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Are Viruses a Hazard in Waste Water Recharge of Urban Sandstone Aquifers?

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Abstract
Urban waste waters will often contain viruses, including human (and, topically, avian) viruses. Use of waste water in artificial recharge therefore requires a risk assessment of virus hazard, and establishing the knowledge needed for this in an example sandstone aquifer is the aim of the present SWITCH project (WP3.2). Presently there is some limited evidence that, even in predominantly matrix flow aquifers such as the Birmingham sandstone aquifer, viable human viruses can be transported to depths of at least 40 m. Horizontal transport distances are (even) less certain, but laboratory studies suggest survival times of < 2 years. To gain the knowledge necessary to develop rules for operation of AR schemes, a four-stranded approach is proposed: (i) field experimentation on a borehole array using bacteriophage as surrogates for human viruses; (ii) laboratory experimentation on intact cores; (iii) monitoring of virus concentrations at multi-level piezometers and pumping wells; and (iv) modelling. Work to date has concentrated on establishing the basic design of the field experiments, and has included hydraulic testing and checking for virus presence in the groundwaters of the test site.

Keywords: virus; phage; sandstone; artificial recharge; ASR; Birmingham; waste water

1 Introduction

Urban waste waters will often contain mammalian, avian, or bacterial viruses. Use of waste water for artificial recharge therefore requires an assessment of risk from viruses to abstraction wells and surface water base-flow, and the development of rules for mitigating this risk. The aim of the SWITCH sub-project described here (WP3.2) is to acquire the knowledge needed to assess this risk for one of the

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Demonstrator Cities - Birmingham. This paper summarizes previous work and outlines the approach being taken to achieve this aim.

The waste waters which might be used in urban artificial recharge schemes are likely to come from: (i) re-routing of storm water runoff; (ii) rainwater harvesting, including from brown/green roofs; and (iii) process water discharges. The types of recharge scheme which could be used include: (i) intensive high-technology well injection of pre-treated waters; (ii) low volume / low technology well injection of partially treated or untreated waters; (iii) basin flooding; and (iv) permeable pavements. It is not possible to investigate all these waste water types and methods of recharge within a small project, and hence we intend to concentrate on the second line of defense - the attenuation capacity of the aquifer: if risk assessment can be economically based on aquifer attenuation, then the necessity of accounting for variation in loadings, waste water compositions, and injection technologies is obviated.

2 The aquifer

The project will be carried out using, as the main example aquifer, the Birmingham Permo-Triassic sandstone (Figure 1). It is a typical continental redbed sandstone of a type found, with relatively minor variations, across and well beyond Europe (Tellam and Barker, 2006). It comprises fluvial and aeolian sandstones, with some minor mudstone beds often less than 0.2m thick. The sandstones contain predominantly quartz, K-feldspar, and lithic framework clasts, with detrital and authigenic clays and often carbonate cement: almost all grains are coated in haematite. It is overlain by a lithologically variable cover of Quaternary fluvial, glacial, aeolian, and anthropogenic deposits (Powell, J.H., et al., 2000) up to at most 30m thick, but often much less or absent (Knipe et al., 1993).

