Ground water flow and storage in weathered crystalline rock: evidence from Uganda

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Abstract

Deeply weathered crystalline rock aquifer systems consisting of an unconsolidated weathered regolith and underlying fractured bedrock underlie 40% of sub-Saharan Africa. The vulnerability of this aquifer system to over abstraction and fecal contamination, particularly in rapidly urbanising areas, remains poorly understood. Forced-gradient tracer tests using chloride were conducted in order to assess ground water flow and storage in a deeply weathered, gneissic rock in southeastern Uganda. *Escherichia coliphage* ΦX174 was also investigated as a possible tracer of viral transport. Analytical solutions to drawdown data, selected on the basis of the pressure derivative and flow dimension, indicate a bulk hydraulic conductivity of 1.2 m·d^{-1} and a specific yield of 0.23±0.05. Application of a radial advective-dispersion model with an exponentially decaying source term to the recovered conservative tracer, chloride, indicates a dispersivity of 0.8±0.1 m over a distance of 4.15 m. Based on the recovery of the chloride tracer, average linear velocity of ground water is 1.6 m·d^{-1}. The bacteriophage tracer was largely unrecovered; adsorption to the weathered crystalline rock matrix is inferred and promoted by the low pH (5.7) of site ground water and the bacteriophage's relatively high isoelectric point (pI = 6.6). This study presents the first field determinations of aquifer storage (specific yield) and dispersivity in weathered crystalline rock in sub-Saharan Africa. Despite the limitations of single-site observations, these data provide a starting point for assessing the vulnerability of weathered crystalline rock to contamination and estimating quantitatively the impact of climate and abstraction on ground water levels in this aquifer.

Key words: ground water, tracer, bacteriophage, transport, crystalline rocks

Introduction

Thick regoliths of deeply weathered crystalline rock occur across low-latitude, cratonic regions of Africa, Asia and the Americas. Aquifers which occur in the *in situ* weathered regolith (saprolite) and underlying fissured 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). Although considerable research in the tropics has focused on the hydrogeological characteristics of fissured bedrock (e.g., Houston and Lewis, 1988; Howard et al., 1992; Briz-Kishore, 1993; Maréchal et al., 2004), comparatively fewer studies have examined ground water flow and storage in the weathered regolith despite its importance not only as a source of water via shallow wells but also as a source of ground water storage to underlying fracture systems (Rushton and Weller, 1985; Taylor and Howard, 2000).

The weathered regolith and fissured bedrock form an integrated aquifer system that underlies 40% of sub-Saharan Africa (Figure 1). Both aquifers are generally low yielding (Bannerman, 1973; Omorinbola, 1984; Owoade, 1993; Chilton and Foster 1995; Taylor and Howard 2000) but have a long history of development for low-intensity, handpump abstraction. Ground water development has recently intensified in an effort to provide low-cost, town water supplies throughout sub-Saharan Africa, the most rapidly urbanizing area in the world (Clark, 1998). Despite the increased density of sewage disposal facilities and other contaminant sources (e.g., refuse dumps) in urban Africa, the susceptibility of boreholes drawing ground water from weathered crystalline aquifers to contamination from point-source pollution remains very poorly understood. Localised contamination of aquifers in weathered crystalline rock from fecal sources sewage has been indicated by elevated concentrations of nitrate and thermotolerant coliforms in the discharge of handpumped wells and springs (e.g., Barrell and Rowland 1979; Malomo et al. 1990; Taylor and Howard 1995; Gelinas et al., 1996; Nkotagu, 1996; Miret Gaspa, 2004).

Current guidelines for wellhead protection zones (e.g. Schmoll et al., 2006) require specific knowledge of aquifer characteristics and, ideally, transport of actual microbial pathogens (e.g., enteric viruses) by ground water in deeply weathered aquifers. There is also no clear understanding of the impact of more intensive ground water abstraction on ground water levels in the aquifer system and, hence, the sustainability of intensive abstraction (Taylor et al., 2004a). Published measurements of several, key hydrogeological properties of deeply weathered crystalline rock in Africa such as storage (e.g. specific yield) and dispersivity do not exist. The overall objective of this study is, therefore, to improve understanding of ground water flow and contaminant transport in deeply weathered crystalline rock. Two forced-gradient tracer tests were conducted over 5-day intervals in March (1999) and August (2000) in order to derive field-based estimates of key aquifer characteristics including specific yield and dispersivity, and to assess the transport of bacteriophage (ΦX174), a proxy for enteric viruses, relative to a conservative (unreactive) tracer.

Tracer Selection

Chloride was selected as a conservative tracer of solute transport because it is simply and reliably analysed 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 non-pathogenic (i.e., it is 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 titres of 10^8 to 10^{12} pfu·ml^{-1} and detected in concentrations of 1 pfu·ml^{-1}, 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 tail-less, 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 severe diarrhoea 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 is the subject of active research.

Study Site

The tracer test was conducted on the property of the District and Town Water Offices of Iganga in southeastern Uganda (Figure 2). This area is underlain by Precambrian gneisses and granites of the Granitic-gneissic complex which extends throughout much of central and northern Uganda. A prolonged cycle of deep weathering since the Miocene (Taylor and Howard 1998) has produced a thick (>20 m) regolith of *in situ* weathered rock overlying bedrock. The stratigraphy of the weathered mantle at the test site is determined from drill cuttings collected during well construction, and shown in terms of graphical logs of weathered lithofacies (Figure 3) proposed by Taylor and Howard (1999a).

