PREDICTING CONTAMINANT TRANSPORT
ALONG VEINS AND FRACTURES IN SAPROLITE
ABOVE THE WATER TABLE

by

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ABSTRACT

Saprolite is not permitted for use in on-site wastewater disposal in North Carolina if quartz veins or fractures occur within 60 cm (2 ft) of the septic trench bottom because such features might transmit raw sewage quickly to ground water. This study evaluated the time of travel (TOT) of a Br\textsuperscript{-} solute through quartz veins and fractures in saprolite. Eight 150 cm by 150 cm drainfields were constructed over quartz-diorite and mica-schist saprolites that contained quartz veins. Following saturation of the saprolite, a Br\textsuperscript{-} tracer and dye were applied for a specific time period. The drainfields were then excavated to 90 cm, the dye pattern mapped, and soil samples collected for Br\textsuperscript{-} analysis. There was no significant difference (\(P = 0.10\)) in depth of Br\textsuperscript{-} penetration in saprolite with and without quartz veins. On the other hand, mean depth of Br\textsuperscript{-} penetration increased from 14 cm for saprolite without macropores to 40 cm in saprolite with macropores (root channels) that extended to depths between 40 to 90 cm. A simple time of travel model predicted maximum depth of solute movement accurately where macropores were not present.

Accurate hydraulic conductivity data are needed to predict solute transport. Undisturbed cores were not considered reliable for hydraulic conductivity measurements because they produced variable results due to sample disturbance and their small size which did not contain representative numbers of macropores. In situ techniques were better for measuring hydraulic conductivity. These included the large (150 by 150 cm) drainfields and the compact constant-head permeameter, both of which produced similar results.
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SUMMARY AND CONCLUSIONS

Two different saprolite deposits, quartz-diorite and mica-schist saprolites, were examined to determine whether water and solutes moved along quartz veins and fractures in the saprolites at rates which were significantly faster than found for the saprolites’ matrix. A simple time of travel model was used to not only predict how far solutes could move but also to estimate the hydraulic conductivities of veins and fractures. Four different techniques for measuring saturated hydraulic conductivity were compared to determine which techniques were best for estimating this parameter. Hydraulic conductivity is used in models that predict the distances that solute will move in a specific time. Principal conclusions of the study were:

1. Quartz veins that ranged from 2 to 45 cm in width and which contained clay and iron or manganese oxides in between the gravels of the vein, conducted water at rates identical to those of the adjacent saprolite matrix.

2. Fractures that were filled in with black coatings of manganese oxides did not conduct water faster than the saprolite matrix conducted water. The materials in the fractures did not completely seal the fractures and allowed some water to flow along the fractures.

3. Saprolite that was within 3 m of the soil surface contained root channels which conducted water.

4. Undisturbed cores were not reliable samples to use for making measurements of saturated hydraulic conductivity, particularly where the purpose was to predict the distances that solutes will move through saprolite. The cores were too small to contain representative numbers of macropores, and in some cases could be fractured during sample collection.

5. The compact, constant-head permeameter produced saturated hydraulic conductivity values that were identical to those measured in situ with drainfields as large as 150 by 150 cm. The permeameter was convenient and fast.
RECOMMENDATIONS

1. Quartz veins and fractures in saprolite that contain clay and oxides of iron and manganese pose no apparent hazard to on-site waste disposal. State regulations governing on-site waste disposal should be changed to reflect this fact.

2. All veins and fractures examined contained coatings of clay and oxide minerals. During on-site inspections, field personnel can assume that veins and fractures containing clay and oxides pose no hazard for on-site waste disposal. However, it is not known how veins and fractures without clay and oxide coatings behave, because these were not studied. No such "unfilled" veins and fractures have been observed in North Carolina by the author.

3. Predictions of solute movement through saprolite in North Carolina can be made by assuming that most movement below a depth of 3 m will be through the saprolite matrix.
INTRODUCTION

Saprolite is bedrock that has weathered in place to the point that it is porous and can be dug with a spade (Becker, 1895). Saprolite occurs throughout the Piedmont and Mountains of the southeastern United States (Daniels et al., 1984). As the land available for conventional septic systems decreases, wastewater disposal in saprolite is gaining in popularity in some states. Health regulations will generally not permit its use if the saprolite contains fractures or veins. Fractures are simple planes of weakness or cracks in saprolite. Veins are tabular or plane-shaped bodies which contain minerals that differ from those in the surrounding saprolite (Guilbert and Park, 1986).

Most saprolites contain geologic fractures and fractured mineral veins that "appear" capable of conducting water rapidly. When fractures and veins are present in saprolite, it has been assumed that they are the primary voids for conducting water (Pavich, 1986). The lack of conclusive scientific data on water movement through quartz veins has caused public health officials in North Carolina to prohibit installation of septic-system drainfields in saprolites that contain veins or fractures. Any site will be declared unsuitable for waste disposal if veins or fractures are present within 60 cm (2 ft) of the trench bottom (NCDEHNR, 1991).

Williams et al. (1994) used core samples (7.6 cm in diam. and 7.6 cm in height) to determine hydraulic conductivities of quartz-phyllite saprolite with and without quartz veins. There was no statistical difference in the geometric mean hydraulic conductivities between populations. It is not known whether the results from this study apply to longer and wider veins which also occur in saprolite. The results do suggest that quartz veins are not causing by-pass flow to occur in saprolite.

Solute Travel Time

In soils that are suitable for waste disposal, effluent moves through the soil relatively slowly so that there is ample time for bacteria and viruses to be removed from the effluent by filtration or adsorption onto particle surfaces. Bouma et al. (1972) proposed that for a sandy loam soil, adequate purification would occur if effluent traveled downward a distance of 60 cm in 24 h or more. This suggests that time of travel computations could provide a way of estimating a soil's waste purifying potential, which is difficult to assess exactly, by using soil properties which are more easily measured.

The time of travel (TOT) for solutes to move specific distances \(L_v\) in soil or saprolite by convection or mass flow can be estimated from the average pore water velocity \(v\) where:

\[
TOT = \frac{L_v}{\bar{v}}
\]
The average pore water velocity is determined from Darcy's Law as:

\[ \bar{v} = \left[ -K(\theta) \cdot \frac{\Delta H}{L_w} \right] \theta \]  

where \( \theta \) is the volumetric water content, \( K(\theta) \) is the hydraulic conductivity at the water content \( \theta \), and \( \Delta H/L_w \) is the hydraulic gradient where \( \Delta H \) is the difference in total soil water pressure head between two points that are a distance \( L_w \) apart. Equations 1 and 2 can be combined to determine solute travel times from Darcy's Law as:

\[ TOT = -L_s \cdot \frac{\theta}{\left[ K(\theta) \cdot \frac{\Delta H}{L_w} \right]} \]  

Because \( K(\theta) \) is an average rate of water movement over an area, the above TOT model may perform poorly when there are spatial variations in hydraulic conductivity due to macropores (or quartz veins) rapidly conducting solute faster than the soil or saprolite matrix. The TOT model might be improved by using separate \( K \) values to account for flow along macropores and matrix. These effective hydraulic conductivity values could be determined experimentally by applying solute to the saprolite for a specific time period, and then observing how deep the solute traveled through the matrix and macropores separately. With such data the effective hydraulic conductivity could be calculated by the equation:

\[ Ke(\theta) = -L_s \cdot \frac{\theta}{\left[ T \cdot \frac{\Delta H}{L_w} \right]} \]  

where \( Ke(\theta) \) is the effective hydraulic conductivity of the macropore or matrix, \( L_s \) is the depth the solute has moved in a vertical profile, \( T \) is the time that the solute was applied to the profile and \( \theta, H, \) and \( L_w \) are the same as defined previously.

**Hydraulic Conductivity Measurements**

Evaluation of saprolite for waste disposal includes measuring its saturated hydraulic conductivity \( (K_{sat}) \) (Amoozegar et al., 1991).

The \( K_{sat} \) values can be used to estimate the amount of land area needed for the disposal and treatment of home sewage. Obviously, accurate \( K_{sat} \) values are needed if the area required for waste disposal is not to be made too large or too small for a given site. Various methods can be used to measure \( K_{sat} \), but it is not always clear whether different techniques provide similar \( K_{sat} \) values (Bouma, 1983). Because saprolite occurs below the soil solum at depths frequently exceeding 2 m, most \( K \) data for saprolite have been collected with small cores or in bore-holes of narrow diameter.

