ground water

Convergent Radial Tracing of Viral and Solute Transport in Gneiss Saprolite

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Abstract

Deeply weathered crystalline rock aquifer systems comprising unconsolidated saprolite and underlying fractured bedrock (saprock) underlie 40% of sub-Saharan Africa. The vulnerability of this aquifer system to contamination, particularly in rapidly urbanizing areas, remains poorly understood. In order to assess solute and viral transport in saprolite derived from Precambrian gneiss, forced-gradient tracer experiments using chloride and *Escherichia coli* phage ΦX174 were conducted in southeastern Uganda. The bacteriophage tracer was largely unrecovered; adsorption to the weathered crystalline rock matrix is inferred and enabled by the low pH (5.7) of site ground water and the bacteriophage's relatively high isoelectric point (pI = 6.6). Detection of the applied ΦX174 phage in the pumping well discharge at early times during the experiment traces showed, however, that average ground water flow velocities exceed that of the inert solute tracer, chloride. This latter finding is consistent with observations in other hydrogeological environments where statistically extreme sets of microscopic flow velocities are considered to transport low numbers of fecal pathogens and their proxies along a selected range of linked ground water pathways. Application of a radial advection-dispersion model with an exponentially decaying source term to the recovered chloride tracer estimates a dispersivity (α) of 0.8 ± 0.1 m over a distance of 4.15 m. Specific yield (S_y) is estimated to be 0.02 from volume balance calculations based on tracer experiments. As single-site observations, our estimates of saprolite S_y and α are tentative but provide a starting point for assessing the vulnerability of saprolite aquifers in sub-Saharan Africa to contamination and estimating quantitatively the impact of climate and abstraction on ground water storage.

Introduction

Thick regoliths of deeply weathered crystalline rock occur across low-latitude, cratonic regions of Africa, Asia, and the Americas. Aquifers that occur within an in situ weathered regolith (saprolite) and underlying fractured bedrock (saprock) are the product of long-term geomorphic evolution of the landscape that has occurred through tectonically controlled cycles of deep weathering and erosion (Taylor and Howard 1998, 2000). Saprolite and saprock derived from Precambrian crystalline rocks form integrated aquifer systems that underlie 40% of sub-Saharan Africa (Figure 1). Although both aquifers are generally low yielding (Bannerman 1973; Omorinbola 1984; Owoade 1995; Chilton and Foster 1995; Taylor and Howard 2000), they are a daily source of drinking water to more than 220 million people across sub-Saharan Africa via low-intensity, hand-pump abstraction and spring discharges (MacDonald and Davies 2000).

Ground water use from the saprolite-saprock aquifer system has recently intensified in an effort to provide low-cost town water supplies throughout sub-Saharan

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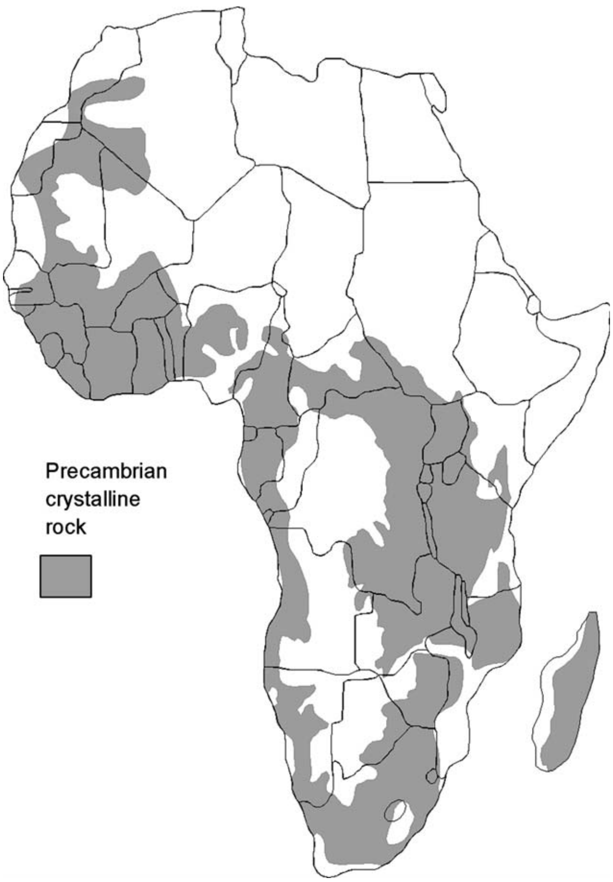

Figure 1. Distribution of Precambrian crystalline rock in Africa (Key 1992).

Africa, the most rapidly urbanizing area in the world (United Nations Population Fund 2007). Intensive abstraction of ground water for irrigation has also been proposed to overcome the threat posed to rainfall-fed agriculture by climate variability and climate change.[6] Knowledge of how intensive abstraction will impact ground water levels in the saprolite-saprock aquifer system of sub-Saharan Africa is limited (Taylor et al. 2004a; Tindimugaya 2008) and constrained by uncertainty in aquifer storage. Considerable research has focused on the hydrogeological characteristics of fissured bedrock in Africa (e.g., Houston and Lewis 1988; Howard et al. 1992) and India (e.g., Briz-Kishore 1993; Maréchal et al. 2004), yet comparatively few studies in the tropics have examined ground water flow and storage in saprolite despite its importance not only as a source of water via shallow wells and springs but also as a source of ground water storage to underlying fracture systems (Rushton and Weller 1985; Sekhar et al. 1994; Taylor and Howard 2000).