Below topsoil, reddish-brown clay loam (USDA classification) comprising hydrous iron and aluminium oxides and kaolinite is succeeded with depth by a coarse-grained horizon of angular quartz fragments. This coarse-grained layer is underlain by brown sandysilt and sandy loam in which the frequency of mineral fragments increases with depth. Below the water table at ~17 metres below ground level (mbgl), gray and yellowish orange loamy sand of bedrock fragments persists to the bedrock surface between 22 and 23mbgl. Examining the lithology of weathered profiles similarly derived from gneissic bedrock, Taylor and Howard (1999a) observed bimodal particle-size distributions that, in the saturated zone, comprise binary clays (smectite, vermiculite) and kaolinite along with sand-sized grains of quartz and potassic feldspar relatively resistant to weathering.

The pumping well and injection well were drilled by air-rotary methods using a boring diameter of 203 mm. Both wells partially penetrate the aquifer in the weathered overburden. PVC well screens (ID: 140 mm; 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 injection well and pumping well respectively (Figure 3). In each well, backfilling occurred to a depth of 2mbgl where a concrete seal and skirting were installed to ground surface. Well development was achieved by air lifting and a step pumping test. The study site (Figure 1) is situated on a topographic divide with drainage occurring along very gentle slopes to the west and east of the town centre. Iganga Town experiences a humid climate which is characterised by two rainy seasons occurring around April and September each year. Due, in part, to low relief and permeable soils that favour infiltration of rainfall, recharge exceeds runoff and is roughly in the order of 120 $mm \cdot a^{-1}$ (Taylor and Howard 1999b).

Materials and Methods

Bacteriophage ΦX174 was grown and assayed in *Escherichia coli* (NCIMB 12416) using the plaque-forming-unit technique described by Adams (1959). Phage and host bacteria were reconstituted from freeze-dried culture. Innoculation of the host culture with reconstituted phage produced a phage titre of 10^8 to 10^9 pfu·ml^{-1}. The precise titre 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 injection and pumping wells was established. Phage and aqueous chloride (0.54 kg) were injected directly into the observation well through a 20 m length of HDPE tubing (OD: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. Physico-chemical measurements and samples for tracer analysis were taken every 2 hours over each 5-day test. Aqueous samples for bacteriophage analysis were collected in sterile glass universals, fixed with 1 to 2 ml of chloroform, placed in dark, cold storage (<10°C), and analysed within 48 hours. Analysis of chloride in ground water was conducted by colorimetry at the Water Resource Management Department in Entebbe.

To monitor tracer migration and dispersion from the injection well, samples for chloride and phage analysis were obtained directly from the injection well using disposable bailers at regular intervals. The inactivation rate of phage ΦX174 in site ground water was determined by inoculating 1L ground water samples with 1mL of a tite of phage ΦX174 (6×10^8 pfu·ml^{-1}) and storing these samples at 25°C, the *in situ* temperature of ground water. Over a 5-day 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.

Results and Discussion

hydraulic response to pumping

For each forced-gradient tracer test, drawdown (*s*), the derivative of drawdown with respect to the natural logarithm of time ($ds/d \ln t$), and flow dimension (*n*) are plotted versus elapsed time on logarithmic axes in Figure 4. The log-log plot of $ds/d \ln t$ versus time, also known as the "pressure derivative" (Spane and Wurstner, 1993), is a diagnostic tool for constant-rate pumping tests that provides insight into the ground water flow conditions such as the establishment of radial flow and presence of flow boundaries, that operate during the test interval (Walker and Roberts, 2003; Renard, 2005; Tindimugaya, 2007). Analysis of flow dimension (*n*) is based on the generalized radial flow approach of Barker (1988) in which the relationship between cross-sectional area of flow (*A(r)*) and distance (*r*) from the pumping borehole is governed by equation 1 wherein α_n (eq. 2) is the surface area of a unit sphere in n dimensions, Γ is the gamma function, and b is the extent (thickness) of the flow zone.

$$A(r) = \alpha_n \cdot r^{n-1} \qquad \text{(eq. 1)}$$

$$\alpha_n = b^{3-n} \cdot \left(\frac{2\pi^{\frac{n}{2}}}{\Gamma\left(\frac{n}{2}\right)} \right) \qquad \text{(eq. 2)}$$

The flow dimension (n) defines the rate at which cross-sectional flow area changes with respect to distance from the pumping well. Both the pressure derivative and flow dimension 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 which occurred during each tracer test 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 $m^3 \cdot hr^{-1}$ after 72 hours. As a result, the applied hydraulic gradient between the injection and pumping wells increased slightly from -0.066 to -0.086. In 2000, the pumping rate remained fairly constant between 1.7 and 2.0 $m^3 \cdot hr^{-1}$ throughout the test but was interrupted by a temporary cessation of pumping after 21 hours. Apart from this interruption, the hydraulic gradient applied over the entire test ranged from -0.089 to -0.094.

The response of the aquifer to pumping during both tests suggests that it is unconfined. During the 1999 tracer test (Figure 4a), stabilization of drawdown between 4 and 24 hours of pumping is followed by a small but steady increase in drawdown. The former, indicated by negative deflections in the pressure derivative, reflects the contribution of depression storage whereas the latter, supported by a generally constant derivative drawdown between 24 and 72 hours, suggests that gravity storage has been exhausted. A generally similar pattern is observed during the test of 2000 though the stabilization of drawdown indicated by negative deflections in the pressure derivative between 9 and 17 hours, is less pronounced. An unconfined aquifer response to pumping is consistent with the observation that the static water level in each well approximates the depth (17 m below ground level) at which water was struck in the aquifer during drilling (Figure 3).