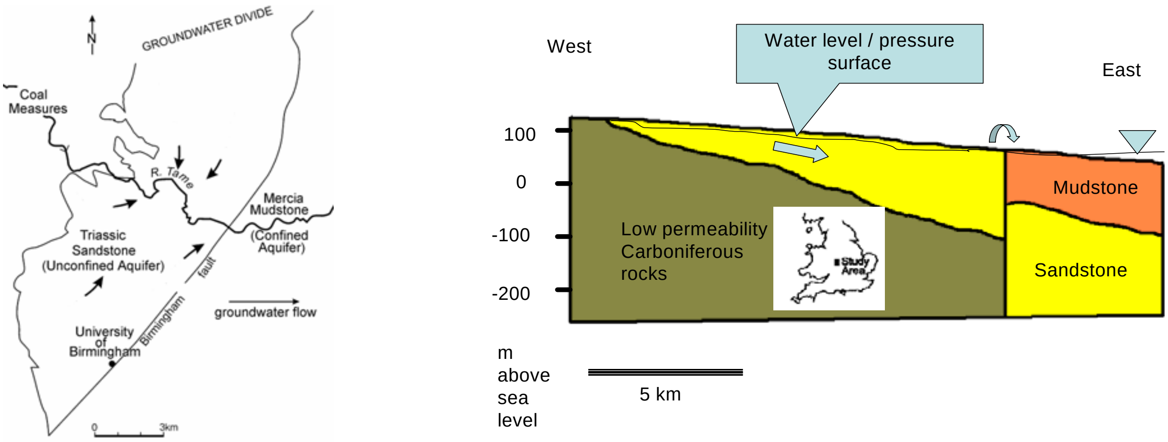

Fig. 1: Outline geological map (with generalized groundwater flow directions) (left) and section (right) of Birmingham. City covers entire area shown on map. From Tellam (In Press).

Median pore sizes of the sandstone are typically a few tens of μm (Digges la Touche, 1998; Bloomfield et al., 2001; Bouch et al., 2006). Matrix permeability typically averages a few m/d, porosity ~ 0.25, and specific yield ~ 0.15 (Allen et al., 1997): the aquifer therefore has a slow response time. Regional-scale rock mass permeability is slightly enhanced by fracturing, though rock mass permeability still does not rise above a few m/d, except around wells where apparent permeability can be significantly increased (Tellam and Barker, 2006).

The aquifer has been heavily exploited, mainly for industrial use. Prior to ~1920, it was also used for public supply, but since 1900, most of the city's water has been supplied by reservoirs ~180 km away in Wales (e.g. Upton, 1993). As a result of this pumping, water levels fell considerably, reaching a minimum at around 1960 after which industrial demand decreased rapidly as manufacturing industry declined (Knipe et al., 1993; Figure 2). Water levels are now rising.

The aquifer attenuation capacity is limited, with modest cation exchange capacity (< few meq/100g usually, but locally to 20 meq/100g), some pH buffering capacity from carbonates, especially below the upper 10m or so of the aquifer, and low organic carbon [f_{oc} (fraction of organic carbon) range 0.001 to 0.15% (Tellam and Barker, 2006)]. Inorganically, well-water quality is on average reasonable, with only median NO_3 (sewage) and possibly Ba (?natural) concentrations close to the UK drinking water standards (Figure 3). Although median concentrations are good, distributions are 'spotty' and locally are very poor (Jackson and Lloyd, 1983; Ford and Tellam, 1994; Ford et al., 1992; Taylor et al., 2006; Tellam, In Press) with the highest heavy metal concentrations exceeding 10 mg/l (Figure 3): wellwater quality is landuse related, with metal-working, the predominant industry, having wellwater chemistry enriched in metals, B, and TDS (Ford and Tellam, 1994). Volatile organic compounds (VOCs) are found in wellwaters at all sites where they have been used, and concentrations appear to be increasing (Rivett et al., 1990; 2005; Shepherd et al., 2006): TCE and TeCE are found at much higher concentrations than the other solvents (Figure 3). Hydrocarbons are only found at much lower concentrations.

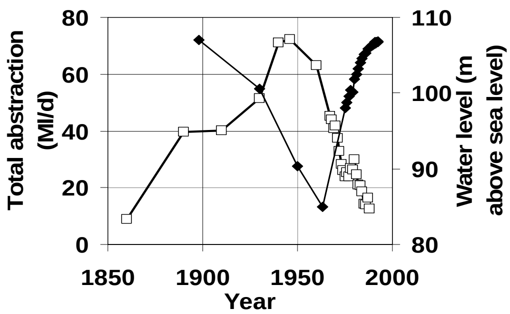

Fig. 2: Abstractions and a hydrograph. From Tellam (In Press).