Several studies have shown conclusively that the \( K_{sat} \) values measured for a single soil horizon containing macropores (root channels and cracks) can vary greatly depending upon the volume of
sample used for an individual measurement. For example, Ritchie et al. (1972) measured the infiltration rate of a Houston Black Clay (a Vertisol) using field basins and undisturbed cores. Two field basins were enclosed by dikes to confine surfaces for infiltration that had areas of 6 and 100 m². Large undisturbed cores were collected which had diameters of 73 and 21 cm and lengths that ranged from 6 to 55 cm. The $K_{sat}$ values (infiltration rates) for the A horizon were approximately 0.1 cm hr⁻¹ for both field basins. The $K_{sat}$ values for the cores ranged from 0.1 to 0.5 cm hr⁻¹. There was no consistent relationship between core diameter or length and the measured $K_{sat}$.

The major water-conducting macropores in the Houston Black Clay were shrinkage cracks formed by the soil's wetting and drying. The cracks formed an interconnected network of planar voids that were oriented at angles of about 45° from the vertical. Ritchie et al. (1972) believed that the lower $K_{sat}$ values found in the cores were due to the metal cylinders that surrounded the cores having cut off some of the macropores. It was concluded that cores should not be used to measure $K_{sat}$ in this soil.

Anderson and Bouma (1973) measured the $K_{sat}$ of an aggregated silt loam B horizon using cores having a diameter of 7.5 cm and lengths ranging from 5 to 17 cm. The water-conducting macropores in this horizon were cracks between aggregates which formed continuous, vertical planar voids through the horizon. It was found that $K_{sat}$ decreased from approximately 29 to 4.2 cm hr⁻¹ as the cores became longer. The variability among the replicated measurements also decreased with increasing core length. Dye studies showed that "necks" occurred in most voids which determined the amount of water that could move through the voids. A neck is a constriction in a portion of a void (i.e. bottleneck) that controls the rate of water flow through the void. To represent field conditions, the cores had to be long enough so that the water-conducting voids contained the necks. Watts et al. (1982) have also shown that $K_{sat}$ values determined on soil cores can be up to 700 times greater than the $K_{sat}$ determined by in situ techniques. On the other hand, Zobeck et al. (1985) found that small cores can produce low $K_{sat}$ values when they don't contain a representative number of macropores.

Representative Elementary Volume

Appropriate sample volumes for measurements have been based on the concept of a representative elementary volume (REV) (Bear, 1972; Bouma, 1983). In theory, the REV is the smallest sample volume that should be used for measuring a property whose values vary with the sample volume. For example, mean $K_{sat}$ values determined for the REV of a given soil horizon should be the same as the $K_{sat}$ values found for samples of larger volume, although there may be an upper limit to sample volume. On the other hand, $K_{sat}$ values measured on samples whose volume is smaller than the REV may be either larger or smaller than the $K$ values found for the REV and larger samples.

Both the magnitude and variability of a soil horizon's $K_{sat}$ will vary with sample volume when macropores (e.g. root channels) conduct water through the sample. For example, the $K_{sat}$ may be
very high in a small soil core taken from a clayey soil horizon, if a root channel penetrates the core from top to bottom and conducts most of the water moving through the sample. However, another core from the same horizon may have a very low \( K_{sat} \) value if it does not contain any root channels, because the clayey matrix cannot conduct water quickly. The volume of the cores in both examples would be less than the soil horizon's REV for \( K_{sat} \) because either high or low \( K_{sat} \) values can be obtained depending upon whether the sample contained a root channel or not. The REV for \( K_{sat} \) measurements in this horizon is large enough for the numbers of channels per unit volume to remain relatively constant regardless of where the sample is taken within the horizon.

The REV for \( K_{sat} \) is not constant among soils, and may not even be constant among horizons within the same soil. It will vary when the numbers and sizes of macropores per unit volume changes, or when the pore size distribution of the soil horizon's matrix changes (Bouma, 1983). There is also an upper limit to the sample volumes that will provide \( K_{sat} \) values similar to those found for the REV (Bear, 1972). Large samples can have \( K_{sat} \) values different from those of the REV if they include material that has a different porosity, or material that contains larger or more numerous root channels per unit volume than was found in the smaller volume of the REV.

Lauren et al. (1988) measured the \( K_{sat} \) of the B horizon of a Glossaquic Hapludalf which had a silty clay loam textural class. In situ measurements were made at each of 37 sampling locations for five different sample volumes that ranged from 884 to 240,000 cm\(^3\). It was found that as the sample volume decreased, the \( K_{sat} \) values increased and the standard deviation of the measurements for a given volume of sample increased as well. The REV of the horizon examined was found to be 50,000 cm\(^3\), and in cross-section consisted of a 50 by 50 cm plane containing 58 macropores formed by structural planes and channels. The true \( K_{sat} \) of the horizon was considered to be 0.58 cm hr\(^{-1}\). In situ measurements made on samples whose volumes were less than the REV had average \( K_{sat} \) values as high as 1.5 cm hr\(^{-1}\), and detached core samples produced \( K_{sat} \) values that were greater than 167 cm hr\(^{-1}\).

Previous work on the effects of sample volume on \( K_{sat} \) was done on soil with well-defined, water-conducting macropores in the form of stable structural cracks or root channels. Saprolite poses a different challenge for \( K \) measurements because it has a rock-controlled structure without well-defined macropores. Virtually no work has been done to determine the effect of sample volume on \( K \) for materials having rock-controlled structure.

**Purpose and Objectives**

The purpose of this study was to determine the rates at which water and solute moved along the fractures in both quartz veins and in the saprolite matrix. Specific objectives were: 1) to evaluate water and solute flow along quartz veins and fractures in quartz-diorite and mica-schist saprolites, 2) to evaluate the accuracy of a time of travel model that predicts depth of solute movement under field conditions, 3) to estimate appropriate sample volumes for making hydraulic conductivity measurements in saprolites with macropores; and 4) to identify techniques for measuring hydraulic conductivity accurately in saprolite.
PROCEDURES

The study was conducted at two locations in the North Carolina Piedmont. Site 1 was located in Randolph County near the town of Ramseur. Site 2 was located in Raleigh on a research farm owned by North Carolina State University (Unit 1). Procedures used were similar at both sites, and will be described in detail for site 1 and only major differences noted for site 2.

Solute Transport Studies

Preliminary Site Characterization

Site 1 occurred in a metamorphosed quartz-diorite saprolite (Carpenter, 1982). The soil at the study site was classified as Vance (clayey, mixed, thermic Typic Hapludults). A truck-mounted soil probe, 7.5 cm in diameter, was used to collect soil and saprolite samples to a depth of 3.5 m from seven separate core locations that were selected randomly within a 12 x 12 m area. The extracted samples were cut to 6 cm lengths, and each core section was encased in wax and its saturated hydraulic conductivity determined (Amoozegar, 1988). The hydraulic conductivity with depth was graphed to determine the upper boundary of the C horizon where the permeable saprolite normally occurs (Schoeneberger and Amoozegar, 1990). A narrow trench was then excavated within the 12 x 12 m sampling area to identify quartz veins and to describe the soil-saprolite profile. Bulk samples and 10 Uhland cores (7.6 cm diam. by 7.6 cm in length) were collected from the C horizon. Bulk samples were oven-dried (105°C), and crushed to pass a 2-mm mesh sieve. Particle size distribution was determined using the pipette method (Gee and Bauder, 1986). Bulk density was determined after Uhland cores were oven-dried (105°C).

A large pit (11 m by 6 m) was excavated to a depth of approximately 2 m to reach the C1 horizon and to expose quartz veins. The pit bottom contained three main quartz veins (Fig. 1) that ranged from 2 to 12 cm in width and were continuous for horizontal distances that exceeded 11 m. Many smaller veins were present both parallel and perpendicular to the main veins.

Drainfield Construction

The base of the pit was carefully cleared and leveled by hand using shovels. Two watertight dikes (150 by 150 cm) made of commercial plywood were assembled and placed over the quartz veins (Fig. 1). Dike sidewalls were buried to a depth of 15 cm leaving 15 cm above the surface. After installation, the outside edge of the dike was backfilled with bentonite pellets, and capped by a thin layer of concrete to shed rainwater away from the dike. Within the diked drainfield, loose saprolite within 8 cm of the dike walls was compacted to ensure that sidewall leakage would not occur.
Figure 1. Plan view of study site showing the quartz veins studied and locations of the two drainfields (DF1 and DF2). The diagram is idealized as veins varied in width and in orientation.
Four tensiometers were installed in each drainfield to determine hydraulic gradients (Fig. 2). Two tensiometers were installed at each of two depths (30 and 60 cm) near a vein, and two were installed away from the vein at the same depths using standard techniques (Cassel and Klute, 1986). Soil water pressure head was measured by pressure transducer (Tensimeter, Soil Measurement Systems, Tucson, AZ). Tensiometers away from the vein appeared to be in the saprolite matrix that was not affected by the vein.

Two neutron access tubes were installed to a depth of 60 cm in each drainfield (Fig. 2). The tubes were sealed at the drainfield surface with 2 cm of bentonite. A calibration curve was developed outside the drainfields to determine volumetric water content (Θ) using standard methods (Gardner, 1986).