The establishment of radial-flow conditions during each test is clearly indicated by plots of the pressure derivative and flow dimension (Figure 4). A generally consistent pressure derivative observed after the first day of pumping in each tracer test (apart from temporary disruptions in pumping discussed above), signals radial flow unaffected by constant-head or no-flow boundary conditions. Consistent with this inference, mean flow dimension closely approximates 2 (i.e. radial flow) after the first day of pumping in both 1999 ($n = 1.8$) and 2000 ($n = 1.9$) (Figure 4).

Having deduced conditions of radial flow and unconfined aquifer storage at the test site, the analytical solutions of Neuman (1975) and Moench (1993) for an unconfined aquifer were applied to the drawdown responses in the injection well and closely approximated field observations (e.g. Figure 5). Estimates of hydraulic conductivity (K) for the weathered crystalline rock aquifer derived from each solution are identical (1.2 m·day^{-1}) and consistent with values for this aquifer observed in other areas of Uganda (Taylor and Howard 2000). An estimate of 0.23±0.5 for the specific yield (S_y) is derived from the Moench (1993) solution as it incorporates a correction for the underestimation of S_y recognized in the Neuman (1975) solution.

Solute transport - chloride

The breakthrough curve for the conservative solute tracer, chloride, is plotted versus time in Figure 6. Reported concentrations of the chloride tracer are in excess of a stable, background chloride concentration of 39.4 mg·l^{-1}. Chloride recovered over the test period represents 70% of the mass applied in the injection well. The average linear velocity of ground water flow, based on 50% recovery of applied chloride tracer, is 1.6 m·day^{-1}. An exponential decline in the concentration of chloride in the injection well was observed and follows a decay constant of $1.2 \pm 0.1 \times 10^{-3}$ min^{-1} (Figure 7). Based on deductions from the drawdown response (i.e. establishment of radial flow) and tracer concentrations in the injection well discussed above, a radial dispersion model for a constant source (Moench and Ogata, 1981) was adopted but employed with an exponentially decaying source term. In the solution of Moench and Ogata (1981), radial dispersion is described by numerical inversion of the Laplace transform.

The radial advective-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, separation distance) and the observed half-life of the chloride tracer in the injection well. Estimated dispersivity (α) of 0.8±0.1 m over a distance (x) of 4.15 m is at the upper end of the scale-dependent relationship between dispersivity and distance ($\alpha \sim 0.1(x)$) observed by Gelhar (1986). The radial dispersion model is, however, sensitive to variations in the half-life of the applied chloride tracer in the injection well ($t_{1/2}$). Decreasing $t_{1/2}$ to 4500 min., outside of the error in the regression of the decay constant (Figure 7, Table 1), improves the model's representation of the breakthrough curve (Figure 6) and increases estimated dispersivity to 0.94 m.

Viral transport - bacteriophage ΦX174

Phage ΦX174 was detected in the discharge of the pumping well after 6 hours yet, overall, the phage tracer was largely unrecovered over the period of the test. Laboratory experiments of the inactivation of phage ΦX174 in site ground waters at 25°C yield a half-life of 86 hours (i.e., inactivation rate of 20 to 22% per day or 0.11 log unit per day) that is unaffected 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 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-hour tracer test. The movement of a very small proportion of a microbial source at velocities (17 $m \cdot day^{-1}$) exceeding average linear ground water flow (1.6 $m \cdot day^{-1}$) is, however, consistent with observations in other terrain (e.g. Powell et al., 2003) and 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). A decrease in the concentration of bacteriophage in the injection well was observed during the test (Figure 8). The method of sampling in which bailers are periodically inserted into the injection well 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 injection well from 8×10^6 to 5×10^4 $pfu \cdot ml^{-1}$ over 120 hours can 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 which 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's 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 de-protonated end groups).

At the test site in southeastern Uganda, the pH of ground water (5.7) was below the pI (6.6) of bacteriophage ΦX174 (Dowd et al. 1998) rendering a positive, aggregate charge on the surface of the bacteriophage. 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 are also likely to be retarded under the commonly acidic (pH = 5 to 7) conditions of ground water in deeply weathered crystalline rock. The pI and size of enteric viruses, transmitted by water (Moe 1997), and a series of bacteriophage tracers are summarised in Table 2. Caution must be exercised, however, in drawing simple connections between virus transport and pI as the complexity of virus transport is such that pI not only varies 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 EC water has been demonstrated experimentally (Ryan and Elimelech, 1996; Bales et al. 1997). Field evidence in weathered regoliths is lacking but recent high-frequency sampling of a spring discharge in Kampala, Uganda (Miret Gaspa, 2004) where recharge events coincide with monsoonal rainfall (Taylor and Howard 1999b), shows a strong correlation between recharge pulses and gross contamination of ground water by thermotolerant (fecal) coliforms (Figure 9).