3 Human virus occurrence in the Birmingham aquifer

Investigations of virus occurrence in urban aquifers are uncommon. However, limited work has been previously undertaken in the Birmingham aquifer, and also in the Nottingham aquifer, the latter being a hydrogeologically very similar system located 80 km to the northeast of Birmingham (Powell, K.L. et al., 2000). Samples were collected from deep industrial wells and shallow, Quaternary deposit piezometers using glass wool traps (Anon, 2000). Viable human viruses were found in four of the five wellwaters, and three of the four piezometer water samples. Both enteroviruses and rotaviruses were found, and although concentrations were usually only up to 1 or 2 plaque-forming units (pfu) / litre, maximum concentrations reached well over 100 pfu/L. These early results were confirmed by data collected from a series of multi-level piezometers in the two cities (Powell et al., 2003). In this latter study, viable human viruses and sewage-associated bacteria were detected, usually at low concentrations, to depths of at least 40 m in the unconfined aquifers. There was also some limited indications at one site of seasonal fluctuations in-phase with expected sewage system discharges, suggesting extremely rapid transport (Taylor et al., 2004; Cronin et al., 2003; Powell et al., 2003).

Although there are few data, it appears that low concentrations of viable human viruses can be mobile in the aquifer, and that therefore the aquifer may be vulnerable to injecting virus-containing waste-waters.

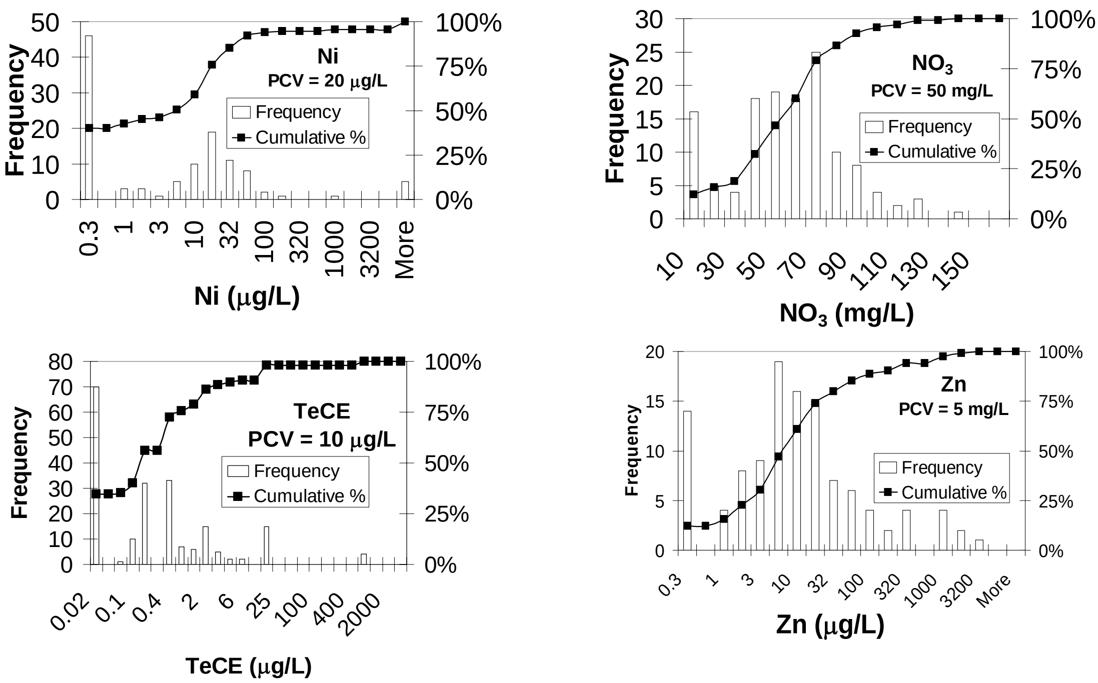

Fig. 3: Concentration frequency plots for the (industrial) wellwaters of the unconfined zone for the surveys of Ford & Tellam (1994) and Rivett et al. (1990). All samples included (number ~ 140; 61 wells). PCV = (UK) prescribed conc. or value. From Tellam (In Press).

