquad (1)$$

where

K = Hydraulic Conductivity
κ = Intrinsic Permeability
ρ = Fluid Density
g = Acceleration Due to Gravity
μ = Fluid Dynamic Viscosity

(Freeze and Cherry 1979)

Here the intrinsic permeability, κ, is a function of the medium alone, and includes factors describing mean grain diameter, the packing arrangement of grains, and the sphericity and roundness of grains, among other factors. It is a term best suited to the idealized D'Arcian elemental volume concept, and less well suited to more complex fluid flow such as that which exists in fracture flow controlled terrains. The terms which describe fluid properties are density, ρ, and dynamic viscosity, μ. These properties are well known and tabulated for a number of fluids at standard temperature and pressure, and for water at standard pressure over a wide range of temperatures. For water flow in a near-surface, non-hydrothermal, non-brine environment, these properties may be safely assumed to be constant. Similarly, the earth's gravitational force, which is acting on the fluid, decreases exponentially with distance away from the core, but may be considered constant within a small range of elevations.

Unsaturated Hydraulic Conductivity

For any given medium and fluid, saturated hydraulic conductivity represents the limiting case in that it is the maximum measure of this fluid transmitting capacity. As a medium becomes increasingly unsaturated with respect to a fluid, the volume of the medium transmitting the fluid decreases. Because there is a loss of fluid transmitting volume measured in L^3, expressed in a term of L/T, the decrease in hydraulic conductivity with increasing unsaturation is often dramatic and may span several orders of magnitude or more.

The degree of unsaturation can be expressed by a number of parameters, two of which are volumetric water content, θ, and matric potential, Ψ. Volumetric water content is the volume of water in a unit volume of medium, commonly expressed as a percentage. Thus if a medium has a porosity of 20 percent, and a volumetric water content of 20 percent, it is fully saturated. Increasing air content reflects increasing unsaturation. It should be noted that porosity does not imply permeability, because the void spaces are not necessarily interconnected.

Alternatively, matric potential is a measure of the tension at which water is held within the medium. In the literature, the symbol Ψ is commonly used to express the pressure head portion of the total hydraulic head relation, and thus includes both positive and negative pressure regimes. Here, we use Ψ to indicate only the nonpositive pressures which exist in the unsaturated zone. In adherence with established conventions, matric potential pressures are expressed as equivalent height of a column of water. This is a function of the mean grain size of the medium, among a number of other factors, and can be expressed by a capillarity relation.

$$\Psi = (2 \sigma \cos\theta)/(r \rho g) \tag{2}$$

where

Ψ = Height of Capillary Rise
σ = The Surface Tension of the Water-Rock Interface
θ = The Angle of Contact of the Capillary Force
r = The Radius of the Pore
ρ = Fluid Density
g = Acceleration Due to Gravity (after Miller 1982)

Consistent with potential theory, fluid will flow from higher to lower matric potential pressures. Thus one way to view matric potential is as the nonpositive part of the continuum between negative and positive fluid pressures, with zero matric potential at the wator table. Commonly, above the water table there exists a tension-saturated zone where water is stored in the medium under capillary force. Both matric potential and volumetric water content can be measured with field instrumentation and are of direct bearing on unsaturated hydraulic conductivity. Thus, unsaturated hydraulic conductivity is commonly expressed as a function of matric potential, K(& Ψ&), or as a function of volumetric water content, K(& θ). By either measure, saturated hydraulic conductivity is the upward limiting case.

The phenomenon of unsaturation has many important and complicating consequences. Among these, one of theoretical significance is the behavior of a slug of water associated with a single infiltration event. This slug will have a leading wetting front and a trailing drying front as it percolates downward through the unsaturated zone. A graph of either volumetric moisture content or matric potential versus unsaturated hydraulic conductivity has two hysteretic curves, one describing each front. This is because the wetting front has a greater hydraulic conductivity than the drying front. Because the tracer experiment is not strictly infiltration event-oriented, an investigation into this transient phenomenon is beyond the scope of this study.