Conclusions

The hydrogeological characteristics of deeply weathered crystalline rock have been estimated, some for the first time, through a forced-gradient tracer test in southeastern Uganda where drawdown in the aquifer was monitored in an adjacent piezometer. The establishment of radial flow conditions within an unconfined aquifer during each test is demonstrated using plots of derivative drawdown and flow dimension. The unconsolidated aquifer at the base of the weathered mantle possesses a hydraulic conductivity of $1.2\ m{\cdot}d^{-1}$ and a specific yield of 0.23±0.05. Application of a radial advective-dispersion model with an exponentially decaying source term to the recovered conservative tracer, chloride, indicates a dispersivity of 0.8±0.1 m over a distance of 4.15 m. The average linear velocity of ground water flow, based on the recovery of the chloride tracer, is $1.6\ m{\cdot}d^{-1}$. Bacteriophage ΦX174, applied to the injection well as a potential field tracer of viral transport by ground water in deeply weathered crystalline rock, is considered to have largely adsorbed to the aquifer matrix. Detection of low numbers of the phage tracer in the pumping-well discharge at early time during the test is, however, consistent with observations in other hydrogeological environments where statistically extreme sets of microscopic flow velocities are considered to transport microorganisms along a selected range of linked ground water pathways.

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Table 1. Estimates of dispersivity (α) from the radial advective-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

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; Dowd et al., 1998)
[2] (Harper, 1993)

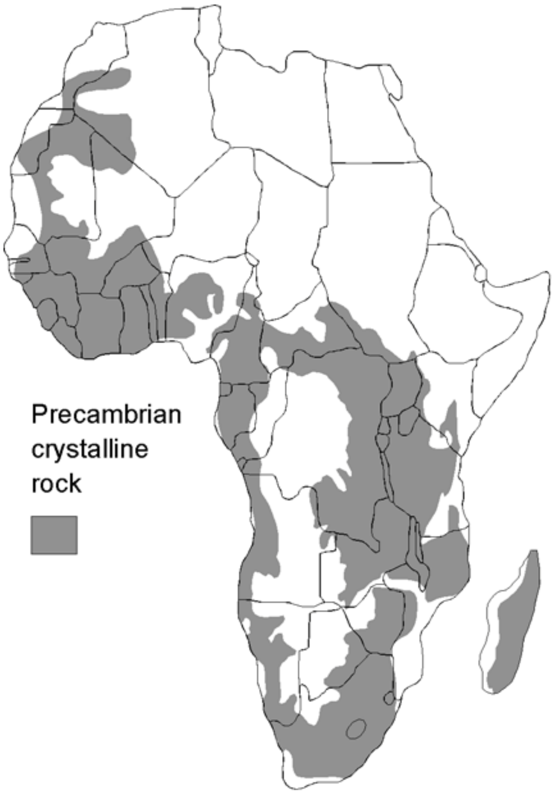

Figure 1. Distribution of Precambrian crystalline rock in Africa (Key, 1992).

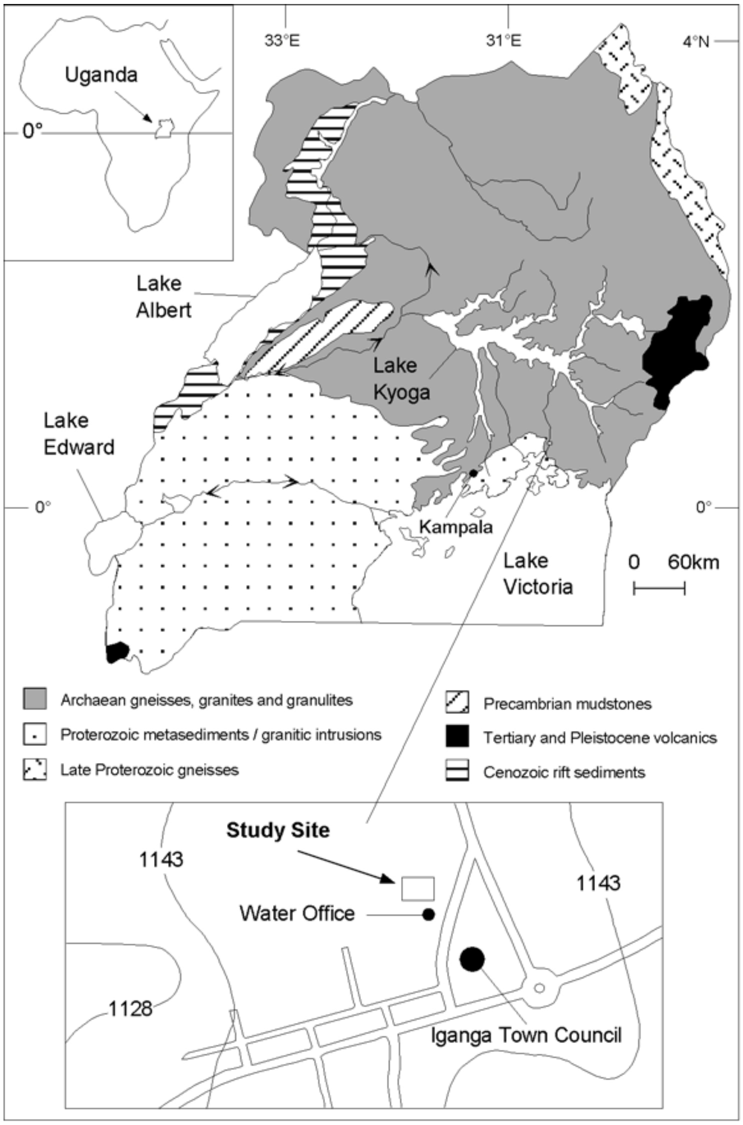

Figure 2. Generalised geological map of Uganda with location of the tracer-test site in Iganga (inset).