In rapidly urbanizing areas of Africa, the rising density of sewage disposal facilities and other contaminant sources (e.g., garbage dumps) increases the vulnerability of boreholes drawing ground water from the saprolite-saprock aquifer system to contamination. Localized contamination of saprolite and saprock aquifers from fecal sources has been indicated by elevated concentrations of nitrate and thermotolerant coliforms in the discharge of hand-pumped wells and springs (e.g., Barrell and Rowland 1979; Malomo et al. 1990; Taylor and Howard 1995; Gelinas et al. 1996; Nkotagu 1996; Howard et al. 2003; Miret Gaspa 2004; Bordalo and Savva-Bordalo 2007). Adoption of current guidelines to protect ground water–fed water supplies (e.g., Schmoll et al. 2006) requires specific knowledge of aquifer characteristics and, ideally, transport of actual microbial pathogens (e.g., enteric viruses) by ground water in developed aquifers (e.g., saprolite).

The overall objective of this study was to improve understanding of viral and solute transport in saprolite aquifers of sub-Saharan Africa. Two forced-gradient tracer experiments were conducted in Uganda over 5-d intervals in March 1999 and August 2000 in order to assess the transport of bacteriophage (ΦX174), a proxy for enteric viruses, relative to a conservative (unreactive) tracer. Tracing experiments also enabled in situ estimates of key aquifer characteristics including storage. Experiments were conducted in saprolite derived from Archean gneiss of the granulitic-gneissic complex, which extends throughout much of central and northern Uganda. The saprolite developed on preweathered gneissic bedrock through a prolonged cycle of deep weathering since the Miocene (Taylor and Howard 1998) that is consistent with saprolite development on the low-relief, post-Gondwana, "African" surface, which extends throughout eastern and southern Africa.

Tracer Selection

Chloride was selected as a conservative tracer of solute transport because it is simply and reliably analyzed in the field and its unreactive character is well established. Use of chloride also avoided the possibility of significantly affecting the potability of a nearby public water supply borehole. Bacteriophages have been widely applied as a tracer of viral transport in ground water (e.g., McKay et al. 1993; Bales et al. 1997; Ryan et al. 1999) because they are nonpathogenic (being specific to a host bacteria), are relatively easy to culture and assay, and exhibit good survival characteristics. The sensitivity of bacteriophages, which can be prepared in titers of 10^8 to 10^{12} plaque-forming units (pfu)/mL and detected in concentrations of 1 pfu/mL, is unmatched by most chemical tracers. Added advantages to the use of bacteriophage are that culturing and assaying of the virus do not require sophisticated microbiological equipment and are inexpensive. In this study, *Escherichia coli* phage ΦX174 (NCIMB 10382/ATCC 13706 B6), which is a tailless, single-stranded DNA bacteriophage with an icosahedral head morphology and a diameter of approximately 27 nm, was selected as a potential viral tracer because it is comparable in size to enteric viruses. Rotavirus, for example, is considered to be the most important cause of

[6] The Kampala Statement (http://www.gwclim.org/), Groundwater and Climate in Africa conference (June 25 to 28, 2008).

severe diarrhea in African children (Cunliffe et al. 1998). The representivity of bacteriophages as tracers of enteric virus transport is, however, uncertain (Cronin and Pedley 2002) and the subject of active research.

Study Site

Tracing experiments were conducted on the property of the District and Town Water Offices of Iganga in southeastern Uganda (Figure 2). The stratigraphy of the saprolite at the study site was determined from drill cuttings collected during well construction and is shown in terms of graphical logs of weathered lithofacies (Figure 3) proposed by Taylor and Howard (1999a). Below topsoil, reddish-brown clay loam (U.S. Department of Agriculture classification) comprising hydrous iron and aluminum oxides and kaolinite is succeeded with depth by a coarse-grained horizon of angular quartz fragments. This coarse-grained layer is underlain by brown sandy silt and sandy loam in which the frequency of mineral fragments increases with depth. Below the water table, gray and yellowish-orange loamy sand of bedrock fragments persists to the bedrock surface between 22 and 23 mbgl. Examining the lithology of weathered profiles similarly derived from gneissic bedrock in Uganda, Taylor and Howard (1999a) record bimodal particle size distributions that, in the saturated zone,