4 Experimental studies of virus survival

Recent work using both plaque assay and PCR methods suggests that survival of human viruses in groundwater will be unlikely to exceed 2 years (J. Sellwood, pers. comm.; Joyce et al., Submitted). Typically, in 2 years groundwater travel would be < 100m as estimated using horizontal head gradients. Estimating vertical travel distances is a little more difficult, as vertical permeability is less well constrained, but taking it to be 10% of horizontal, and taking the vertical head gradients measured in the aquifer (Taylor et al., 2003; unpublished data), matrix transport might be 20 to 200 m. However, these vertical flow rates are large, suggesting that effective vertical permeability is much lower than assumed: for a reasonable recharge rate for the aquifer (Knipe et al., 1993; Thomas and Tellam, 2006), an effective vertical permeability consistent with the vertical head gradients would be ~ 5×10^{-4} to 4×10^{-3} m/d. Given the presence of mudstones within the sequence, these bulk permeabilities are not unreasonable: a sequence of 100 m of sandstone of vertical permeability of 0.1 m/d with three 10 cm mudstones of 10^{-6} to 10^{-5} m/d permeability (Tellam and Barker, 2006) would result in a harmonic mean of 10^{-4} to 10^{-3} m/d. At these permeabilities / flow rates, vertical penetration would be very limited within 2 years - a metre or so. As viruses have been recorded to have travelled over at least 60m vertically, it appears that there are fast pathways through the sandstone.

5 Experimental studies of virus mobility

Laboratory experiments on sandstone cores from the Birmingham University campus borehole test site and elsewhere in the UK show that attenuation of bacteriophage is rapid (Joyce et al., Submitted; K. Charles, pers. comm.)(Figure 4). The bacteriophages used were of similar size and point of zero charge to human viruses. Simple up-scaling from the laboratory data suggests that viruses will be almost completely removed within a few metres travel distance. However, experiments have not been completed where all viruses are removed, and the presence of even very low concentrations is still of public health concern.

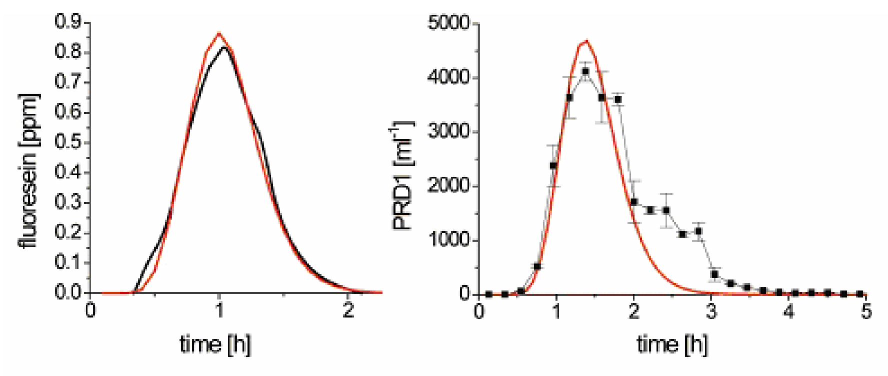

Fig. 4: Laboratory experiment on intact sandstone column showing fluorescein and PRD1 breakthroughs (Joyce et al., In Press). Injection concentrations: fluorescein = 1 mg/L; PRD1 = 36,000 pfu/mL. The core is 4.9 cm long. Solid line is a model fit.

Field experiments have been carried out on the University test site (Figure 5). Phage suspensions were injected in one well in a packered off interval, and recovered by pumping from a second borehole, similarly packered off, 7.5 m distant. A range of phages was used: PRD1, ϕX174, MS2, and H40/1. At all intervals tested, including an apparently fractured one, despite fluorescein breakthrough, no phage were recovered from the pumping well. However, when phage solution was introduced into the whole ~45 m depth of water in the injection well, and the whole depth of the abstraction well was pumped, each of the phages used was recovered, albeit in small concentrations (~few plaque forming units / mL compared with injection concentrations of 10^3 to 10^7 pfu / mL).