A 5 cm thick layer of coarse sand was placed on the instrumented drainfield to protect the surface. A portable shelter was installed to protect drainfields from rainfall.

Hydraulic Conductivity

Hydraulic conductivity was measured in situ for each drainfield. Water application was controlled by a float valve attached to the sidewall of the drainfield and connected by hose to a mobile 1900 L tank. The float valve maintained a 2 cm head of water above the sand-covered surface in the drainfield. When flooded, the drainfield was covered tightly by plastic film to prevent evaporation. After tensiometers at the 30 cm depth had indicated that the soil water pressure head was approximately 0 cm and that steady-state conditions had been reached, the volume of water infiltrating into the drainfield over a 24 h period was carefully measured and hydraulic conductivity was determined by using the following form of Darcy's equation:

\[ K = -\frac{Q}{A \cdot T \cdot \Delta H/L_w} \]  

where \( K \) is equal to the hydraulic conductivity, \( Q \) is the volume of water infiltrating the drainfield, \( A \) is the drainfield area, \( \Delta H/L_w \) is the hydraulic gradient between the depths of 0 and 30 cm, and \( T \) is time.

Application of Dye and Bromide

After completion of \( K \) measurements, a 0.1% dye solution of Acid Blue 29 was added to the drainfield water. The dye was applied for the duration of the experiment to stain water-conducting macropores.

After a hydraulic gradient of approximately -1 cm/cm was attained by the flooding regime, a 1000 mg L\(^{-1}\) solution of Br\(^{-}\) (as KBr) was added to the dye solution in the drainfields for the time determined using Eq. 3 for each drainfield. For Eq. 3, \( L_w \) was chosen to be 30 cm, \( \Theta \) was measured by neutron probe at the 30 cm depth, \( K(\Theta) \) was determined as described previously, and \( \Delta H/L_w \) was the hydraulic gradient between the depths of 0 and 30 cm. When the desired time had
Figure 2. Plan view of a diked drainfield showing dimensions and instrumentation. Dashed lines represent sampling faces. Tensiometers were installed in duplicate at depths of 30 and 60 cm. Access tubes were installed to 60 cm.
elapsed, excess water was drained from the surface, and the shelter, plumbing and instruments were removed.

Soil samples for Br⁻ analysis were collected from three vertical faces that were exposed in each drainfield. The sampling faces were approximately 40 cm apart, 90 cm deep, and perpendicular to the quartz veins (Fig. 2). Each face was excavated by backhoe to a depth of 90 cm and smoothed by knife and shovel. A sampling grid (120 by 90 cm) with 10 by 10 cm square cells was then placed against the exposed face. Approximately 100 g of moist soil was collected by knife from the center of each grid cell and placed in an air-tight soil moisture can. A total of 648 samples were collected from the two drainfields for Br⁻ analysis.

Each soil sample was oven-dried (105°C) to determine water content. The soil was then crushed, mixed, and a 10 g subsample collected. Fifty mL of distilled water were added to each subsample and the suspension was shaken for 15 min. Bromide concentration was determined by a commercial ion analyzer (Orion Research Microprocessor Ionalyzer Model 901, Cambridge, MA) with a Br⁻ electrode that detected Br⁻ in concentrations as low as 0.04 mg L⁻¹. The Br⁻ concentration was expressed as mg L⁻¹ and graphed by sampling grid location for each of the six sampling faces (Fig. 3).

**Depth of Br⁻ Penetration and Effective Hydraulic Conductivity**

The sampling cells from each profile face were grouped into miniprofiles to determine the maximum depths that Br⁻ moved downward through the quartz veins and saprolite matrix. A miniprofile was a section of the sampling face that consisted of one column of sampling cells. Each column contained nine vertical cells that extended from the drainfield surface to the base of the sampling grid at a depth of 90 cm (Fig. 3).

Miniprofile dimensions were 10 by 90 cm. Across each sampling face there were 12 miniprofiles, and each drainfield contained 36 miniprofiles. The maximum depth of Br⁻ penetration was determined separately for each miniprofile. This maximum depth was defined as the lowest cell of a miniprofile that had a Br⁻ concentration ≥ 100 mg L⁻¹ (10% of the 1000 mg Br⁻ L⁻¹ added). This cutoff concentration was selected because Br⁻ concentrations < 100 mg L⁻¹ were close to background Br⁻ concentrations in some drainfield faces. The Br⁻ concentrations in each miniprofile were examined in order from the bottom-most cell to the top-most cell to identify the maximum depths. Figure 3 illustrates maximum depths of Br⁻ penetration for 12 miniprofiles that were defined using this procedure.

To evaluate the accuracy of Eq. 3, the maximum depths of Br⁻ penetration found for each miniprofile were compared to target values. For this study, the model's prediction was considered successful if maximum depth of Br⁻ penetration within a miniprofile was between 10 and 40 cm. Because Br⁻ samples were collected from a square 10 by 10 cm grid cell, the samples collected from what we term "the 40 cm depth" represented Br⁻ that was actually collected between the depths of 30 to 40 cm. The model prediction was considered to have failed when maximum depth
Figure 3. Typical drainfield face with Br⁻ concentrations (mg L⁻¹) identified in each cell. A miniprofile is represented by the hashed cells. Maximum depth of 100 mg L⁻¹ Br⁻ in each miniprofile is given by the underlined concentration. Miniprofiles 5, 6, 7, and 8 contain a quartz vein which is represented by the double lines.
of penetration was > 40 cm within a miniprofile.

The effective hydraulic conductivity, Ke, of each miniprofile was calculated with Eq. 4. For each miniprofile, La was equal to the observed maximum depth of Br⁻ penetration found for that miniprofile, θ was the water content determined by neutron probe, T was the time interval over which the Br⁻ was applied, and ΔH/Lw was computed for depths of 0 and 30 cm.

The maximum depth of Br⁻ penetration and Ke values were compared among the miniprofiles using analysis of variance procedures (SAS, 1985). Each drainfield was considered to be one experimental replicate. Mean values for maximum depth of Br⁻ penetration and Ke were compared. In the first comparison separate means were determined for miniprofiles with quartz veins and without quartz veins to evaluate whether solute moved along veins faster than through the matrix. If a miniprofile contained a quartz vein in any of its nine cells, it was classified as a miniprofile containing a quartz vein. Mean values were also compared between miniprofiles with and without macropores. A miniprofile was considered to contain a macropore if blue dye was observed in a cylindrical channel at a depth > 40 cm below the drainfield surface at the time of sampling. The presence of dyed channels above 40 cm did not affect our classification of the miniprofile, because the channels could not directly transmit Br⁻ to depths > 40 cm.

Hydraulic Conductivity Comparisons

Hydraulic conductivity was measured on three different kinds of samples that differed in volume: undisturbed cores (volume of 347 cm³), in situ columns (6280 cm³), and in situ drainfields (675,000 cm³). These sample volumes were selected because they represent common sizes used to determine K values by standard techniques. For example, the smallest volume is used routinely to determine the variation in Ksat with depth in saprolite (Amoozegar, 1988) as well as to characterize Ksat in soils (Anderson and Cassel, 1986). A volume of 6280 cm³ has been used by Bouma and co-workers for the crust test procedure (e.g., Bouma and Denning, 1972). The largest volume selected for this experiment represents the largest size that was practical for our purposes.

Sample locations were selected so that saprolite containing veins and matrix were equally represented (Fig. 4). To facilitate sampling, locations of the cores and drainfields also had to be accessible to a backhoe. The drainfields were located at positions where the quartz vein lying inside the drainfield would be continuous and approximately of a uniform width. Locations of cores and columns were placed outside the drainfields, because the drainfields needed to be excavated to examine dyed macropores. As shown in Fig. 4, the cores and columns were located in the area between the drainfields that contained quartz veins. Field examination showed that the saprolite between the drainfields was like that within the drainfields with respect to texture and structure, such that no difference in hydraulic conductivity due to a change in saprolite characteristics was anticipated across the saprolite examined.
Core Measurements

Twenty-nine intact cores (7.6 cm in diam. by 7.6 cm in height) were collected from the base of the pit using a Uhland core sampler attached to a hydraulic ram that was mounted on the boom of a backhoe (Vepraskas et al., 1990). All cores were collected from a vertical orientation. Fifteen of the cores contained quartz veins. The cores were carefully examined in the field for cracks and other sampling induced disturbance. Cores with such features were discarded. Previous work (Vepraskas et al., 1990) indicated that this sampling procedure produces virtually no compaction in the saprolite core sample.