EXPERIMENTAL METHODS

Two sets of background samples were collected from the 55 pressure-suction lysimeters installed at the site, the first on November 5, 1985 and the second on April 5, 1986. Subsequently, on April 4, 1986, a 4,080 mg/L aqueous bromide solution was applied around each of the lysimeter nests, except for TR2LY5, which has only one functioning sampling device. The application pattern is illustrated schematically in figure 3. The application was in a radial hexaseptate pattern designed to emulate a diffuse source. The bromide application emulated a diffuse source in an effort to mimic the behavior of both the rainwater and the limestone quarry waste and flue dust abatement application, all of which are diffuse sources. Each radius was 25 ft in length and received 5 gal of solution. Care was taken to avoid application immediately on the lysimeter nest, so as to avoid any possibility of downhole piping or channeling through backfill sediments. 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 increased in intensity at a slow and steady rate over the next 6 to 12 hours, ensuring maximum infiltration of the tracer.

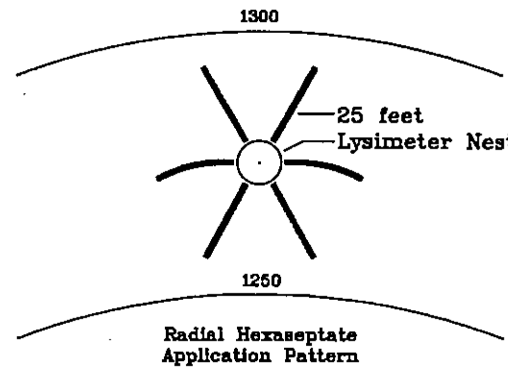

Figure 3. Schematic of tracer application pattern with contour lines.

Water samples were collected from the pressure-vacuum lysimeters installed in the 17 lysimeter nests at the site, from surface waters which flow through and off the site, and from ground water wells. The collection schedule varied according to precipitation and evapotranspiration, but averaged about three times a month during the initial four month period beginning April 14, 1986. For the next eight months sampling was conducted on a monthly basis. After April 14, 1987, one full year of bromide sampling had been completed, and the sampling schedule was reduced to a bimonthly one. The last sampling was in August 1987. A careful sampling procedure ensured that the integrity of the samples is maintained during collection. Because of the stability of the bromide anion, samples are safely stored at room temperature for several months.

The sampling procedure involves several anti-contamination safeguards. Sample bottles are kept sealed prior to and following sampling. While the lysimeter sampling tubes are held earthward, they are rinsed with distilled water and dried with paper towels. This cleaning is designed to eliminate the presence of contaminants which may have been derived from surficial sources. Initially, as the sample is being drawn, a small volume is discharged to the ground in order to further flush the sample tube. During sampling, the lids of the bottles are kept off the ground, as the ground potentially contains very high levels of Br^-. The sample is collected in the bottle, taking care to prevent the outside of the sample tube from coming in contact with the inside of the bottle, and the lid of the bottle is reattatched.

Neutron activation analysis is a straightforward procedure. Five mL portions of the samples are placed in 2 dr poly vials and irradiated with gamma radiation. Neutron activation produces a number of short-lived isotopes of bromide-79, including bromide-80 and bromide-82. A 50 cm^3 ge(li) detector counts the disintegrations, and feeds the data to an ND-680 pulse height analyzer. Because each isotope has a unique spectrum of escape energies, isotopes may be readily identified. 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, concentrations can easily be calculated.

The method of calculation for bromide concentration in neutron activated water is simplified by holding several of the variables constant. For any given run, all samples, including standards, are activated at a constant flux energy level for the same amount of time, and counted with the detector mounted at a constant distance for the same amount of time. A correction must be made for decay times for all of the samples, including the standards. Most sample group activations were performed at 900 kW for 1 minute, although some were at 1,000 kW for 1 minute. In every case, counts lasted 45 minutes. The governing relation for radioactive decay is

$$N = N_0 \exp[-\lambda t/T_{1/2}] \tag{4}$$

where

N = The observed sample activity after decay time, t.
N_0 = The initial sample activity.
λ = A decay constant, 0.693.
t = Decay time, time elapsed between sample activation and counting.
$T_{1/2}$ = The half-life of the isotope of interest.

