Transport of Pathogen Surrogates in Saprolite Subsoils in East Tennessee

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Introduction

Investigations by researchers at the University of Tennessee and Oak Ridge National Laboratory indicate that groundwater flow in the 2-10 m thick mantle of fine-grained saprolite (highly weathered rock) that covers the bedrock in much of east Tennessee is strongly influenced by fractures and macropores such as root holes. Flow through the fractures and macropores can be very rapid, in the order of 10s to 100s of meters per day. This can potentially cause rapid migration of contaminants from sources such as landfills, septic fields, sewage sludge applications, etc., which may result in contamination of streams or underlying aquifers. This paper provides a brief review of saprolite hydrogeology and describes a series of field and laboratory tracer experiments that were carried out to examine the potential for rapid migration of microbial pathogens in saprolite.

Saprolite Hydrogeology

Typical east Tennessee saprolite is a fine-grained, friable material, that has lost all of its original mineral cements, but usually contains well-defined sedimentary layering and relict fractures from the parent bedrock (most often shale, siltstone or limestone). In addition, there are numerous desiccation fractures, root holes and other large pores formed during weathering. As a result of these features, hydraulic conductivity values tend to be much higher ($10^{-7}$ to $10^{-4}$ m/s) than suggested by the clayey appearance of the material. Hydraulic conductivity values tend to highest in the upper 1.0-1.5 m and perched water table conditions, with rapid downslope flow, often develop in this “stormflow” zone during rainstorms (Solomon et al. 1992; Driese et al. 2001). Just beneath the stormflow zone many of the fractures and macropores are infilled with pedogenic clays and Fe/Mn oxides, which tend to inhibit downward flow (Driese et al. 2001; Smith 2001). The degree of infilling varies with parent bedrock lithology and tends to decrease with depth, resulting in another higher hydraulic conductivity zone just above the bedrock-saprolite contact. In many cases the water table tends to occur in the lower saprolite, resulting in rapid downslope flow in the lower saprolite and the shallow bedrock (Solomon et al. 1992; McKay et al. 2000). Downslope flow in the stormflow zone and the upper portion of the water table zone can either discharge into local streams or be diverted deeper into the bedrock through major fractures or sinkholes. A hydrogeologic conceptual flow model for the saprolite is shown in Figure 1.
Field-scale Tracer Experiments

A series of field-scale tracer experiments were carried out in east TN saprolite using bromide salts, dyes, dissolved gases, bacteriophage, bacteria and fluorescent latex microspheres, which indicate the potential for rapid downslope migration of contaminants in the stormflow and water table zones. A study by Wilson et al. (1993) involved infiltrating bromide into the soil through a 30 cm deep buried drainage pipe in the stormflow zone in a small, forested watershed on the Oak Ridge Reservation (ORR). Within 3 hours of the release, which occurred during a rainstorm, bromide was detected in infiltration pans set in the wall of a shallow trench approximately 70 m downslope. Intermittent pulses of bromide continued to appear the entire monitoring period (> 1 year), indicating that although flow was very rapid, a substantial portion of the bromide was temporarily retained in the fine pore structure within the saprolite. This experiment indicates that contaminants from near-surface sources such as septic fields, pesticide applications, etc. have the potential to move very rapidly in the stormflow zone.

A natural gradient tracer experiment was carried out by McKay et al. (2000) in the water table zone of the ORR saprolite. A 1 liter slug of tracer solution containing two strains of bacteriophage (MS-2 and PRD-1), *Pseudomonas syringae*, and 0.1 micron diameter latex microspheres was added to a 6 m deep well screened in the saprolite just above the bedrock. The tracers were detected in monitoring wells located at distances of 2-35 m downslope within a few hours of the addition of the tracers (Table 1). Solute tracers (dyes and dissolved gases) used previously at the same site (Lee et al. 1993) migrated much more slowly, apparently because they were retarded by diffusion into the

Figure 1. A conceptual model of sedimentary rock saprolite morphology and hydrology (modified from Solomon et al. 1992; Driese et al. 2001; and Smith 2001).
fine pore structure of the saprolite matrix. The microbial tracers and the microspheres were largely size-excluded from fine pore structure, and hence remained in the fast flow regime in the fractures and macropores. The first arrival transport times for dissolved tracers and particle tracers in the same monitoring well differed by a factor of up to 500, indicating that “matrix diffusion” is a powerful attenuating mechanism for solutes, but not microorganisms. This experiment confirms that rapid flow occurs in the water table zone, and indicates that any contaminants reaching this zone can rapidly migrate downslope until they discharge into streams or are diverted into underlying bedrock aquifers by major fractures or sinkholes.

Table 1. Measured solute and particle transport rates from field tracer experiment in the water table zone of ORR saprolite (adapted from McKay et al. 2000).