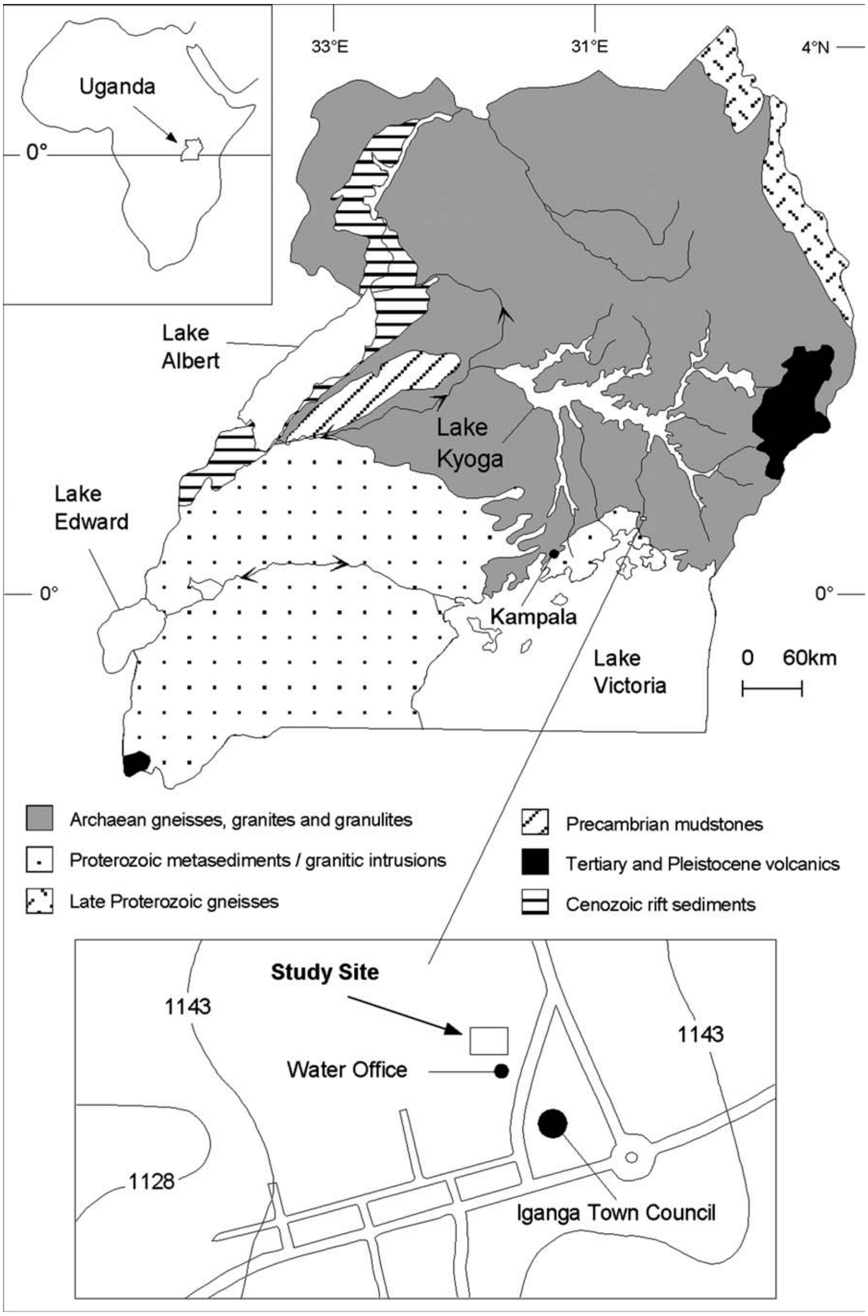

Figure 2. Generalized geological map of Uganda with location of the study site in Iganga inset.

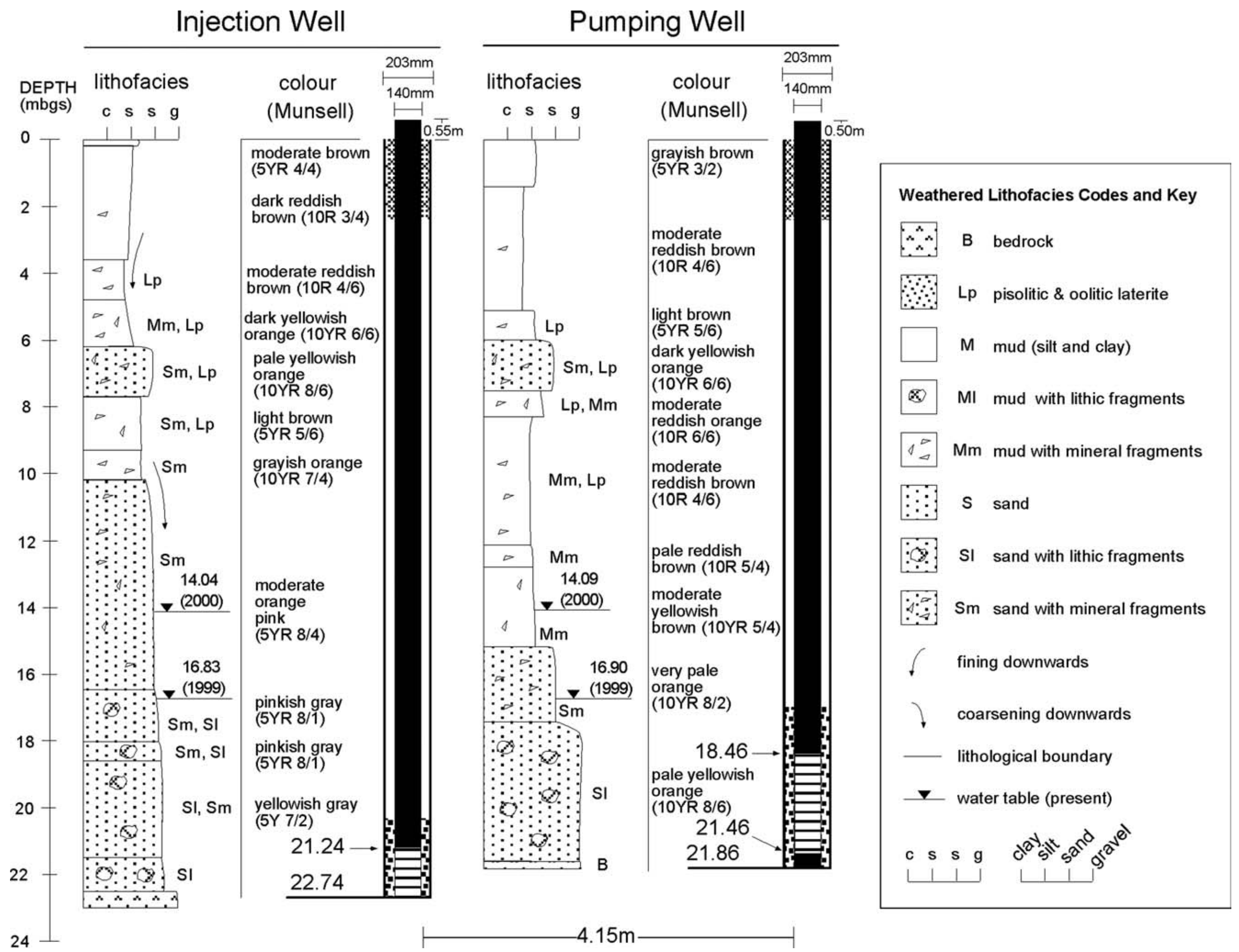

Figure 3. Lithological and borehole construction logs for the study site in Iganga.

comprise binary clays (smectite and vermiculite) and kaolinite along with sand-sized grains of quartz and potassic feldspar relatively resistant to weathering.