Having completed a series of activations and counts, the initial activity of the standard must be calculated. Rearranging (4),

$$N_0 = N \exp[\lambda t/T_{1/2}] \tag{5}$$

Here, N_0 is the number of counts that the 50.0 parts per million standard would have produced at $t = 0$. Next, the initial activity of the sample is calculated, using the previous relation. Finally, the bromide concentration of the sample is calculated using the relation

$$[\text{Br } sample] = N_0\, sample\ (50.0 \text{ ppm} / N_0\, std) \tag{6}$$

When a preliminary run revealed some interference from manganese (an isotope of which has an escape energy close to that of bromide-80) in the water, it was decided to count the longer lived isotope bromide-82 after waiting a day for the manganese-56 to decay. Because of this, it was necessary to make a correction to allow for the decay time prior to counting for all of the samples, including the standards.

Six lysimeter nests were identified as representive of the range hydrologic and lithologic conditions found at the site. These were selected for intensive study. Their identification numbers, TR1LY1, TR1LY3, TR2LY1, TR2LY4, CLY5, and CLY6, are an artifact of the acid mine drainage abatement experiment, reflecting the existence of two treatment plots and one control plot. These nests contained a total of 23 functioning pressure-suction lysimeters buried at successive depths. A total of 257 neutron activation analyses have been successfully completed. This includes 17 ground water samples, 4 background samples, 2 application samples and 234 soil water samples. This represents an average of over ten analyses per lysimeter. In addition, some sample activations were duplicated to ensure the validity of the results.

INTERPRETATION OF RESULTS

The use of concentration peaks to infer unsaturated hydraulic conductivities hinges on several assumptions. These can be divided into three categories pertaining to the behavior of the tracer, the integrity of the sampling program, and the behavior of the fluid flow in the reclaimed and revegetated strip mine. First, it is necessary to assume that bromide is a truly conservative tracer. With this in hand, we can assume that concentration peaks at a particular sampling point are proportional to average arrival times of tracer-bearing waters. Second, sampling protocol must be rigorous enough to prevent contamination of samples, which would lead to erroneous results. Also, the sampling schedule must be sufficiently dense to successfully define concentration peaks. In this case, the sampling schedule was limited not only by labor considerations, but also by the sampling devices themselves. Pressure-suction lysimeters collect water from the unsaturated zone at a decreasing rate with increasing unsaturation, as was the case in the early summer months of the study. However, the many well-defined peaks produced by this study suggest that the sampling schedule was sufficiently dense. Finally, for purposes of calculation of unsaturated hydraulic conductivity, it is necessary to assume that fluid flows in the shortest path from the land surface to the buried lysimeter. This assumption eliminates the evaluation of the nearly infinite variety of flow paths which infiltrating waters may have followed. Further, it is assumed that fluid flow occurs in a continuous and not discrete or pulsed manner. With a time scale on the order of days, this assumption may not be unreasonable. These two assumptions concerning the behavior of fluid flow will tend to skew the values obtained for unsaturated hydraulic conductivity downwards.

With these assumptions in mind, the unsaturated hydraulic conductivites which exist around the pressure-suction lysimeter sampling points may be calculated by simply observing the time of the concentration peak at a particular lysimeter and dividing the depth at which the lysimeter is buried by this time. The unsaturated hydraulic conductivities presented in ascending order in table one are calculated based on the sampling date which yielded the highest concentration of bromide.

Table 1. Computed unsaturated hydraulic conductivities.