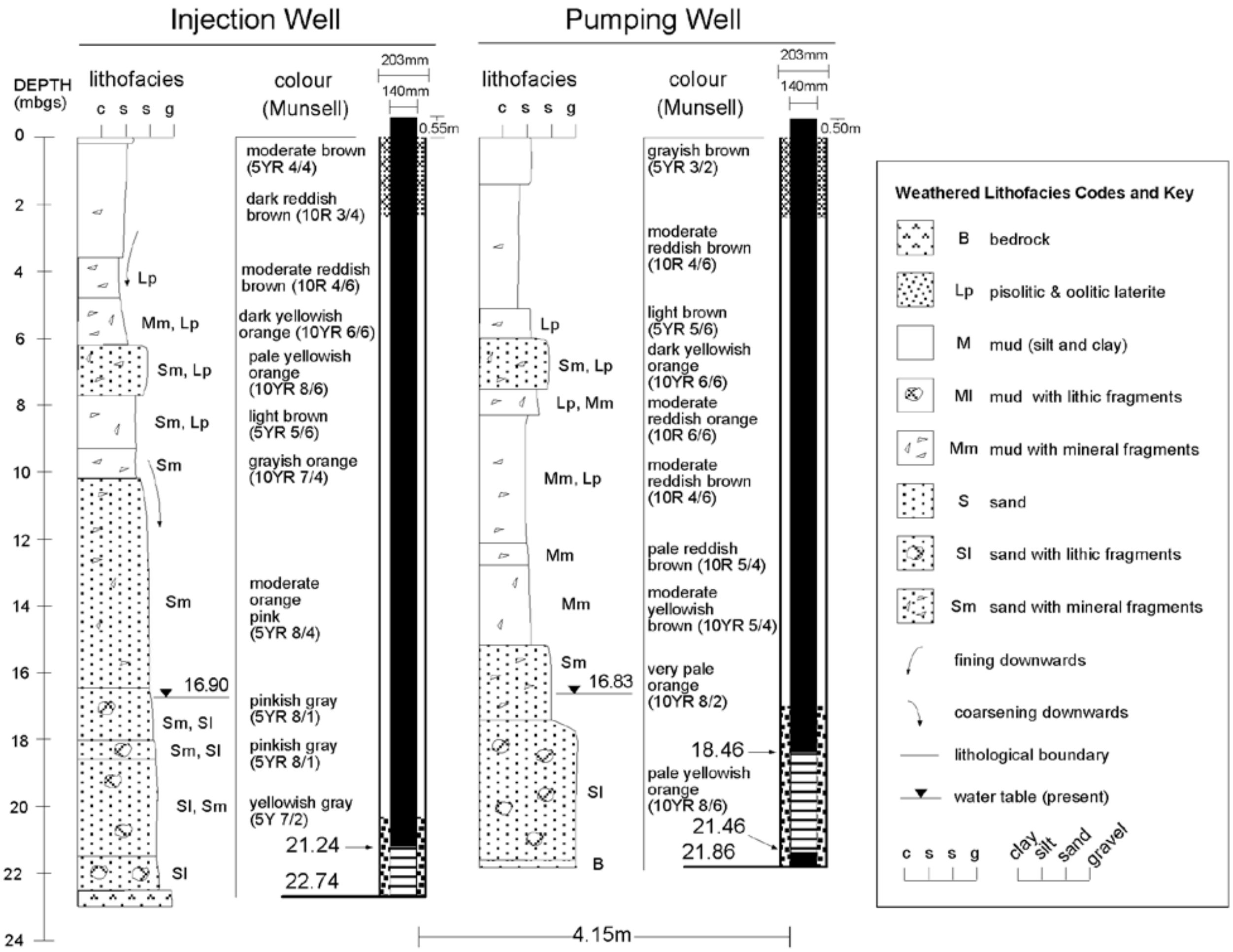

Figure 3. Lithological and borehole construction logs for the tracer-test site in Iganga.