The pumping well (PW) and injection well (IW) were 4.15 m apart and were drilled by air rotary methods using a boring diameter of 203 mm. Both wells partially penetrate the aquifer in the weathered overburden. Polyvinyl chloride well screens (inner diameter 140 mm and slot size 1.5 mm) and filters of quartz gravel (grade: 2 to 6 mm) were installed through 1.5- and 3.0-m intervals of the saturated zone in the IW and PW, respectively (Figure 3). In each well, backfilling occurred to a depth of 2 mbgl where a concrete seal and skirting were installed to ground surface. Well development was achieved by airlifting and a step pumping test. The study site (Figure 2) is situated on a topographic divide with drainage occurring along very gentle slopes to the west and east of the town center. The forced-gradient tracer experiments amplified the prevailing hydraulic gradient from IW to PW of 0.012. Iganga Town experiences a humid climate that is characterized by two rainy seasons occurring around April and September each year. Due, in part, to low relief and permeable soils that favor infiltration of rainfall, recharge exceeds runoff and is roughly in the order of 120 mm/annum (Taylor and Howard 1999b).

Materials and Methods

Bacteriophage ΦX174 was grown and assayed in *E. coli* (NCIMB 12416) using the pfu technique described by Adams (1959). Phage and host bacteria were reconstituted from freeze-dried culture. Inoculation of the host culture with reconstituted phage produced a phage titer of 10^8 to 10^9 pfu/mL. The precise titer was determined by serial dilution followed by the phage detection method described by Borrego et al. (1987). Ground water samples collected on site prior to the application of tracers confirmed that bacteriophage ΦX174 was absent. Prior to the application of tracers, a pseudo–steady-state flow field between the IW and PW was established after 6 h of pumping. Injection of phage and aqueous chloride (0.54 kg) into the IW was effectively instantaneous through a 20 m length of high-density polyethylene (HDPE) tubing (outer diameter: 25 mm), perforated (slot diameter: 5 mm) over a 0.5-m interval at its base. The tracers were mixed with the well volume using the emplaced HDPE tubing. Physicochemical measurements and samples for tracer analysis were taken every 2 h over each 5-d experiment. Aqueous samples for bacteriophage analysis were collected in sterile glass universals, fixed with 1 to 2 mL of chloroform, placed in dark, cold storage (less than 10 °C), and analyzed within 48 h at the Environment and Public Health Laboratory at Makerere University (Kampala). Analysis of chloride in ground water was conducted by colorimetry at the Water Resource Management Department in Entebbe.

To monitor tracer loss, samples for chloride and phage analysis were obtained directly from the (nonpumping) IW using disposable bailers at regular intervals. The inactivation rate of phage ΦX174 in site ground water was determined by inoculating 1 L ground water samples with 1 mL of a titer of phage ΦX174 (6×10^8 pfu/mL) and storing these samples at 25 °C, the in situ temperature of ground water. Over a 5-d period, 10 mL samples were then taken from the infected water, fixed with chloroform, and refrigerated (~4 °C) before assaying. The effect of salinity and hence simultaneous application of phage and NaCl tracers on the inactivation rate of phage ΦX174 were also investigated.

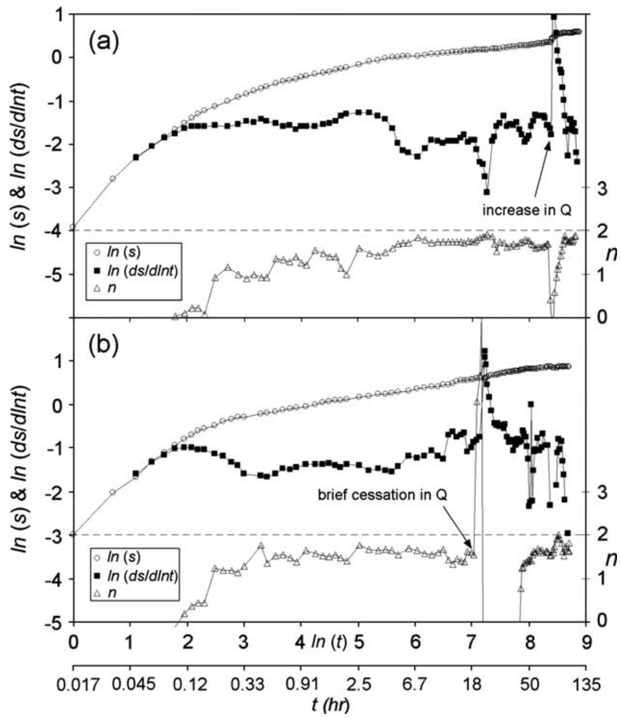

Figure 4. Log-log plot of observed drawdown in the monitoring (injection) well and its smoothed (moving five-point average) head derivative together with the flow dimension along the second, linear axis vs. elapsed time for the (a) 1999 and (b) 2000 tracer experiments.