Lysimeter Nest	Lysimeter Number	Lysimeter Depth (ft)	Unsaturated Hydraulic Conductivity (ft/day)
CLY5	74	14.0	0.0279
CLY5	73	7.0	0.0376
TR1LY1	24	11.6	0.0466
CLY5	75	17.6	0.0550
TR1LY3	34	22.4	0.0585
CLY6	78	20.0	0.0685
TR2LY4	56	27.9	0.0728
TR2LY4	54	15.5	0.0833
CLY6	76	6.5	0.1083
TR2LY4	55	20.0	0.1266
TR1LY3	32	8.5	0.1417
TR2LY1	83	25.0	0.1582
TR1LY1	23	8.0	0.1633
CLY6	79	27.5	0.1741
TR2LY1	43	32.4	0.1742
TR1LY1	27	34.3	0.2171
TR2LY1	84	9.0	0.2813
TR1LY1	25	17.0	0.3469
TR2LY1	82	12.0	0.3750
TR2LY1	42	21.0	0.4286
TR2LY4	57	53.2	0.4325
TR2LY4	53	8.5	0.5313
TR1LY3	35	37.2	1.1625

It can be seen that these data range from 0.0279 to 0.5313 ft/day unsaturated hydraulic conductivity with one case of 1.1625 ft/day. The bulk of the data fall in the lower end of the range. The high value almost certainly represents piping or

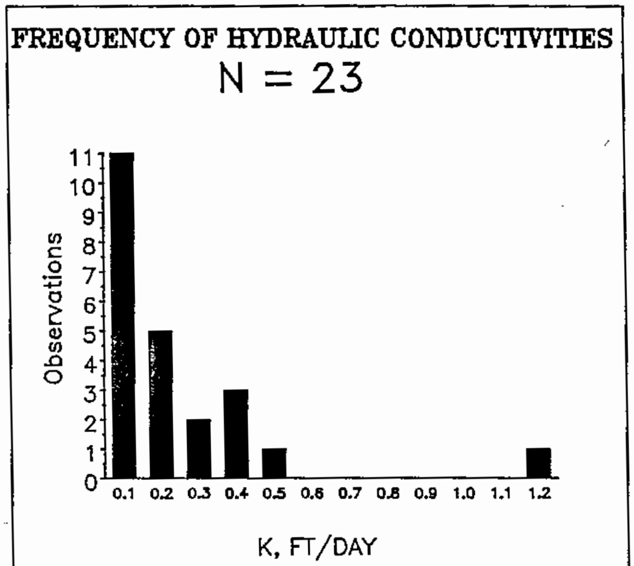

Figure 4. A frequency plot of the data from table 1.

channeling of infiltrating waters. Figure 4 is a frequency plot of the data from table 1.

Several of the lysimeters exhibited concentration peak curves which had no rising or falling limbs. That is, instead of being smoothly increasing and decreasing, the curves had step-like jump discontinuities. This can be explained as a consequence of insufficient sampling frequency for the particular peak. However, the sampling frequency was sufficiently dense to capture the concentration peak itself in all cases. In two cases an initial concentration spike was separated by a period of six months from later bromide occurrence. In the case of lysimeter 34, the two highest values, 1,161 ppb on April 14, 1987 and 1,169 ppb on August 10, 1987, are not significantly different from each other. This evidence of unsaturated fluid flow behavior is somewhat problematic. One of us (Parizek) has suggested that this may be an artifact of a dual-porosity type mechanism. Here, fluid flow might be occurring 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. The capillarity of finer grained matrix materials and whole rock would tend to impede flow while the interblock voids would be much more conductive. If this model is correct, then it would be possible for a lysimeter to collect waters conducted through macropores very rapidly and through micropores much later.

It is interesting to compare the values found in table 1 with those yielded from pumping tests previously conducted (Henke 1985). These saturated hydraulic conductivities ranged from about 1 ft/day in coal tipple waste composed of about 50% clay and silt-sized particles to 100 to 110 ft/day in predominantly sandstone spoil. Other values included 8 ft/day in siltstone and shale, and 55 and 60 ft/day in sandstone spoil-centered pump tests. Excluding the high and low values from table 1, the mean and median unsaturated hydraulic conductivities found at the reclaimed and revegetated mine site are 0.1876 ft/day and 0.1582 ft/day, respectively. These are between 0.14 and 18.76 percent of the saturated hydraulic conductivities.

Figure 5 is an example bromide concentration versus time plot for lysimeter 76 from Control lysimeter nest 6. The large primary peak is used for the calculation of unsaturated hydraulic conductivities. The exponential die-off curve suggests that storage capacities of the medium are not insignificant.