In the laboratory, the core surfaces were carefully picked with a small knife to expose fresh surfaces. The bottoms of the cores were then covered with cheesecloth and the cores were placed in a large pan. The level of tap water in the pan was slowly raised over a 1 week period. After the water level reached the tops of the cores, the cores were allowed to stand for an additional 48 h to saturate. The $K_{sat}$ of each core was measured with a constant head permeameter similar to that used by Hill and King (1982).

Unsaturated hydraulic conductivity ($K(h)$) was measured using a one-step outflow procedure in Buchner funnels (Klute and Dirksen, 1986). A plexiglass cap was placed over the funnel to create a pressure chamber which was connected by hose to an air pressure-regulating system. Saturated cores were placed in the chamber and the chamber was quickly pressurized to desorb the sample under a soil water pressure head of -90 cm water. The water outflow was collected during desorption at regular intervals until the outflow appeared to cease; this usually occurred after 20 h. Cores were then removed from the funnels and oven-dried (105°C) to determine water content by weight and bulk density. The samples were then removed from the rings and crushed to pass a 2-mm mesh sieve. Soil water content at a soil water pressure head of -15,000 cm was determined in a pressure chamber by standard techniques.

Unsaturated hydraulic conductivity was computed from the outflow-time data using the SFIT computer model of Kool and Parker (1987). For this study, known inputs for the model included $K_{sat}$, volumetric water content at saturation, and volumetric water content at a soil water pressure head of -15,000 cm. The SFIT model estimated the residual water content and the coefficients alpha and n of the van Genuchten equation (van Genuchten, 1980). A second computer program used the coefficients from SFIT to compute $K(h)$ from the van Genuchten equation for soil water pressure heads between -5 cm and -50 cm.

Column Measurements

The suction crust infiltrometer (modified crust test) technique of Booltink et al. (1991) was used to determine $K_{sat}$ and $K(h)$ in situ. The experimental set-up was similar to that shown in Fig. 30-3 of Green et al. (1986). Ten stainless steel collars measuring 20 cm in diam. were placed on columns (20 cm high) carved out in situ (Fig. 4). The edge of the column surface which abutted
Figure 4. Plan view of the site showing locations where hydraulic conductivity measurements were made in the C1 horizon of a quartz diorite saprolite at a depth of 1.95 m from the soil surface. Drainfield locations (DF1 and DF2) are shown relative to quartz veins. Columns marked "S" were used for $K_{sat}$ measurements, while those marked "U" were used for $K(h)$ measurements. The diagram is not drawn to scale. Quartz veins varied in width from 2 to 12 cm.
the collar was smeared within 1 cm of the edge to prevent boundary flow. Two tensiometers (pencil-type cups 4 cm long and 1.1 cm in diam.) were used in each column to determine hydraulic gradients. Tensiometers were monitored with a pressure transducer (Tensimeter, Soil Measurement Systems, Tucson, AZ). Each collar was fitted with a watertight plexiglass cap containing ports to release air and also to admit water. Water was supplied by a graduated cylinder containing a mariotte tube. The bottom of the mariotte tube could be placed at vertical distances that extended from the top of the soil column to 50 cm below the column top.

Saturated hydraulic conductivity was measured by slowly wetting each column until the tensiometer showed that soil water pressure heads ≥ 0 cm had been attained. Such heads were attained in only five columns, and these columns were used for \( K_{sat} \) measurements (Fig. 4). The plexiglass cap was then cemented to the steel collar using a rubber gasket cement, and the mariotte cylinder was adjusted to maintain a depth of water on the column surface of approximately 1 cm. When the soil water pressure heads had stabilized, indicating that steady-state conditions had been attained, the volume of water infiltrating the column was measured in the graduated cylinder over a 4 hr period. The \( K_{sat} \) value was then determined by using Darcy's Law:

\[
K = \frac{-QL}{At(\Delta H)}
\]  

where \( K \) is the hydraulic conductivity, \( Q \) was the volume of water infiltrating the column, \( A \) was the column's cross-sectional area, \( \Delta H \) was the change in total hydraulic head (including gravitational and matric soil water pressure heads) between the tensiometers which were separated by a distance \( L \) (5 cm), and \( t \) was time. Five separate \( K_{sat} \) measurements were made on each column over a period totaling 20 hr and these were averaged to estimate one \( K_{sat} \) value per column.

After \( K_{sat} \) was determined, the plexiglass cap was removed from the column and a gypsum crust was applied to the surface to determine \( K(h) \). The crust consisted of a mixture of gypsum (plaster of paris) and fine sand in the ratio 2:3 by volume. The crust ingredients were mixed with water and were applied to the column as a thick paste that was spread by hand. After the crust had hardened the plexiglass cap was cemented to the column and water was introduced through the mariotte bottle. The bottom of the mariotte tube was placed at a depth of approximately 5 cm below the top of the crust. Its elevation was then adjusted up or down until a soil water pressure head of approximately -5 cm was attained at the position of the uppermost tensiometer. When steady-state conditions were achieved at this pressure head, the volume of water infiltrating the column was determined over a 4 hr period. The \( K(h) \) value was then computed using Eq. 1. For each column, five separate \( K(h) \) values were also determined and averaged to compute one \( K(h) \) value for a given soil water pressure head.

To determine \( K(h) \) at lower soil water pressure heads, the mariotte tube was lowered and the process was repeated. Unsaturated hydraulic conductivities were determined for soil water
pressure heads of -5, -10, -20, -30, and -40 cm. The crust test procedure has normally been used
to determine wetting curves by beginning the measurements with a low soil water pressure head
and slowly wetting the column (Booltink et al., 1991). In contrast, our measurements progressed
from saturation to lower soil water pressure heads to determine a desorption K(h) curve for
comparison with the desorption curve determined by the one-step outflow procedure.

Drainfield Measurements

These measurements were the same as described previously. In addition, five undisturbed blocks
of saprolite (5 by 11 by 15 cm) were collected from five of the six drainfield faces to make thin
sections. Water was removed from all samples by solvent exchange, and then the samples were
impregnated with an unsaturated polyester resin diluted with acetone. Two thin sections (7.5 by
10 cm) were made from each block by standard methods (Murphy, 1986). Each thin section was
examined to describe the fabric and measure the diameters of channels (Vepraskas et al., 1991).

Mean values for $K_{sat}$ and K(h) at different soil water pressure heads were compared among the
different samples using analysis of variance procedures for a completely randomized design (SAS,
1985).

At the completion of these measurements the pit at site 1 was excavated to a depth of 4.5 m to
expose the C2 horizon. The analyses as described above were repeated with the exception of the
measurements of unsaturated hydraulic conductivity.

Site 2 - Mica Schist Saprolite

Four drainfields were evaluated as shown in Fig. 5. Two drainfields contained a vein while two
did not. Because the vein was large (45 cm wide) it was felt the saprolite matrix in plots with
veins were different than the matrices away from the veins. Therefore, hydraulic conductivities
were measured and compared between plots with veins and plots without veins.

The experiments within drainfields were conducted as previously described. Two different target
values for Br⁻ penetration depth were used. For drainfields 1 and 2, Br⁻ was applied long enough
for it to leach 30 cm as was used in the other drainfields. For drainfields 3 and 4, Br⁻ was applied
long enough for it to leach to 40 cm to determine if the model applied to slightly greater
penetration depths.

Hydraulic conductivities were measured in the drainfields and also around the drainfields using the
compact, constant-head permeameter (Amoozegar, 1989). The permeameter was considered a
more practical technique to use than either columns or cores. Due to time constraints, the
permeameter was used only around the two drainfields shown. Two depths, 25 and 50 cm, were
used to measure hydraulic conductivity with the permeameter.
Figure 5. Plan view of the site in the mica-schist saprolite showing locations of the drainfields with and without veins, along with locations used to measure saturated hydraulic conductivity with the compact constant-head permeameter.
RESULTS AND DISCUSSION

Solute Movement Along Veins and Fractures

Quartz-Diorite Saprolite

C1 Horizon. The saprolite matrix had a loam textural class (Table 1). Saturated hydraulic conductivity measured on waxed cores decreased to 0.01 cm hr\(^{-1}\) in the Bt horizon, but was greater than 4 cm hr\(^{-1}\) in the C horizons (Fig. 6). Drainfields for the first series of measurements were installed at a depth of 1.95 m, near the upper boundary of the C1 horizon where hydraulic conductivity increased with depth. However, the slowly permeable BC horizon had a diffuse, wavy lower boundary, and each drainfield included portions of the BC horizon. Shallow excavations were made around each drainfield during the experiment to determine if lateral flow was occurring. No saprolite containing dye was seen outside the diked enclosure. This indicated that substantial lateral flow probably had not occurred. Hydraulic conductivities for the drainfields are reported in Table 2.