Results and Discussion

Hydraulic Response to Pumping

For each forced-gradient tracer experiment, drawdown (s), the drawdown derivative ($ds/d \ln t$), and flow dimension (n) are plotted vs. elapsed time on logarithmic axes in Figure 4. Analysis of flow dimension is based on the generalized radial flow (GRF) approach of Barker (1988). The GRF model shows that for large times and flow dimension less than 2, the drawdown tends asymptotically to a power of time:

$$s \sim t^{1-n/2}, \quad n < 2 \tag{1}$$

Taking logarithms and differentiating, we can obtain an (instantaneous) apparent dimension:

$$n = 2\left(1 - \frac{\mathrm{d}\ln s}{\mathrm{d}\ln t}\right) \tag{2}$$

Both the head derivative and the flow dimension given by Equation 2 were used to constrain the range of potential conceptual models of the tested system and, hence, analytical solutions to be applied to the drawdown response and transport of applied tracers.

Brief changes in the pumping regime that occurred during each tracer experiment are detectable in both plots of the drawdown response in Figure 4. In 1999, the pumping rate (Q) was increased from 0.8 to 1.0 m^3/h after 72 h. As a result, the applied hydraulic gradient between the IW and the PW increased from 0.066 to 0.086. In 2000, the pumping rate remained relatively constant at 1.9 m^3/h throughout the experiment but was interrupted by a temporary cessation (40 min) of pumping after 21 h. Apart from this interruption, the hydraulic gradient applied over the entire experiment was 0.092.

Drawdown responses during both experiments indicate radial flow conditions within an unconfined aquifer. During the 1999 tracer experiment (Figure 4a), stabilization of drawdown between 4 and 24 h of pumping is followed by a small but steady increase in drawdown. This stabilization of s, indicated by negative deflections in the head derivative, reflects the contribution of depression storage, whereas the latter, supported by a generally constant derivative drawdown between 24 and 72 h, suggests that near-well gravity storage has been exhausted and conditions of radial flow unaffected by constant head or no-flow boundary. A similar pattern is observed during the experiment of 2000 (Figure 4b), though the stabilization of s indicated by negative deflections in the head derivative between 9 and 17 h is less pronounced. Unconfined aquifer conditions diagnosed in the gneiss saprolite of Iganga contrast with semiconfined and confined conditions that have been observed in saprolite in many parts of Africa (Taylor and Howard 2000 and references therein), Australia (e.g., Rasiah et al. 2007), and United States (e.g., Seaton 2002). Consistent with the inference of radial flow conditions, mean flow dimensions closely approximate 2 (corresponding to cylindrical radial flow) after the first day of pumping in both 1999 ($n = 1.8$) and 2000 ($n = 1.9$).

Having deduced conditions of radial flow and unconfined aquifer storage at the study site, the analytical solution of Neuman (1975) for an unconfined aquifer was applied to the drawdown responses in the IW and closely

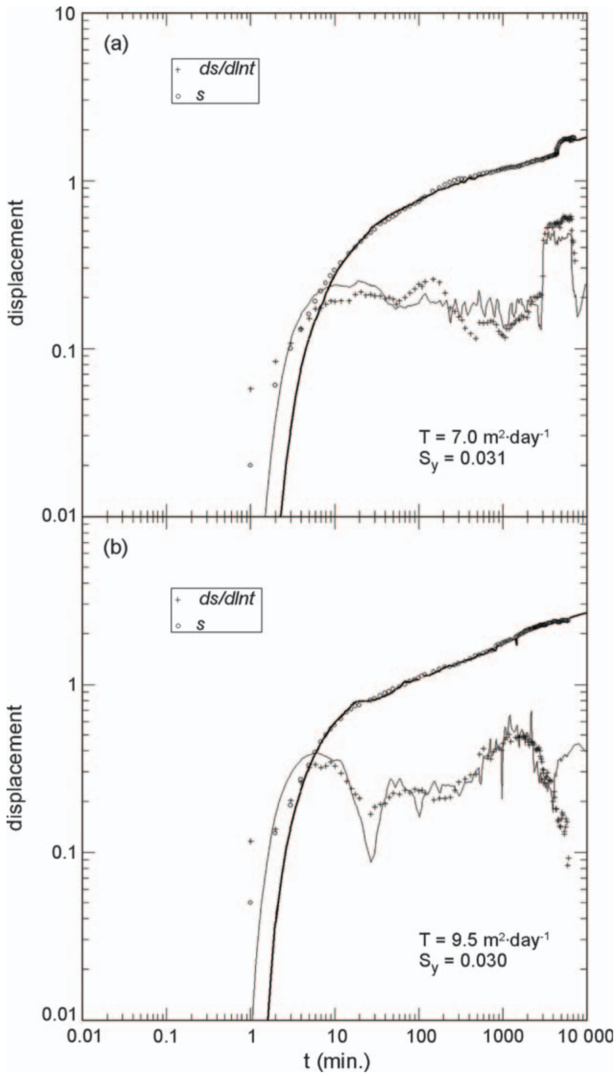

Figure 5. Analytical solution of Neuman (1975) for an unconfined aquifer (lines) fitted to observed drawdown and the head derivative (symbols) in the IW for the (a) 1999 and (b) 2000 tracer experiments using AQTESOLV™/Pro v4.5. Residual sum of squares in each solution is less than 0.13.

approximates field observations (Figure 5). Bulk hydraulic conductivity (K) of the saprolite is estimated to be 1.1 m/d, consistent with values for gneiss and granite saprolite (0.2 to 1.8 m/d) determined elsewhere from hydraulic tests on the African surface in Uganda (Taylor and Howard 2000) as well as Malawi and Zimbabwe (Chilton and Foster 1995). The specific yield (S_y) of the gneiss saprolite is estimated to be 0.003 and differs by 2 orders of magnitude from estimates based on recharge modeling (2×10^{-5}) in Zimbabwe (Butterworth et al. 1999) and laboratory analyses of saprolite sampled from unlined wells (0.20 to 0.21) in Nigeria (Omorinbola 1984).