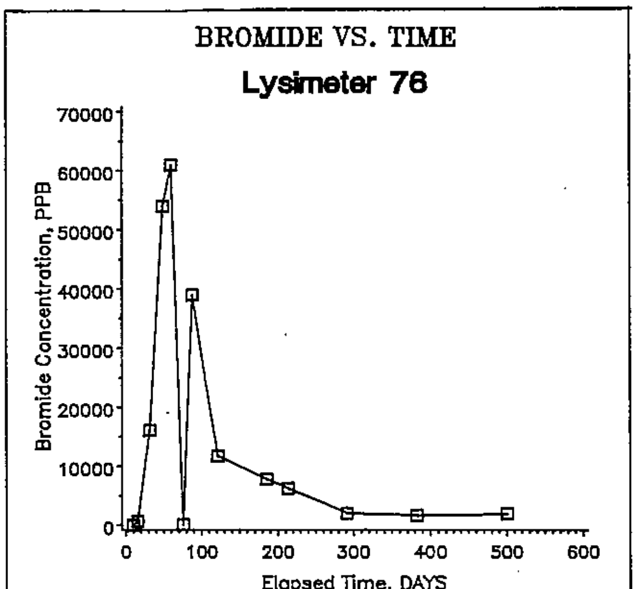

Figure 5. A plot of Br concentrations versus time for a single lysimeter. Background concentration is below detection limits (20 ppb). Application date is day zero.

Figure 6 shows the concentration values for all of the lysimeters installed in Control lysimeter nest 6. Non-ideal infiltration behavior is demonstrated here but is difficult to see because the magnitude of the concentrations varies over a wide range of values.

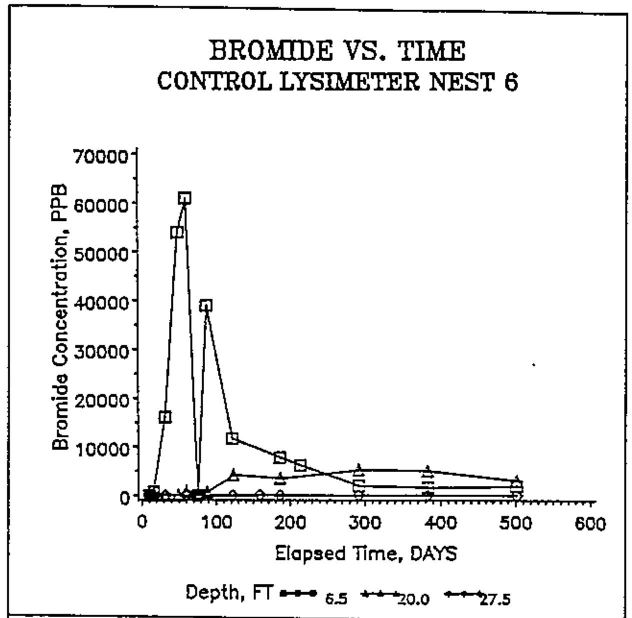

Figure 6. A plot of Br concentrations versus time. Background concentration is below detection limits (20 ppb). Application date is day zero.

For this reason the concentration peaks for each lysimeter were normalized by dividing observed concentrations by the maximum observed concentration for that lysimeter. This simplified peak identification and interpretation. An example plot of these normalized values is shown in figure 7.

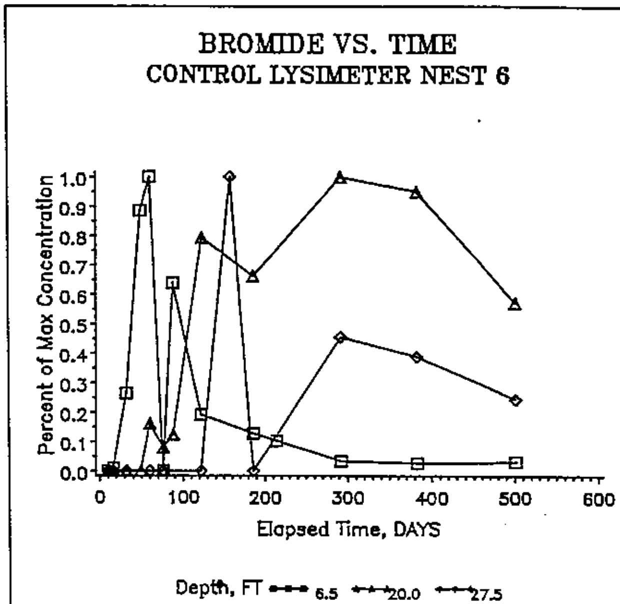

Figure 7. An example plot of normalized Br concentrations versus time. Background concentration is below detection limits (20 ppb). Application date is day zero.