<table>
<thead>
<tr>
<th>Tracer</th>
<th>Transport rate based on first arrival in downslope monitoring wells (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacteriophage (MS-2 and PRD-1) and Pseudomonas syringae</td>
<td>5 to 56</td>
</tr>
<tr>
<td>Fluorescent latex microspheres (0.1 micron diameter)</td>
<td>21 to 200</td>
</tr>
<tr>
<td>Rhodamine WT dye and dissolved Helium and Neon</td>
<td>0.05 to 1.0</td>
</tr>
</tbody>
</table>

**Laboratory-scale Tracer Experiments**

A series of laboratory-scale tracer experiments were carried out in large undisturbed columns of sedimentary rock saprolite that were collected from excavations at depths of 0.5 to 1.5 m at ORR sites. The 25 cm diameter columns were carved from the saprolite using hand tools to minimize disturbance. A PVC casing was placed around the sample *in-situ*, and the annulus between the sample and the casing was filled with paraffin wax in the field. The columns were then brought back to the laboratory and end caps were fitted on so that they could be used for saturated flow tracer experiments, as described in McKay et al. (in press).

The objective of the laboratory-scale studies was to determine the main controls on particle transport in saprolite, and to relate these to conditions likely to exist in the field. The previous field study of particle transport by McKay et al. (2000) indicated very rapid transport of microbial and microsphere tracers, but also indicated highly variable rates of concentration decline with travel distance. For example, over the first 18 m of travel, concentration of microspheres declined by a factor of $10^7$, but from 18 to 35 m distance there was virtually no decline in concentration. The lab experiments help gain insight into the mechanisms and environmental factors responsible for these losses.

The principal expected mechanisms of particle loss during transport through saprolite are:

1) Electrostatic attachment to the walls of fractures or macropores. This is a function of groundwater chemistry and tends to have a greater effect on smaller particles (such as viruses) because of their higher diffusion coefficients and greater tendency to collide with fracture walls.
2) Gravitational settlement, which will have a greater effect on larger particles (for example protozoa).
3) Physical straining, meaning the lodging of particles in small aperture regions of fractures or macropores, which again preferentially affects larger particles.
4) Inactivation or die-off of microorganisms, which is a function of temperature, groundwater chemistry and microbial predation.

The principal environmental controls on the above loss mechanisms are fracture or macropore aperture, flow rate, particle size, ionic strength, valence state of the dominant cations, pH, and temperature. Each of the laboratory scale experiments addressed a different factor, usually by varying that factor while keeping the others constant. The results of the laboratory-scale tracer experiments are summarized in Table 2. They indicate that there is an optimum size for transport, of about 0.5 to 1 micron, which is about midway between the size of typical bacteria and typical viruses. This indicates that both bacteria and viruses are likely to be mobile in groundwater in saprolite. The study also indicates that under conditions of high flow rate and low ionic strength, losses of particles due to the above mentioned factors are minimal. These conditions (high flow and low ionic strength) typically occur during periods of high precipitation, which suggests that pathogen transport will tend to be intermittent. In summary, both bacterial and viral pathogens are likely to be mobile in saprolite, and there is potential for them to be transported quickly and with little concentration loss during seasonally wet periods or during heavy rainstorms.

Table 2. Summary of laboratory-scale particle tracer experiments.

<table>
<thead>
<tr>
<th>Experimental factor varied</th>
<th>Summary of results</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle diameter (microspheres)</td>
<td>Optimum particle size of 0.5 to 1 micron. Electrostatic attachment dominates, with settling as a secondary factor.</td>
<td>Cumbie and McKay (1999)</td>
</tr>
<tr>
<td>Flow velocity (bacteriophage)</td>
<td>Losses due to attachment are strongly effected by flow rate, with almost no loss at high flow rates</td>
<td>McKay, Harton and Wilson (in-press)</td>
</tr>
<tr>
<td>Groundwater chemistry (microspheres)</td>
<td>Particle losses are minimized at low ionic strength and in solutions dominated by monovalent cations</td>
<td>McCarthy, Bruner and McKay (in review) Bruner (1998)</td>
</tr>
<tr>
<td>Type of microbial tracer (MS-2, PRD-1, E. coli, P. fluorescens, and protozoa) and groundwater chemistry.</td>
<td>Protozoa are completely lost to straining or settling. Losses of bacteria and viruses are strongly influenced by ionic strength.</td>
<td>Rietti-Shati, McKay and Layton (in-preparation)</td>
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Implications

The above studies indicate that microbial pathogens from contaminant sources such as septic fields, sewage waste or livestock, are likely to be highly mobile in typical east Tennessee saprolite. There is good potential for these contaminants to move from the saprolite into streams or aquifers. This is consistent with results of groundwater and surface water monitoring in the USGS National Water Quality Assessment for the Upper Tennessee River Basin, which shows that at many of the surface water monitoring sites and almost all of the groundwater monitoring sites there was evidence of contamination with either total coliform or E. coli. Since there are numerous small water supply systems in east Tennessee using wells, springs, or surface water intakes, it is important to determine the actual extent of pathogen contamination in these sources. This is especially important because pathogen monitoring or treatment for many of the smaller water systems, such as those used for individual homes, trailer parks or churches, is very rare. To help investigate pathogen occurrence in waters in east Tennessee, the authors recently began two projects funded by the Tennessee Department of Environment and Conservation. One project is aimed at developing methods to distinguish between human and livestock pathogens in streams, and the other investigates the prevalence of viral pathogens in fractured and karst aquifers and relates them to the effectiveness of wellhead protection plans. These studies are very preliminary in nature and a great deal of additional research and monitoring is needed to fully assess the risk posed by pathogens in groundwater in east Tennessee.

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