Comparisons in S_y estimates are complicated by different methods and scales of analysis (Healy and Cook 2002) but are particularly problematic in saprolite where strong vertical anisotropy in hydrogeological properties results from its genesis (i.e., in situ weathering of bedrock). For example, the value from Zimbabwe (2×10^{-5}) was estimated for a shallow (less than 10 mbgl) clay-rich saprolite that is consistent with shallower and more highly weathered lithofacies that occur in the unsaturated zone at Iganga (Figure 3). The basis (e.g., sample depth, size, and number) for the high saprolite S_y estimates reported by Omorinbola (1984) is unclear, and their representivity at the borehole catchment scale is questionable. The S_y estimate of 0.003 for gneiss saprolite is, however, considered to represent a minimum value since analytical solutions to pumping test data (e.g., Neuman 1975) ignore delayed yield from the unsaturated zone and thus provide unrealistically low values of S_y (Nwankwor et al. 1992).

Solute Transport—Chloride

The breakthrough curve for the conservative solute tracer, chloride, is plotted vs. time in Figure 6. Reported concentrations of the chloride tracer are values in excess of a stable background chloride concentration of 39.4 mg/L. Chloride recovered over the experiment represents 70% of the mass applied in the IW. The concentration of chloride in the IW is observed to decline exponentially as

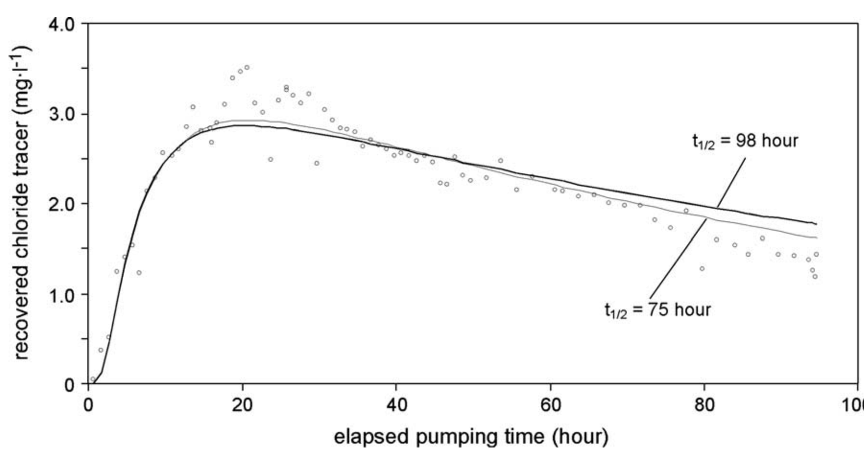

Figure 6. Observed breakthrough curve for the applied chloride in the 2000 tracer experiment fitted by the radial advection-dispersion model of Moench and Ogata (1981) but with an exponentially decaying source term.

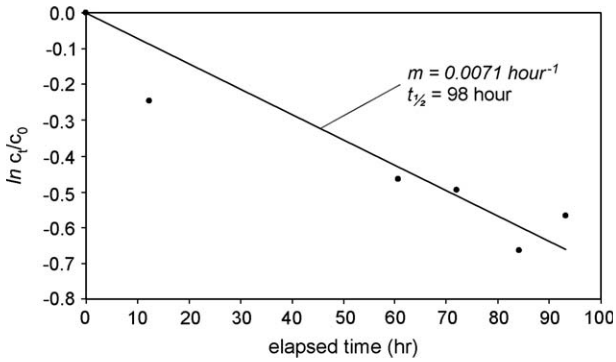

Figure 7. Semilogarithmic plot of the exponential decline in the concentration of the applied chloride tracer in the IW vs. time.

a result of dilution with a half-life of 98 h (Figure 7). As a result of deductions from the drawdown response (i.e., establishment of radial flow) and observed decline in tracer concentrations in the IW, a radial dispersion model for a constant source (Moench and Ogata 1981) was adapted to an exponentially decaying source term. To achieve this, the Laplace transform solution of Moench and Ogata (1981) was simply multiplied by $p/(p + k)$, where p is the Laplace transform variable and $k = \ln 2/t_{½}$ is the decay constant. The resulting transform solution was inverted numerically, to give time-dependent concentrations, using the Talbot (1979) algorithm.

The radial advection-dispersion model approximates the breakthrough curve for the chloride tracer in Figure 6. The range of possible solutions to the model was constrained by site details (well radius and separation distance) and the observed half-life ($t_{1/2}$) of the chloride tracer in the IW (Figure 7). Estimated dispersivity (α) of 0.8 ± 0.1 m over a distance of 4.15 m is consistent with the scale-dependent relationship between dispersivity and distance observed by Gelhar (1986). The radial dispersion model is, however, sensitive to variations in the half-life of the applied chloride tracer in the IW. Decreasing $t_{1/2}$ to 75 h, outside of the error in the regression of the decay constant (Table 1, Figure 7), improves the model's representation of the breakthrough curve (Figure 6) and increases estimated dispersivity to 0.9 m. The absence of multiple peaks (modes) in the breakthrough curve (Figure 6) favors the assumption of matrix flow, inherent to our analysis of dispersivity, and is inconsistent with the possibility that multiple channels associated with relict structures, observed in gneiss and mica schist saprolite in the United States (e.g., Vepraskas et al. 1991; Seaton 2002), transport a substantial proportion of the applied chloride tracer.