Here, we can clearly see the non-ideal behavior, with the first peak in the shallow lysimeter, the second peak in the deep lysimeter, and the final peak in the intermediate depth lysimeter.

Figure 8 shows the apparent randomness with respect to depth of the hydraulic conductivities. This is consistent with the type of lithologic configurations one would expect to find in disturbed mine spoil. The vertical alignment of unsaturated hydraulic conductivities may be an artifact of insufficient sampling density, or it may be because of similarities in lithologies found at these various sampling points.

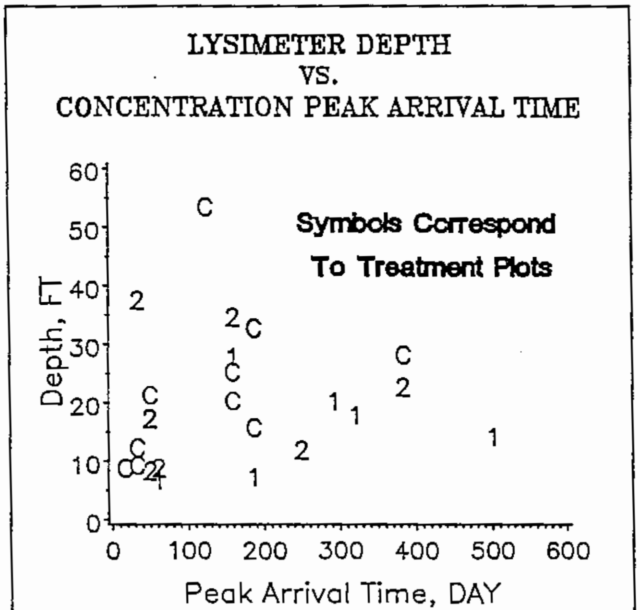

Figure 8. Scatter plot of peak arrival times vs depth. Points labelled 1, 2, and C are from treatments 1, 2, and the control plot, respectively. Rather than early peaks occurring at shallow depths, peak arrivals appear to be independent of depth. This is indicative of non-uniform, non-ideal infiltration and percolation behavior in the unsaturated zone.

With the peak arrival data in hand, and keeping in mind the assumptions previously mentioned, it is possible to calculate unsaturated hydraulic conductivity. Dividing depth by time yields the numbers depicted in figure 9, a scatter plot of depth versus unsaturated hydraulic conductivity. An examination of figure 9 suggests an irregular hydrogeologic regime, where areas of high and low hydraulic conductivity do not occur in distinct horizons, but rather are distributed more randomly with respect to depth. This insight helps us to build a more complete conceptual framework and understanding in regards to fluid flow in disturbed land.

With figures 8 and 9 in mind, table 2 is a listing of the lithologies of the lysimeter sampling points in the same order of increasing unsaturated hydraulic conductivity used in table one. Table 2 describes a highly irregular backfill spoil pile consisting primarily of two sedimentary rock types, sandstones and shales. Perhaps more significant than the lithological descriptions in table 2 is the lack of descriptions. In many cases the log reports no return or poor return and bit drops. Furthermore, the process of backfilling sometimes required quantities of sediment many times the borehole volume to complete. All of this evidence is testimony to the frequent presence of large void spaces in the spoil pile.