Quartz veins that were exposed in drainfield faces of the C1 horizon ranged from 2 to 12 cm in width. Most quartz veins were 2 cm wide, and most quartz gravels in the veins were 2 cm in diameter. Gravel in veins appeared to be coated with clay. Some quartz veins formed an angle of 90° to the horizontal surface. However, most quartz veins examined in the drainfield exposures dipped between 50° and 80° from the horizontal. Four of the six drainfield faces had multiple quartz veins. Five of these faces had at least one vein that extended to the surface of the drainfield. Veins that were continuous to the surface extended to depths between 50 to 90 cm or more. Macropores were observed in most drainfield faces in the C1 horizon. The macropores were cylindrical pores, 1 to 5 mm in diameter that often contained roots. Water-conducting macropores were identified by dye staining. All macropores were root channels.

The frequency distributions for maximum depth of Br\(^{-}\) penetration in miniprofiles of the C1 horizon with and without quartz veins are shown in Fig. 7A. Graphical analysis showed that the frequency distributions for both groups were log-normal. The frequency distribution for maximum depths of Br\(^{-}\) penetration in miniprofiles with dye-stained macropores differed from those noted previously (Fig. 7B). Where macropores were not present, the data appeared to conform to a log-normal distribution.

The soil water pressure heads (Table 2) indicated that drainfield 1 was saturated while drainfield 2 was close to saturation. The hydraulic gradients were near unity, and soil water pressure heads were near 0 cm or greater for both drainfields at a depth of 30 cm. Hydraulic conductivities were low.
Table 1. Bulk density and particle size distribution of the quartz-diorite saprolite's matrix in the C1 and C2 horizon. Bulk density values were determined from 10 core samples.

<table>
<thead>
<tr>
<th>Bulk Density</th>
<th>Sand (2 - 0.05 mm)</th>
<th>Silt (0.05 - 0.002 mm)</th>
<th>Clay (&lt; 0.002 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>g cm$^3$</td>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.39</td>
<td>43.05</td>
<td>37.10</td>
</tr>
<tr>
<td>Range</td>
<td>0.19</td>
<td>23.05</td>
<td>3.35</td>
</tr>
</tbody>
</table>
Figure 6. Saturated hydraulic conductivity with depth as determined from undisturbed waxed cores (7.6 cm diam. by 6 cm in height). Drainfields for the first experiments were placed at a depth of 1.95 m at the top of the C1 horizon.
Table 2. Values for water content, soil water pressure head, hydraulic gradient (0 to 30 cm depth) and hydraulic conductivity for both drainfields in the C1 horizon of the quartz-diorite saprolite. The K values were computed using Eq. 5. Values for water content and soil water heads are means of data collected at the 30 cm depth.

<table>
<thead>
<tr>
<th>Drainfield</th>
<th>Water content (cm$^3$ cm$^{-3}$)</th>
<th>Soil water pressure head (cm)</th>
<th>Hydraulic gradient (cm cm$^{-1}$)</th>
<th>Hydraulic conductivity (cm hr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.42</td>
<td>+13</td>
<td>-0.7</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>0.43</td>
<td>-2</td>
<td>-1.1</td>
<td>0.08</td>
</tr>
</tbody>
</table>

*Difference in total soil water pressure head between the saprolite surface and a depth of 30 cm.*
Figure 7. Frequency distribution of maximum depth of Br⁻ penetration in miniprofiles of the C1 horizon in the quartz-diorite saprolite: A) with and without quartz veins, and B) with and without macropores.
**C2 Horizon.** Veins in the C2 horizon at a depth of 4.5 m ranged from 3 to 16 cm wide. Quartz fragments in the veins ranged from 2 to 15 cm in diameter. Spaces between fragments were up to 2 or 3 mm wide and all spaces were filled in with clay. The clay infillings appeared to be continuous throughout the veins. Some fragments were coated with manganese oxides in addition to clay. Numerous fractures were observed, and all were filled with manganese oxides. Fractures were up to 1 cm wide, and were oriented both horizontally and vertically. Fractures did not conduct any dye solution. Fractures oriented horizontally did not appear to impede flow as dye was observed both above and below the fracture.

Hydraulic data obtained in the drainfields when the dye and Br⁻ were applied are reported in Table 3. Soil water pressure heads at a depth of 30 cm were negative indicating that the drainfields were unsaturated. Hydraulic gradients were approximately 1 cm cm⁻¹ indicating that flow was primarily due to gravitational gradients. The hydraulic conductivities found for both drainfields in the C2 horizon were approximately six-fold greater than found for the C1 horizon.

The distribution of Br⁻ penetration depths observed for miniprofiles with and without veins are reported in Fig. 8. The distributions were similar and appeared normally distributed, as opposed to the log-normal distribution observed in the C1 horizon. The difference in distributions may be partially due to the C2 horizon having virtually no root channels (macropores) that conducted water. The dye patterns showed that water moved primarily in the saprolite matrix in more or less a uniform front. No dye was observed in the exposed faces that suggested flow along channels. The normally distributed penetration depths shown in Fig. 6 for both the vein and matrix are believed to be due to flow being primarily through the matrix, with slight differences in penetration depths due to small variations in hydraulic conductivity that occurred in the drainfields.

**Mica-Schist Saprolite**

The saprolite was found previously to have a loam textural class with clay percentages less than 10% and sand percentages of approximately 55% (Vepraskas et al., 1991). Bulk density of the saprolite at this site ranged from 1.15 to 1.25 g cm⁻³ and had a mean of 1.21 g cm⁻³. The quartz vein was up to 45 cm wide and extended laterally for more than 9 m. Quartz fragments were up to 25 cm in diameter. Like the veins in the previous site, the gravels were separated by infillings of clay and manganese oxides.

Hydraulic data from the drainfield experiments is shown in Table 4. Two of the drainfields, one with a vein and one without, were unsaturated with soil water pressure heads of -37 and -38 cm. Hydraulic gradients for these drainfields were approximately -2 cm cm⁻¹, which indicated that both gravitational and soil water pressure heads were influencing flow. The other two drainfields had soil water pressure heads that were positive or slightly negative, and had hydraulic gradients closer to -1 cm cm⁻¹. The hydraulic conductivities of the drainfields with and without veins were approximately 0.5 cm hr⁻¹.
Table 3. Values for water content, soil water pressure head, hydraulic gradient, and hydraulic conductivity for both drainfields in the C2 horizon of the quartz-diorite saprolite.

<table>
<thead>
<tr>
<th>Drainfield</th>
<th>Water content</th>
<th>Soil water pressure head</th>
<th>Hydraulic gradient</th>
<th>Hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm$^3$ cm$^{-3}$</td>
<td>cm</td>
<td>cm cm$^{-1}$</td>
<td>cm hr$^{-1}$</td>
</tr>
<tr>
<td>1</td>
<td>0.38</td>
<td>-18</td>
<td>0.91</td>
<td>1.96</td>
</tr>
<tr>
<td>2</td>
<td>0.35</td>
<td>-16</td>
<td>1.36</td>
<td>0.64</td>
</tr>
</tbody>
</table>

$^1$ Measured at a depth of 30 cm
Figure 8. Frequency distributions of maximum depth of Br⁻ penetration in miniprofiles of the C2 horizon in the quartz-diorite saprolite: A) in the saprolite matrix, and B) in the quartz veins.
Hydraulic Conductivity of Quartz Veins

Means for maximum depths of Br⁻ penetration are listed in Table 5 for the C1 and C2 horizons of site 1. Mean depths of Br⁻ penetration in miniprofiles with and without quartz veins were not significantly different (P=0.05) for veins in either the C1 or C2 horizons. This indicated that Br⁻ moved downward through the vein at a rate similar to that of the saprolite matrix. The veins were stained by the dye within a depth of 10 cm of the drainfield surface which indicated that water did move along the veins for a short distance near the surface of the drainfield.

Macropores in the C1 horizon that were stained blue did affect Br⁻ movement. The mean depth of maximum Br⁻ penetration was 40 cm where macropores were present at depths ≥ 40 cm and only 14 cm where they were absent (Table 5). This difference in depth of Br⁻ penetration was statistically significant (P=0.05).

The effective hydraulic conductivities (Ke) that were calculated using Eq. 4 were not significantly different between quartz veins and matrix in either the C1 or C2 horizons (Table 5). When macropores were present, the mean Ke of 0.28 cm hr⁻¹ was significantly greater (P=0.10) than that found for the saprolite matrix without macropores which had a Ke of 0.10 cm hr⁻¹.

Results from the Br⁻ application experiments in the mica-schist saprolite are reported in Table 6 and Fig. 9. As shown in Fig. 9, two different target depths (30 and 40 cm) were used for Br⁻ penetration and the experiments for each are referred to as "Test 1" and "Test 2". The distributions of Br⁻ penetration appeared to be log-normally distributed, and so logs of the maximum Br⁻ penetration depths were used in statistical comparisons, and geometric means are reported in Table 6.