The travel time (t_a) of the chloride tracer (5.5 h) determined by the radial advection-dispersion model permits an estimate of kinematic porosity (ϕ) for gneiss saprolite using a simple radial volume balance formula (Equation 3). ϕ, which closely approximates S_y, is 0.02 and exceeds the minimum estimate of 0.003 for S_y derived from the Neuman (1975) solution to pumping test data aforementioned. The value of 0.02 is considered to provide an improved representation of saprolite S_y and is consistent with a mean estimate (0.02) for similarly basal portions of saprolite derived from granite and gneiss in Western Australia (George 1992).

$$\phi = \frac{Qt_a}{\pi r^2 b} \tag{3}$$

where Q = pumping rate (m^3/h), r = distance between pumping and IW (m), and b = aquifer thickness (m).

The average linear velocity of ground water flow ($\bar{v}$) leaving the IW can be approximated from the dilution of the chloride tracer in the IW (Figure 7). Assuming that dilution results from differences in mass fluxes in and out of the IW, $\bar{v}$ is defined by Equation 4 (Ward et al. 1998), where ρ is the ratio of the width of the aquifer contributing flow to the borehole to the borehole diameter. ρ is calculated from the relationship developed by Klotz et al. (1972). $\bar{v}$ is estimated to be approximately 4 m/d.

$$\bar{v} = \frac{\pi R b m}{2\phi L_{scrn}\rho} \tag{4}$$

where R = well radius (m), m = rate of dilution of the chloride tracer in the IW (/d), and L_{scrn} = screen length (m).

Viral Transport—Bacteriophage ΦX174

The phage ΦX174 tracer was detected in the discharge of the PW after 6 h (2 pfu/mL) but otherwise absent in the discharge (i.e., unrecovered) over the period of the experiment. Laboratory experiments of the inactivation of phage ΦX174 in site ground water at 25 °C yield a half-life of 86 h (i.e., inactivation rate of 20% to 22% per day or 0.11 log unit per day) that is unaffected

Table 1
Estimates of Dispersivity (α) from the Radial Advection-Dispersion Model of Moench and Ogata (1981) with an Exponentially Decaying Source Term

x (m)	r_w (m)	$t_{1/2}$ (min)	α (m)
4.15	0.07	5800 ± 500	0.8 ± 0.1
4.15	0.07	4500	0.94

Note: $t_{1/2}$ = the half-life of the tracer in the IW; r_w = the well radius; x = the distance between IW and PW.

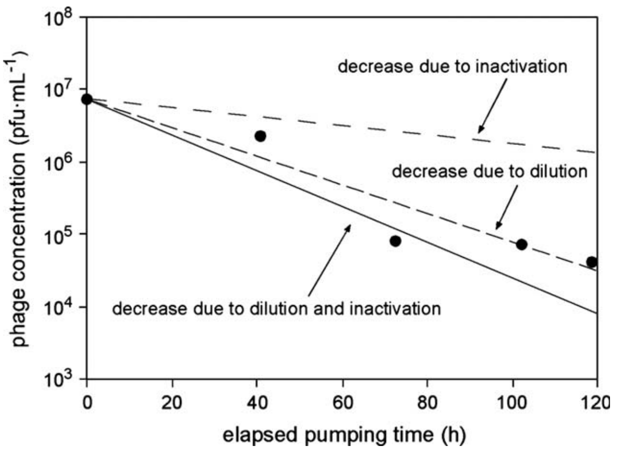

Figure 8. Semilogarithmic plot of bacteriophage ΦX174 concentrations in the IW vs. time. Decreases in phage ΦX174 concentrations through inactivation, dilution, and both inactivation and dilution are indicated. Inactivation is derived from laboratory survival experiments, whereas dilution rate is derived from chloride data in Figure 7.

by the addition of the conservative tracer, NaCl. Although observed inactivation of phage is more rapid than rates recorded in temperate areas (e.g., Bales et al. 1991; McKay et al. 1993), due to the higher ground water temperatures (25 °C) that prevail in Uganda, this rate of inactivation does not explain the near absence of detected phage in the pumping well discharge during the 120-h tracer experiment. The movement of a tiny proportion of a microbial source at an average linear velocity exceeding that of conservative solutes has been observed in a variety of hydrogeological environments and is considered to result from statistically extreme sets of microscopic flow velocities transporting microorganisms along a selected range of linked ground water pathways (Taylor et al. 2004b). In saprolite, such pathways may include fracture networks and quartz veins retained from the parent bedrock.

A decrease in the concentration of bacteriophage in the IW was observed during the experiment (Figure 8). The method of sampling in which bailers are periodically inserted into the IW is, however, complicated by the fact that viruses are not "true" solutes so that their population is not uniformly distributed in aqueous solutions. The observed reduction in the concentration of bacteriophage in the IW from 8×10^6 to 5×10^4 pfu/mL over 120 h can, however, be explained by the processes of inactivation and dilution (Figure 8).

Retardation of the bulk of the bacteriophage, relative to chloride, results from the competing processes of adsorption and desorption. These processes depend, in part, upon the ionic strength and pH of ground water. The ionic strength of ground water is a measure of the total dissolved ions that can act as "salt bridges" to facilitate adsorption of the virion to the aquifer substrate. The pH of ground water determines the net charge on the surface of the virus and, hence, its electrostatic attraction to the aquifer matrix. This dependence of a virus' surface charge on pH arises from the fact that the polypeptide coat of viruses contains amino acids with carboxylic and amino end groups whose charge varies continuously with pH (Gerba 1984). Viruses are, therefore, amphoteric, capable of holding positive and negative charge. When the pH of ground water is below an isoelectric point (pI) in which the virion exists in a state of zero net charge, the virion is positively charged (i.e., with protonated end groups). When the pH is above this point, the virion possesses a negative surface charge (i.e., with deprotonated end groups).