ONGOING AND FUTURE STUDIES

In terms of the unsaturated fluid flow characterization, the determination of soil moisture content and bulk density are critical. Volumetric water content is the ratio of volume of water

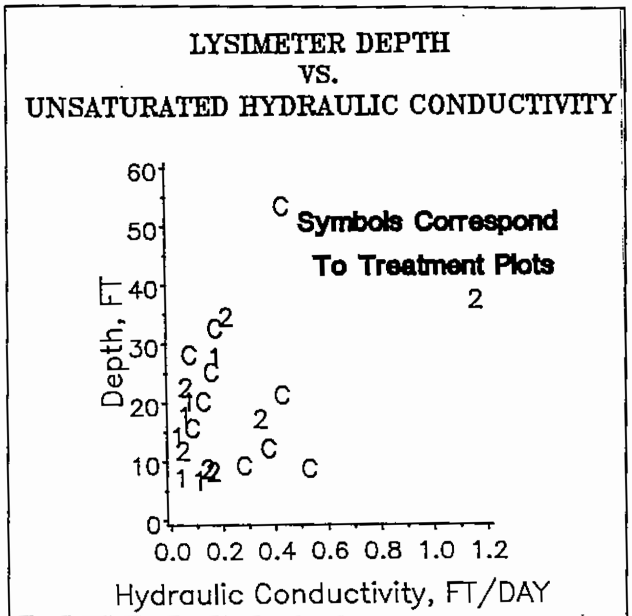

Figure 9. Scatter plot of unsaturated hydraulic conductivities versus depth. Points labelled 1, 2, and C are from treatments 1, 2, and the control plot, respectively. Randomly oriented values provide insight into the nature of fluid flow in disturbed mine spoil.

Table 2. Lithologies of the lysimeters.

Lysimeter Number	Lithology
74	Grayish-br sand and sandstone and shale/siltst frags
73	Grayish-br sand and sandstone and shale/siltst frags
24	Orangish-br sand and sandstone frags
75	Grayish-br sand and sandstone and shale/siltst frags
34	Poor return, bit drop@10 ft, boulder@27 ft
78	Poor return, gray to yellowish-br sand and sandstone frags, some coal frags
56	No return, bit dropped 0.5 ft@5,15 and 20 ft
54	No return, bit dropped 0.5 ft@5,15 and 20 ft
76	Gray to yellowish-br sand and sandstone frags, some dark-gray shale/siltstone and coal frags
55	No return, bit dropped 0.5 ft@5,15 and 20 ft
32	Gray to brownish-gray sandstone fragments
83	Poor return, gray sand and sandstone frags and dark-gray shale frags
23	Gray sandstone frags and yellowish-br sand
79	No return
43	Poor return, gray sand and sandstone frags and dark-gray shale frags
27	Poor return, br sand and sandstone frags
84	Poor return, gray sand and sandstone frags and dark-gray shale frags
25	Orangish-br sand and sandstone frags
82	Poor return, gray sand and sandstone frags and dark-gray shale frags
42	Poor return, gray sand and sandstone frags and dark-gray shale frags
57	No return, bit dropped 0.5 ft@5,15 and 20 ft
53	No return, bit dropped 0.5 ft@5,15 and 20 ft
35	Poor return, bit drop@10 ft, boulder@27 ft

to total volume, while bulk density is the ratio of dry mass of solid to total mass (Fritton 1986). Recalling that unsaturated hydraulic conductivity is a function of volumetric moisture content, this parameter is of interest. Knowing volumetric moisture content and bulk density, total porosity of the conducting medium can be calculated. An understanding of total porosity and bulk density will help to gain insight into the nature of the matric materials and their arrangement, which have a large influence on matric potential. Although the tracer study has been underway for some time, it is still desirable to obtain some representative values for soil moisture content under different meteorological conditions. This enhancement of the breadth and scope of the unsaturated fluid flow characterization of mine spoil is the motivation for the depth-density and depth-moisture profiling that is in progress. The specific relation between bulk density, total porosity, and volumetric moisture content is

$$E = 1 - (\theta_v \rho_w/\rho_s - \rho_t/\rho_s) \qquad (3)$$

where

E = Total Porosity
ρ_t = Bulk Density, M_t/V_t
θ_v = Volumetric Water Content, V_w/V_t

The values for θ_v and ρ_t can be empirically determined from *in situ* investigations using depth-moisture and depth-density neutron thermalization probes. ρ_w is taken to be 1.0 g/cm^3 and ρ_s is taken to be 2.65 g/cm^3. This derivation is based on the relations of Fritton (1986).