As shown in Table 6, the geometric mean for maximum depth in Br⁻ penetration was significantly less in the plot containing the vein than the plot without the vein, although the effective hydraulic conductivities of the two plots were not significantly different. As shown in Table 6, Br⁻ was applied for about one-half the time in the plot with the vein than was used for the plot without the vein. The time difference accounted for the Br⁻ moving a shorter distance where the vein was present. The short application time was determined by using the measured hydraulic conductivity of 0.6 cm hr⁻¹ (Table 4). This value was 50% greater than the effective K of 0.4 cm hr⁻¹ and caused us to apply Br⁻ for a shorter time to the plot with the vein. In test 2, the depth of Br⁻ penetration was similar between the two plots, and there was no significant difference in effective hydraulic conductivities between the two plots.
Table 4. Values for water content, soil water pressure head, hydraulic gradient and hydraulic conductivity for the four drainfields used in the mica-schist saprolite.

<table>
<thead>
<tr>
<th>Drainfield</th>
<th>Vein present</th>
<th>Water content</th>
<th>Soil water pressure head†</th>
<th>Hydraulic gradient</th>
<th>Hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>cm³ cm³</td>
<td>cm</td>
<td>cm cm⁻¹</td>
<td>cm hr⁻¹</td>
</tr>
<tr>
<td>1</td>
<td>Yes</td>
<td>0.42</td>
<td>-37</td>
<td>-2.2</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>0.49</td>
<td>-38</td>
<td>-2.1</td>
<td>0.4</td>
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<tr>
<td>3</td>
<td>Yes</td>
<td>0.41</td>
<td>+2</td>
<td>-1.3</td>
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<tr>
<td>4</td>
<td>No</td>
<td>0.53</td>
<td>-8</td>
<td>-1.6</td>
<td>0.3</td>
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</table>

†Measured at a depth of 30 cm.
Table 5. Mean values for maximum depths of Br\(^{-}\) penetration and effective hydraulic conductivity (Ke) in miniprofiles with and without quartz veins, and miniprofiles with and without macropores in the C1 and C2 horizons of the quartz-diorite saprolite.

<table>
<thead>
<tr>
<th>Miniprofile group(^t)</th>
<th>C1</th>
<th>C2</th>
<th>Effective hydraulic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C1</td>
</tr>
</tbody>
</table>
|                       |    |    | \_\_\_\_\_ cm \_\_\_\_\_ \_\_ \_\_ | \_\_\_\_ cm hr\(^{-1}\) \_\_\_\_\_ \_\_\_\_ |}

Comparison 1

<table>
<thead>
<tr>
<th></th>
<th>Veins</th>
<th>No Veins</th>
<th>Difference</th>
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</thead>
<tbody>
<tr>
<td>Maximum Br(^{-}) penetration(^t)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>21</td>
<td>26</td>
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</tr>
<tr>
<td>C2</td>
<td>32</td>
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Difference

<p>| | | | |</p>
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<tr>
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</table>

Comparison 2

<table>
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<th></th>
<th>Macropores</th>
<th>No Macropores</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Br(^{-}) penetration(^t)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>40</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>--</td>
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Difference

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<tbody>
<tr>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^t\)Maximum depth refers to the lowest cell in a miniprofile that had a Br concentration \(\geq 100\) mg L\(^{-1}\) in the saprolite solution.

\(*\)Significantly different at P=0.05 determined by F test (SAS, 1985), NS is not significantly different, and a dash indicates a comparison was not applicable.
Evaluation of the Time of Travel Model

Quartz-Diorite Saprolite

Evaluation of the time of travel model is shown in Table 7 for the C1 and C2 horizons of the quartz-diorite saprolite of site 1. For the C1 horizon, the proportion of miniprofiles with maximum depths of Br⁻ penetration between 10 and 40 cm was 0.87 across all miniprofiles examined. This value was identical to those found for miniprofiles both with and without quartz veins.

When macropores were not present at depths ≥ 40 cm in the C1 horizon, the proportion of miniprofiles with a maximum depth of Br⁻ penetration between 10 and 40 cm was greater than 0.95; but when macropores were present the proportion dropped to 0.46. In other words, for the 13 miniprofiles that contained macropores at depths ≥ 40 cm, only six of them had maximum depths of Br⁻ penetration that were < 40 cm.

For the C2 horizon, the proportion of miniprofiles with penetration depths < 40 cm ranged from 0.78 to 0.91 for the three groups of miniprofiles shown. These results were similar because the veins conducted water at a rate similar to that of the matrix, and no macropores were present.

Time of travel estimates made using measured and effective K(θ) values are compared in Table 7 for the C1 and C2 horizons. Two predicted values are shown for each horizon, one based on results from each of the two drainfields studied in each horizon. For the C1 horizon, the effective times of travel show that allowance for macropores provides estimates with greater precision than can be obtained using average values determined for the drainfield as a whole. The predicted and effective TOT values for the C2 horizon were virtually identical for the reasons specified earlier. These results indicate that the simple TOT model used does a good job of predicting solute movement in saprolite when root channels or other types of macropores are not present.

Mica-Schist Saprolite

The success of the TOT model is reported in Table 8 for site 2. The proportion of miniprofiles that had maximum Br⁻ penetration depths within the target range were > 0.70 for both tests. The time of travel estimates were in general similar for the predicted values and effective values. The largest difference in relative terms occurred in Test 1 for the plot with a vein, and as noted earlier the difference is due to the discrepancy between the measured and effective K values.
Table 6. Means for maximum depths of Br⁻ penetration, time of Br⁻ application, and effective hydraulic conductivities in the four drainfields examined in the mica-schist saprolite.

<table>
<thead>
<tr>
<th>Drainfield number</th>
<th>Vein present</th>
<th>Mean depth of maximum Br⁻ penetration (cm)</th>
<th>Time of Br⁻ application (hr)</th>
<th>Effective hydraulic conductivity (cm hr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>17</td>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>26</td>
<td>17</td>
<td>0.4</td>
</tr>
<tr>
<td>Difference</td>
<td>*</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>36</td>
<td>21</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>35</td>
<td>43</td>
<td>0.3</td>
</tr>
<tr>
<td>Difference</td>
<td>NS</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
</tbody>
</table>

*Means were significantly different at the P=0.05 level as determined by a two-tailed t-test. NS indicates means were not significantly different at the P=0.10 level.
Figure 9. Frequency distributions of maximum depth of Br⁻ penetration in miniprofiles of the mica-schist saprolite for: A) drainfield 1 with a vein, B) drainfield 2 without a vein, C) drainfield 3 with a vein, and D) drainfield 4 without a vein.
Table 7. Success of the time of travel model on predicting Br⁻ penetration depth, along with a comparison of predicted and effective times of travel estimates for the C1 and C2 horizons of the quartz diorite saprolite. Predicted values were computed using Eq. 3 and drainfield data shown in Tables 2 and 3. Effective values were computed based on the effective K values shown in Table 3 and means of the water contents and hydraulic gradients shown in the table.

<table>
<thead>
<tr>
<th>Saprolite miniprofiles</th>
<th>Miniprofiles with penetration depth between 10 and 40 cm</th>
<th>Time of Travel (30 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prop. of Profiles</td>
<td>Predicted⁠</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- - - -</td>
</tr>
<tr>
<td><strong>C1 horizon</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>0.87</td>
<td>5-147</td>
</tr>
<tr>
<td>With macropores</td>
<td>0.46</td>
<td>NA</td>
</tr>
<tr>
<td>Without macropores</td>
<td>0.95</td>
<td>NA</td>
</tr>
<tr>
<td><strong>C2 horizon</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>0.83</td>
<td>8-10</td>
</tr>
<tr>
<td>With veins</td>
<td>0.91</td>
<td>NA</td>
</tr>
<tr>
<td>Without veins</td>
<td>0.78</td>
<td>NA</td>
</tr>
</tbody>
</table>

¹NA is not applicable  
²Determined using an effective K of 0.165 cm/h as determined from comparison 1 in Table 2.
Discussion of Solute Movement Results

The results of this phase of the study have shown that quartz veins that were 2 to 45 cm in width and occurred in both a quartz-diorite saprolite and a mica-schist saprolite did not conduct water significantly faster than the saprolite matrix. These veins posed no apparent hazard to on-site wastewater disposal.

All veins studied had the spaces between fragments partially plugged with Fe oxides or clay. Fractures were also filled with materials high in manganese oxides. The results of this study can be applied to all veins and fractures that contain such infillings. We don't know whether veins and fractures that are deeper in the saprolite would conduct water and solutes at rates comparable to those of the saprolite matrix. It is possible that deeper veins would have less coatings of clay and therefore would conduct water and solutes at rates greater than those measured here. However, the materials filling the veins and fractures were present at a depth of 4.5 m below the surface, they appeared fresh, and probably extended much deeper into the saprolite.