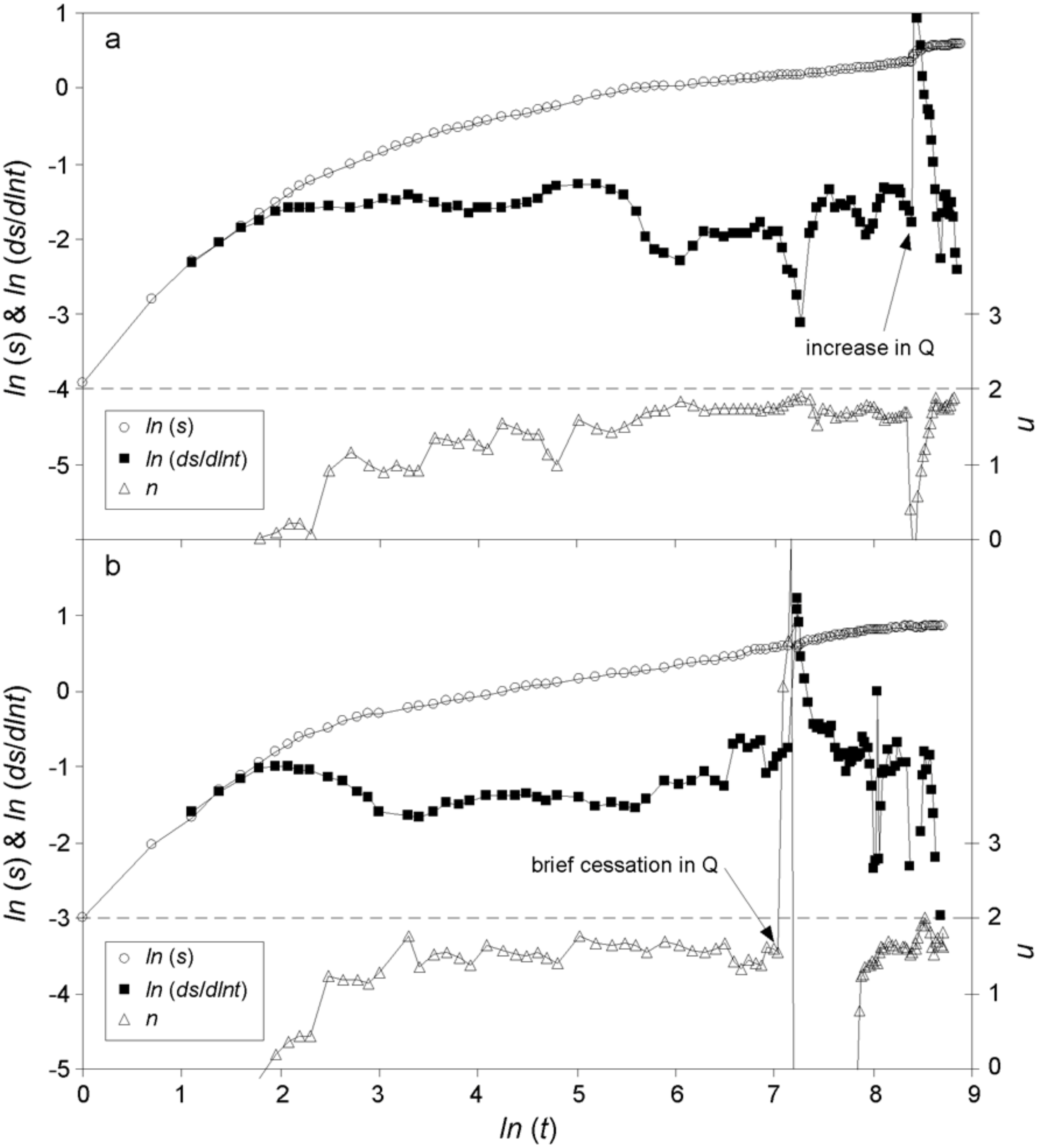

Figure 4. Log-log plot of observed drawdown in the monitoring (injection) well and its smoothed (moving 5-point average) pressure derivative together with the flow dimension along the second, linear axis versus elapsed time for the (a) 1999 and (b) 2000 tracer tests.

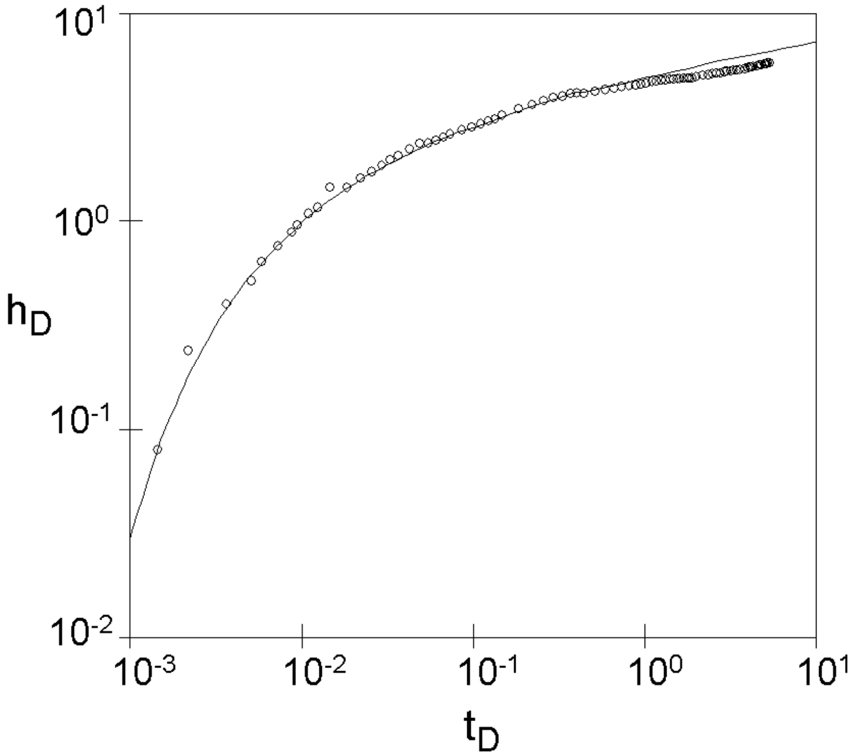

Figure 5. Observed drawdown in the injection well (1999 test) fitted to the Moench (1993) solution for an unconfined aquifer. h_D and t_D are dimensionless drawdown and time respectively as defined by Moench (1993).