With the goal of depth-moisture and depth-density profiling in mind, six 20 ft-long very thin walled (0.035 in.) seamless aluminum access tubes were installed at the site in early September 1987. The installation locations were chosen to investigate the several characteristic heterogeneities and anisotropies found at the site. Further, the access tubes were installed proximal to the lysimeter nests whose flow behavior has been investigated in detail through large numbers of neutron activation analyses. With this strategy, a more definitive and detailed understanding of the fluid flow behavior at the site may be realized.

In addition, we recognize that sampling schedules may produce artificially skewed concentration peak dates and thus alter calculated unsaturated hydraulic conductivity. In the light of this, a remedial solution may be found in geostatistical approaches. That is, the determination of a semivariogram containing the concentration values at the sampling point through time may yield somewhat different peak dates.

CONCLUSIONS

A tracer study using non-radioactive neutron activatable bromide-79 was employed as an investigative technique to determine *in situ* unsaturated hydraulic conductivities in a reclaimed and revegetated strip mine. Subsequent to the application, water samples were collected through time from 55 of the pressure-suction lysimeters installed at various depths at the field area. 23 were selected for study and neutron activation analysis was used to determine Br concentration. Interpretation of the concentration peaks as average arrival times of infiltrating rainwater yielded unsaturated hydraulic conductivities ranging from 0.0279 to 0.5313 ft/day with one value of 1.1625 ft/day. This high value is interpreted as an example of infiltrating water piping through the highly heterogeneous disturbed spoil pile. Excluding the high and low values, the mean and the median unsaturated hydraulic conductivities were found to be 0.1876 ft/day and 0.1582 ft/day, respectively. These values are in the range of 0.14 to 18.76 percent of saturated hydraulic conductivity of the various geologic materials at the site.

The spoil at the site is composed of blocky, often micaceous, sandstones and finer grained disaggregated shales. The presence of many void spaces in these disturbed sediments is suggested both by the lithologic logs of the drill holes and by the difficult experience backfilling some of these same holes, which often required many times the borehole volume to complete. Despite these void spaces, only one suspected case of chanelling was found. Consistent with other undisturbed environments, in the disturbed mine spoil unsaturated hydraulic conductivity is one to three orders of magnitude less than saturated hydraulic conductivity. The values calculated have a narrow range and appear to be largely independent of localized lithologic heterogeneities. This, however, may be an artifact of a sketchy drill log record. Accurate and complete drill logs from disturbed mine spoil materials continue to prove difficult to obtain, as cuttings are often lost to the subsurface voids. With these unsaturated hydraulic conductivity values in hand, it is possible to calculate volumetric and mass flux of percolating waters through a unit cross-sectional area under a unit hydraulic gradient. Given an estimate of alkaline load in percolating soil water, either empirical or theoretical, it is possible to calculate acid neutralization potentials for a given mass or volume of water. Comparing these figures with acid production estimates should yield valuable insight into the effectiveness of a given surficial application of alkaline material. Clearly, the dramatic loss of hydraulic conductivity under unsaturated conditions presents a significant retardation factor in the speed and effectiveness of *in situ* abatement efforts.

Further refinement of the data may be yielded by geostatistical investigations, as the semivariogram of the concentration values at a sampling point through time may suggest alternative concentration peak dates. A second investigative technique, the use of neutron depth-density and depth-moisture probes, will be of use in the determination of soil bulk density and soil moisture content values. These data will help to quantify the range of unsaturation under which these spoil waters moved.

The abatement of acid mine drainage from strip mines through the use of surficial applications of lime plant flue dust and limestone quarry waste depends heavily on alkaline-charged waters percolating through acid-producing spoil material. Thus, an increased understanding of the behavior and transport rates of water through the unsaturated zone is of great value. With the unsaturated hydraulic conductivity values yielded from this study, investigators will be better prepared to evaluate past abatement strategies and plan future abatement strategies.

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