At the study site in southeastern Uganda, the pH of ground water (5.7) was lower than the pI (6.6) of bacteriophage ΦX174 (Dowd et al. 1998) rendering a positive aggregate charge on the surface of the bacteriophage. The pI and size of enteric viruses, transmitted by water (Moe 1997), and a series of bacteriophage tracers are summarized in Table 2. Observed retardation of the positively charged solute by aluminosilicate materials with an abundance of negatively charged sites is sensible. Of significance to public health is that virus strains with a similarly high pI (e.g., echovirus) may also be retarded under the commonly acidic (pH = 5 to 7) conditions of ground water in saprolite and saprock in Africa. Caution must be exercised, however, in drawing simple connections between virus transport and pI as the complexity of virus transport is such that pI varies not only with the type of virus but also its strain (Gerba 1984). It is also worth noting that desorption of sorbed viruses following a pulse of higher pH and lower salinity water has been demonstrated experimentally (Ryan and Elimelech 1996; Bales et al. 1997). Field evidence in saprolite is lacking, but recent high-frequency sampling of a spring discharge in Kampala, Uganda (Miret Gaspa 2004), where recharge events coincide with heavy (more than 10 mm/d) rainfall events

Table 2
pI and Diameter of Selected Enteric Viruses and Bacteriophages

Virus	pI[1]	*d* (nm)[2]
Astrovirus	n.a.	27
Calicivirus	n.a.	35
Coxsackievirus	6.1, 4.8	20–40
Echovirus	5.1–6.4	20–40
Hepatitis A	n.a.	20–40
Poliovirus	3.8–8.2	20–40
Reovirus	3.9	75
Rotavirus	n.a.	70
MS2 phage	3.9	24
PRD1 phage	4.2	63
Qβ phage	5.3	24
ΦX174 phage	6.6	27
PM2 phage	7.3	60

[1]Gerba (1984) and Dowd et al. (1998).
[2]Harper (1993). n.a., not available.

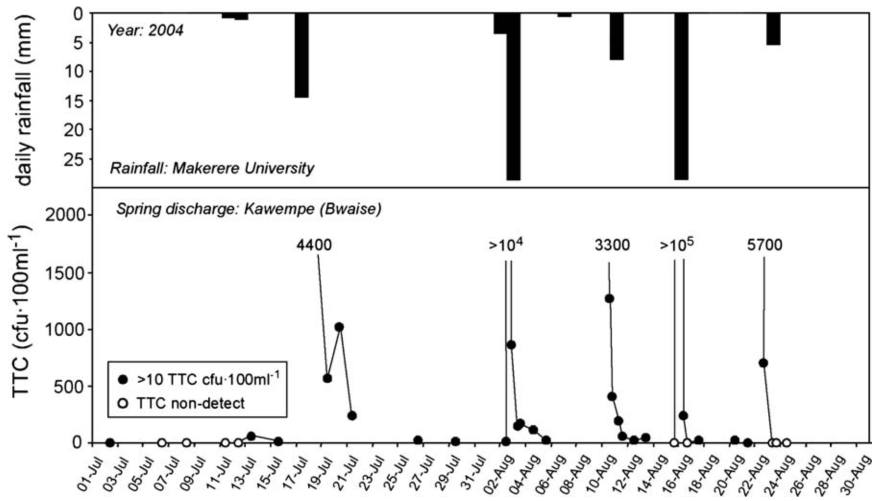

Figure 9. Changes in (fecal) thermotolerant coliform counts (TTC) in the discharge of a protected spring in response to rainfall in Kampala (Uganda) during the months of July and August 2004 (Miret Gaspa 2004).

(Taylor and Howard 1996), shows a strong correlation between heavy rainfall events pulses and gross contamination of ground water by thermotolerant (fecal) coliforms (Figure 9).

Conclusions

Forced-gradient tracer experiments in southeastern Uganda yield new insight into the transport of fecal viruses in saprolite derived from Precambrian gneiss. *Escherichia coli* phage ΦX174, applied to the IW as a field tracer of viral transport, was largely unrecovered and considered to have adsorbed to the aquifer's aluminosilicate matrix. Our observations indicate that fecal viruses with a similarly high isoelectric point (pI) such as echovirus may also be retarded under the commonly acidic conditions of ground water in saprolite and highlight the importance of considering pI, in addition to virion size, in selecting representative tracers of fecal pathogens. Applied ΦX174 phage detected in the pumping well discharge at early times during the experiment traces showed, however, that average ground water flow velocities exceed that of the inert tracer, chloride. This latter finding is consistent with observations in other hydrogeological environments where statistically extreme sets of microscopic flow velocities are considered to transport low numbers of fecal pathogens and their proxies along a selected range of linked ground water pathways. Application of a radial advection-dispersion model with an exponentially decaying source term to the recovered chloride tracer indicates a dispersivity (α) of 0.8 $\pm$ 0.1 m over a distance of 4.15 m. Specific yield (S_y) estimated from volume balance calculations using tracer data is 0.02. As single-site determinations, our estimates of saprolite S_y and α are tentative but provide a starting point for assessing the vulnerability of saprolite aquifers in sub-Saharan Africa to contamination and estimating quantitatively the impact of climate and abstraction on ground water storage.

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