For this study we applied solute over the time period that was sufficient for it to travel to a depth of 30 cm or 40 cm as predicted by Eq. 3. We considered the model's prediction to be successful if the observed maximum depth of Br⁻ penetration was between 10 and 40 cm when our target depth was 30 cm, and between 10 and 40 cm for a target depth of 40 cm. Failure occurred if the maximum depth of Br⁻ penetration exceeded these limits, because for waste disposal purposes adequate purification of effluent does not occur if it travels too quickly. As shown in Table 3, Eq. 3 worked well except where macropores extended from the surface to depths ≥ 40 cm. As shown in Fig. 7, the maximum depth of Br⁻ penetration was 10 cm for most miniprofiles except when macropores extended to depths ≥ 40 cm. Thus, Eq. 3 tended to underestimate the time needed for penetration to occur in most of the miniprofiles examined.

Effective hydraulic conductivities allowed estimating separate TOT values for saprolite with and without macropores. This had the advantage of indicating that there will be at least two different rates of solute movement, with the slower rate occurring through saprolite matrix without macropores. Even where macropores extended to depths ≥ 40 cm, solute travel was still computed to be relatively slow requiring 51 h to move 30 cm. This is probably due to the macropores terminating in saprolite matrix at depths between 40 and 90 cm. While macropores would fill with solute solution, the solution did not penetrate into the surrounding matrix quickly.

A complete site evaluation for wastewater treatment and disposal must consider factors such as water table depth, slope, depth to bedrock, and depth of the septic drainfield. If this saprolite were used for on-site wastewater disposal, preferential flow of water and solutes would occur along biological macropores if an organic clogging mat was not present. Biological macropores are probably found in most (if not all) operating septic drainfields and are not considered to be a problem. Future work in other saprolites must address larger quartz veins and veins without plugging materials.
Table 8. Success of the time of travel model on predicting Br⁻ penetration depth for two target depths, along with a comparison of predicted and effective time of travel estimates for the four drainfields of the mica-schist saprolite (site 2). Predicted travel times were computed using the data in Table 4, while effective travel times were computed using Ke values rather than the measured K values shown in Table 4.

<table>
<thead>
<tr>
<th>Drainfield number</th>
<th>Vein present</th>
<th>Target range cm</th>
<th>Miniprofiles with Br within target range Prop. of profiles</th>
<th>Time of travel Predicted</th>
<th>Effective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Yes</td>
<td>≤ 40</td>
<td>0.94</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>≤ 40</td>
<td>0.85</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Test 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>≤ 50</td>
<td>0.75</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>≤ 50</td>
<td>0.72</td>
<td>44</td>
<td>44</td>
</tr>
</tbody>
</table>
Sample Size Effects on Hydraulic Conductivity

Quartz-Diorite Saprolite

Hydraulic Conductivity. Frequency distributions for the $K_{sat}$ measurements are shown in Fig. 10 for data obtained from cores and columns in the C1 horizon. The $K_{sat}$ values were 0.33 and 0.08 cm hr$^{-1}$ for drainfields 1 and 2. The mean $K_{sat}$ values and related data for the three different sample sizes are compared in Table 9. The sample height of the drainfield measurements was not known precisely, but was assumed to be 30 cm because the drainfields were saturated (soil water pressure heads $\geq 0$ cm) down to a depth of 30 cm, but were unsaturated at 60 cm (data not shown). Thus, the sample volume shown for the drainfields in Table 9 is an estimate; the correct volume probably falls between 675,000 and 1,350,000 cm$^3$.

Mean $K_{sat}$ values were compared following log-transformation of the data. As shown in Table 9, means of the $\log_{10}(K_{sat})$ values for columns and drainfields were significantly greater than the mean value determined for cores. The core data appeared to have had the largest standard deviation. The SD for the drainfields could only be estimated from two data points. The range of $K_{sat}$ was twice as large for the core data as was found for either columns or drainfields.

Bouwer (1986) pointed out that drainfields, like those used here, can overestimate $K_{sat}$ when the drier material that surrounds the saturated zone beneath the drainfield draws water from the saturated zone. There is no evidence that such "lateral divergent flow" occurred here. The saprolite matrix that was stained by methylene blue was found primarily beneath the drainfield; it did not extend beyond the dike boundaries for more than 15 cm. In addition, Williams and Vepraskas (1994) estimated effective $K_{sat}$ values for these same drainfields by measuring the depth that a Br tracer penetrated the saprolite. Depth measurements were made in vertical profiles that were 10 cm wide, and Br penetration depths were measured at 36 points for each drainfield. The effective $K_{sat}$ for quartz veins was 0.16 cm hr$^{-1}$, while for saprolite without veins it was 0.17 cm hr$^{-1}$. These results were virtually identical to the mean $K_{sat}$ of 0.16 cm hr$^{-1}$ reported in Table 9.

Results of the $K(h)$ measurements are shown in Table 10. Mean values were compared for each soil water pressure head separately. Differences in mean values found for columns and cores were significant ($P=0.05$) for soil water pressure heads of -5 and -10 cm, but not for lower pressure heads.

The data in Tables 9 and 10 indicate that the detached cores were inadequate for measuring $K_{sat}$ reliably in the saprolite horizon studied. The large columns were adequate for $K_{sat}$ measurements, because they produced results that were not significantly different than the much larger drainfield samples. Although the drainfield sample volume could not be determined exactly, this lack of precision does not affect this conclusion.
Figure 10. Frequency distributions for $K_{sat}$ as measured on: A) 29 cores and B) five columns in the C1 horizon of the quartz-diorite saprolite.
Table 9. Sample dimensions, numbers, and saturated hydraulic conductivity values for cores, columns, and drainfields in the C1 horizon of the quartz-diorite saprolite.

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Cross-sectional area</th>
<th>Sample height</th>
<th>Sample volume</th>
<th>Number of samples</th>
<th>Saturated hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm²</td>
<td>cm</td>
<td>cm³</td>
<td></td>
<td>Mean†</td>
</tr>
<tr>
<td>Cores</td>
<td>4545</td>
<td>7.7</td>
<td>347</td>
<td>29</td>
<td>Log (cm hr⁻¹)</td>
</tr>
<tr>
<td>Columns</td>
<td>314</td>
<td>20</td>
<td>6,280</td>
<td>5</td>
<td>-1.43a</td>
</tr>
<tr>
<td>Drainfields</td>
<td>22,500</td>
<td>30</td>
<td>675,000</td>
<td>2</td>
<td>-0.79b</td>
</tr>
</tbody>
</table>

†Mean values followed by same letter in the column were not significantly different (P = 0.10) by Fisher's LSD procedure.

‡The SD was estimated from only two data points which were also used to determine the range.
Table 10. Geometric means for unsaturated hydraulic conductivities measured in situ on soil columns and in the laboratory on undisturbed soil cores in the C1 horizon of the quartz-diorite saprolite.

<table>
<thead>
<tr>
<th>Soil water pressure head</th>
<th>Columns</th>
<th>Cores</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
<td>0.180</td>
<td>0.028</td>
<td>8.01</td>
<td>0.01</td>
</tr>
<tr>
<td>-5</td>
<td>0.085</td>
<td>0.025</td>
<td>3.93</td>
<td>0.03</td>
</tr>
<tr>
<td>-10</td>
<td>0.028</td>
<td>0.020</td>
<td>0.78</td>
<td>0.46</td>
</tr>
<tr>
<td>-20</td>
<td>0.016</td>
<td>0.017</td>
<td>0.42</td>
<td>0.66</td>
</tr>
<tr>
<td>-30</td>
<td>0.009</td>
<td>0.014</td>
<td>0.92</td>
<td>0.41</td>
</tr>
</tbody>
</table>
phase) accurately for soil water pressure heads between 0 and -10 cm. The core samples apparently were adequate for measuring \( K(h) \) at lower soil water heads.

**Pore Studies.** We hypothesized that the core samples produced lower mean \( K_{\text{sat}} \) values either because the core did not contain the same number or size of water conducting macropores (e.g. channels) as found in the larger samples, or because the core cylinder cut off water conducting pores. Examination of the dye patterns seen in the six pit walls that were exposed during excavation of the drainfields confirmed that the channels conducted water. No dye was seen coating the fragments of the quartz veins, and it was concluded that no water-conducting macropores were associated with the vein. The distribution of dyed (water-conducting) channels with depth is shown in Fig. 11. For the 0 to 10 cm depth, the proportion of grid cells that contained channels was 0.4. In other words, for every 10 cells observed across the 0 to 10 cm depth, four cells contained at least one water-conducting channel; and on the average one grid cell with dyed channels was found for every 2.5 cells examined. Dyed channels were observed to a depth of 75 cm.