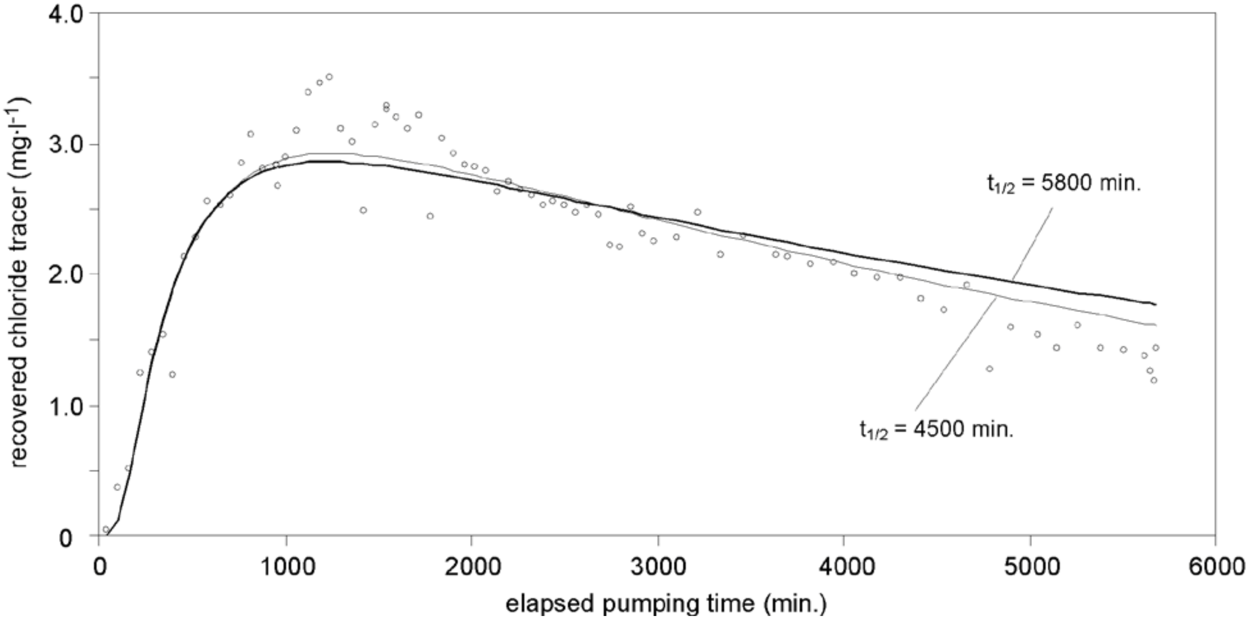

Figure 6. Observed breakthrough curve for the applied chloride tracer fitted by the radial advective-dispersion model of Moench and Ogata (1981) but with an exponentially decaying source term.

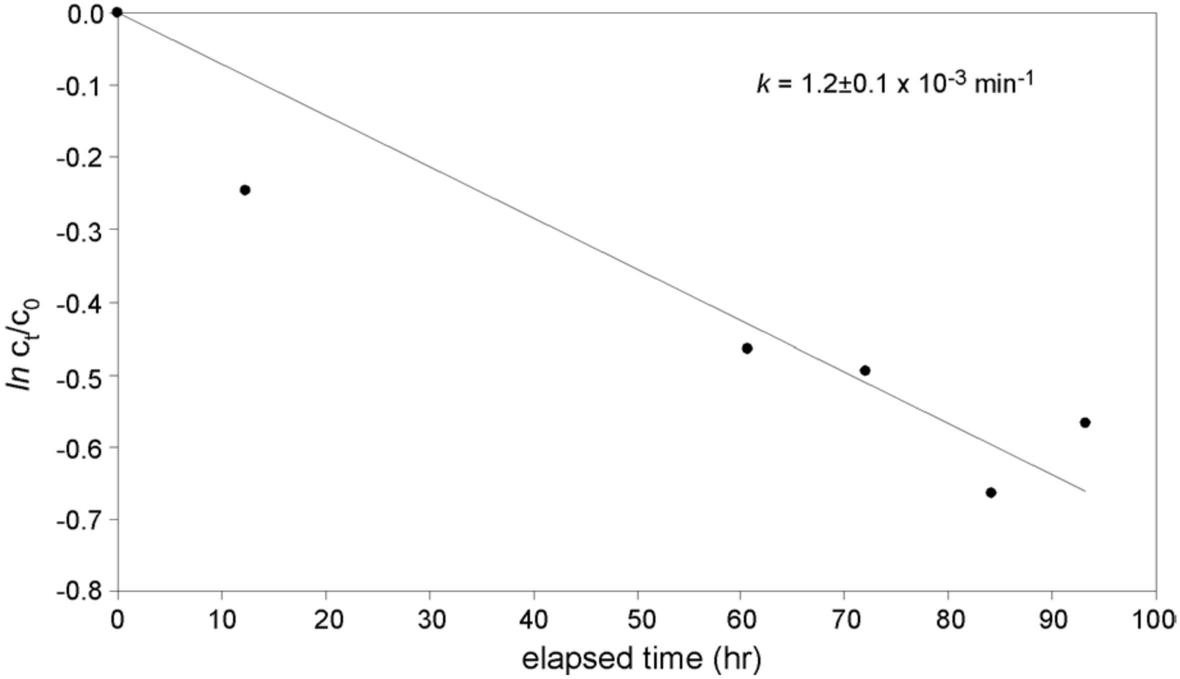

Figure 7. Semi-logarithmic plot of the exponential decline in the concentration of the applied chloride tracer in the injection well versus time.