An examination of thin sections showed that channels were the only kind of open macropore present. Channel diameters ranged from 0.06 to 3.0 mm. Roots were found in some channels and we assumed all channels were made by roots. Fracture planes were seen in some sections, but these were filled with Fe-Mn oxides or clay. Pores between the mineral grains were also generally filled with clay and/or Fe-Mn oxides. Such pore infillings have been observed previously for BC and CI horizons of other saprolites (Guertal, 1992).

**C2 Horizon.** Saturated hydraulic conductivities in the C2 horizon were measured on samples of the same size as used in the C1 horizon. It was hypothesized that because macropores such as root channels were not observed in this horizon, then sample size should have much less effect on \( K_{\text{sat}} \) than was found in the C1 horizon.

Frequency distributions for \( K_{\text{sat}} \) measurements made on cores and columns are presented in Fig. 12. The core data were bimodal with one mode at 1.25 cm hr\(^{-1}\) and a second at 3.75 cm hr\(^{-1}\). Column data had a narrow range, as compared to the core data, but it too had a mode at 1.25 cm hr\(^{-1}\). The drainfield \( K_{\text{sat}} \) measurements were 1.96 and 0.64 cm hr\(^{-1}\), and these measurements spanned the 1.25 cm hr\(^{-1}\) mode found for the other sample sizes. The data show that the three sample sizes did produce similar results, although the core data had a much larger range.
Figure 11. Relative abundance of water-conducting channels (≥ 1 mm diam.) with depth. Data were obtained from both drainfields by putting a grid of 108 cells (nine rows of twelve cells) on six vertical exposures, and observing whether each cell contained dye-stained channels. Mean and standard deviations are shown.
Figure 12. Frequency distributions for hydraulic conductivity measurements made: A) eight columns in the C2 horizon of the quartz-diorite saprolite, and B) on 40 undisturbed cores.
Means of the Ksat measurements were compared and results are shown in Table 11. All data were log-transformed to better approximate a normal distribution. The core mean value for log(Ksat) was significantly larger than the column log(Ksat) mean. There was no significant difference between the means obtained using the cores and drainfields, nor between means obtained using the columns and drainfields. These results suggest that the major difference among the sample sizes is that data obtained from the cores contained some higher values than found for the other sample sizes.

At this point it is not clear why cores tended to produce higher Ksat values than the other sample sizes for the C2 horizons. One explanation is that core samples are disturbed during the sample collection, and perhaps small fractures open up within the sample. In addition, because cores are small they are more sensitive to changes in saprolite properties. Two cores that are collected from small areas of saprolite that differ in hydraulic conductivity will probably have different Ksat values. The larger columns and drainfields tend to average the effects of small areas on hydraulic conductivity.

Mica-Schist Saprolite

In situ techniques are generally preferred for making Ksat measurements. For this saprolite, Ksat measurements were made both with drainfields and with the compact constant-head permeameter (Amoozegar, 1989) and the values were compared. Results are reported in Table 12. The permeameter was used to make measurements at depths of 25 and 50 cm. The geometric mean for the 25 cm depth was virtually identical to that found for the drainfields and the effective Ksat values which were computed from the Br⁻ penetration depths. The geometric Ksat means for the 50 cm depth were larger than the other means, but this is probably due to a change in saprolite permeability rather than an effect of measurement technique. Both the effective Ksat means and drainfield Ksat means reflect the hydraulic conductivity of the surface of the drainfields which are most comparable to the 25 cm depth measurements made by the constant head permeameter.

Discussion of Hydraulic Conductivity Techniques

Because channels were conducting water in the C1 horizon of the quartz-diorite saprolite when the saprolite was saturated, an appropriate sample volume (REV) for Ksat measurements has to be large enough to contain a representative number of water-conducting channels. We could not determine a precise REV from the pore data, but estimate that the REV contains a cross-sectional area equivalent to at least 2.5 grid cells because this was the minimum area needed for the saprolite to contain (on average) water-conducting channels. Two and one half grid cells had an area of 250 cm² because each grid cell had an area of 100 cm². This area is slightly less than the cross-sectional area of the columns (314 cm²) (Table 9) which was considered adequate for Ksat measurements, and for K(h) measurements made for soil water pressure heads between 0 and -10 cm. Thus, for columns 20 cm high the appropriate sample volume for Ksat measurements would be approximately 5000 cm³ or
<table>
<thead>
<tr>
<th>Sample type</th>
<th>Number of samples</th>
<th>Mean(^1)</th>
<th>SD</th>
<th>Geometric mean</th>
<th>Range (Max-min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Log (cm hr(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cores</td>
<td>40</td>
<td>0.25 a</td>
<td>0.24</td>
<td>1.78</td>
<td>6.5 - 0.9</td>
</tr>
<tr>
<td>Columns</td>
<td>8</td>
<td>-0.13 b</td>
<td>0.33</td>
<td>0.74</td>
<td>1.2 - 0.1</td>
</tr>
<tr>
<td>Drainfields</td>
<td>2</td>
<td>0.05 ab</td>
<td>0.34</td>
<td>1.12</td>
<td>2.0 - 0.6</td>
</tr>
</tbody>
</table>

Means followed by different letters were significantly different at the P=0.05 level as determined by a two-tailed t-test.

---

Table 11. Sample numbers and hydraulic conductivities measured for cores, columns, and drainfields of the C2 horizon of the quartz-diorite saprolite.
Table 12. Comparison of geometric mean values for saturated hydraulic conductivity as measured using the constant-head permeameter and drainfields, and estimated by determining effective hydraulic conductivity in two drainfields of the mica-schist saprolite.

<table>
<thead>
<tr>
<th>Drainfield number</th>
<th>Vein present</th>
<th>Constant head permeameter</th>
<th>Drainfield</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25 cm</td>
<td>50 cm</td>
<td>measured</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>0.8</td>
<td>1.6</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>0.4</td>
<td>1.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

- - - - - - - - cm hr⁻¹ - - - - - - -
larger. This estimate is in agreement with the experimental results which showed that an appropriate sample volume for K measurements was between 347 and 6,280 cm³.

Melhuish and Lang (1968) showed that determining the channel abundance (number per unit area) on vertical faces of large soil blocks gives results identical to measurements made on horizontal faces when the channels have a random orientation and distribution. This can occur when the roots making the channels are able to grow in all angular directions and all positions with equal probability. We assumed that the orientation of dyed channels that were observed in the pit faces was random in this saprolite because there were no strongly developed structural cracks that controlled the root distribution. The assumption of random orientation and distribution does not hold for soils with well-developed structural cracks (Vepraskas and Hoyt, 1988).

The results of this study showed that measurements of hydraulic conductivity for soil water pressure heads between 0 and -10 cm in a saprolite horizon containing channels could be made reliably using in situ samples having volumes of approximately 5000 cm³ or larger. Detached cores having volumes of approximately 350 cm³ could be used for determining unsaturated hydraulic conductivities at soil water pressure heads ≤ -20 cm in these horizons. Saprolite horizons containing root or worm channels are common, and have generally been designated as BC, CB, or C1 horizons (Guertal, 1992; Schoeneberger and Amoozegar, 1990). These occur at the base of the soil solum and will usually be the first horizons encountered when a saprolite body is being excavated.

The collection of soil core samples always has the risk that the samples will be disturbed somewhat by the collection process. For this reason, core data probably are best used to characterize the trends in hydraulic conductivity with depth where precise values are not needed. Predictions of solute transport that are based on Ksat data require that the Ksat be measured as accurately as possible. In this case, use of drainfields or the constant-head permeameter are the fastest techniques to use. The columns can provide accurate information, but they are tedious measurements to make. With the proper equipment, drainfield measurements can be performed quickly. The most convenient technique was the constant head permeameter, because measurements for any depth could be made from the soil surface.
REFERENCES


GLOSSARY

Abbreviations

h   soil water pressure head
H   total soil water head, ΔH is difference in head between two points
Ke  effective hydraulic conductivity
K(h) hydraulic conductivity when soil water pressure head is < 0 cm
Ksat saturated hydraulic conductivity
K(θ) hydraulic conductivity at a water content of θ
Ls  distance of solute movement in vertical direction
Lw  distance used for hydraulic gradient
REV representative elementary volume
SD  standard deviation
T   time Br⁻ solute is applied to saprolite
TOT time of travel of solute through a distance Ls
θ   volumetric water content
v   average velocity water flows through pores

Definitions

Effective hydraulic conductivity  A K value determined by calculation using the depth a Br⁻ has leached into saprolite.

Macropore  A large water-conducting pore such as a root channel that allows water to flow quickly through soil or saprolite and bypass the matrix.

Matrix  The volume of saprolite that is not in a vein, fracture, or macropore.

Representative elementary volume  Smallest volume that can be used to measure a property accurately.
PUBLICATIONS