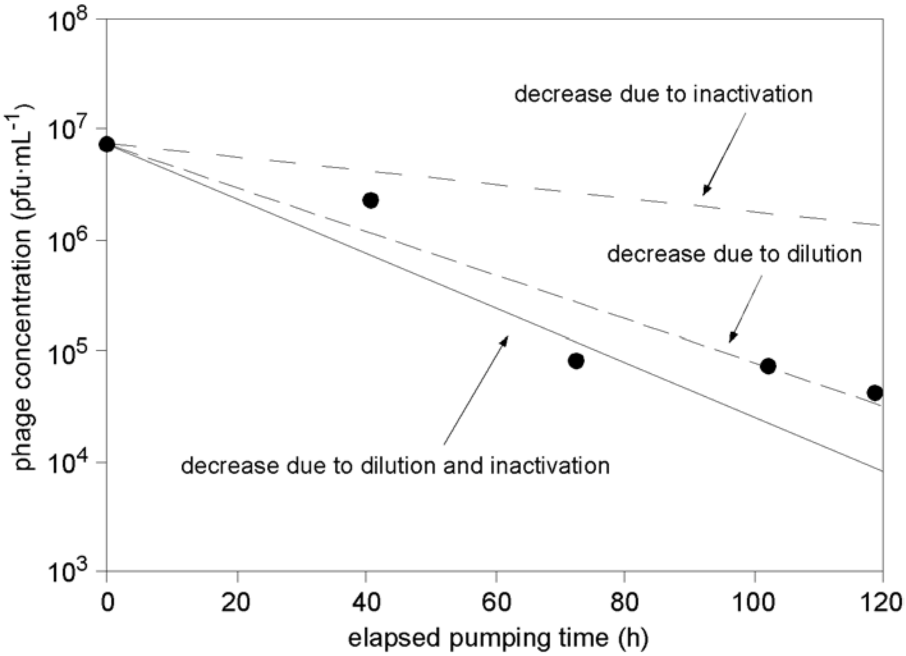

Figure 8. Semi-logarithmic plot of bacteriophage ΦX174 concentrations in the injection well versus time. Decreases in phage ΦX174 concentrations through inactivation, dilution, and both inactivation and dilution are indicated. Inactivation is derived from laboratory survival experiments whereas dilution rate is derived from chloride data in Figure 7.

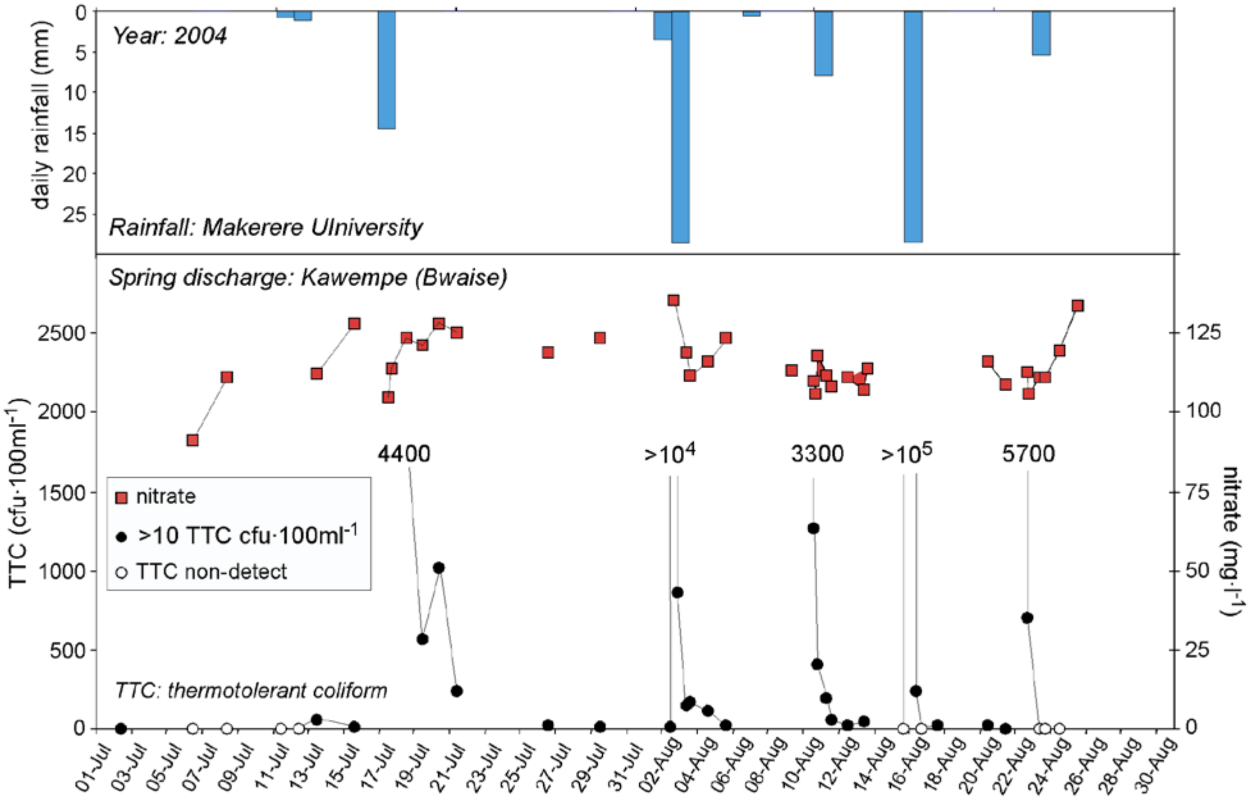

Figure 9. Changes in the concentrations of nitrate and thermotolerant coliform (fecal) bacteria in the discharge of a protected spring in response to rainfall in Kampala (Uganda) during the months of July and August, 2004 (Miret Gaspa, 2004).