It is concluded that there are small numbers of pathways through the sandstone allowing very rapid transport of viruses over distances large enough to threaten well supplies. A possibility is that transport is through fracture networks (Hitchmough et al., Submitted) as suggested by Powell et al. (2003), but there may also be lithological and particle interaction controls as recent work on colloid movement in the sandstone suggests (Rahman, 2006; K.Charles, unpublished data).

6 The SWITCH project WP3.2: issues, design, and progress

From the previous investigations it is clear that artificial recharge of waste water - unintentionally from sewers! - is resulting in virus pollution. However, it is not obvious that this experience is directly transferable to the case of intentional AR schemes where initial concentrations, associated water chemistry, source variation in time, and source frequency will all be different. To evaluate the risk, it is necessary to determine the mobility of viruses in the aquifer saturated zone, both in the horizontal direction and in the vertical direction. If we have a reasonable estimate of the speed and maximum distances of movement, rules can be devised for the operation of AR schemes which will minimize the risk of virus transmission back into the urban population.

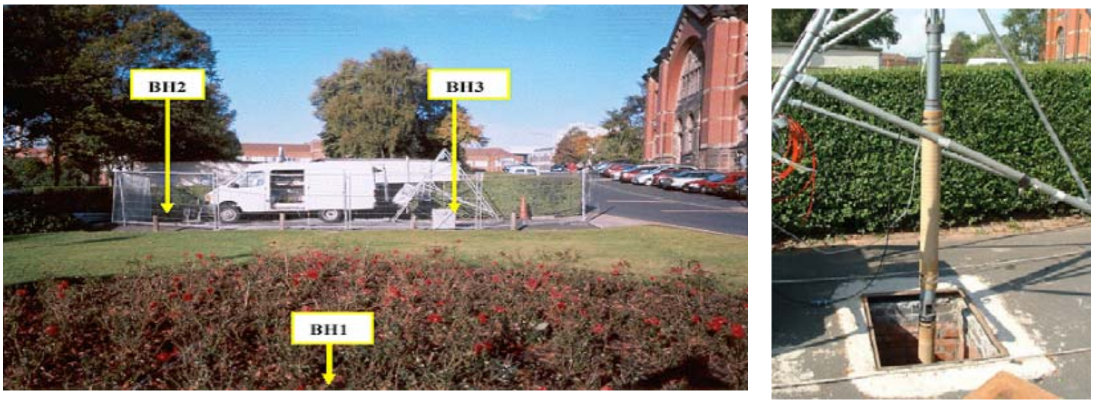

Fig. 5: Birmingham University campus borehole test site.

Four types of investigation will be used to provide the required information: (i) field experimentation; (ii) laboratory experimentation; (iii) field monitoring; and (iv) modelling. As human viruses cannot be used in field experiments, the main source of information on *in situ* mobility will be the monitoring data, despite the concern mentioned above relating to the differences between sewer and AR sources.

(i) field experimentation: The least attenuation of viruses would be expected in an aquifer storage recovery (ASR) scheme, where the injection borehole is used as the pumping borehole, flow rates are high, the same volume of aquifer is repeatedly used, and the injection is directly into saturated aquifer. Accordingly, we intend to undertake small-scale ASR ‘push-pull’ pumping and injection cycles on the University borehole test site (Figure 5). Potential variables to be investigated include pumping rates and times of equilibration. To extend our knowledge of the mobility of viruses in the horizontal direction over a greater distance, a borehole-to-borehole test between two wells separated by 20 m will be undertaken (greater distances are technically impossible within the time-frame of the project): this test will involve the full saturated depth of the wells.

Work has begun on this aspect of the study. Intervals where virus suspensions had been last injected just over a year previously were pumped and sampled for phage (Ferguson, 2006). No phage were detected. This does not mean that the viruses have been inactivated, as they may have been transported further into the aquifer by the regional flow. To investigate this possibility, and to provide the necessary detailed hydraulic understanding of the test site, new hydraulic testing has been also undertaken, and a re-evaluation of the aquifer/borehole system undertaken (Ferguson, 2006). Further testing will commence in early 2007.

(ii) laboratory experimentation: Depending on available resources, it is intended to back up the field experiments with some limited laboratory testing of intact cores. In these experiments, virus solutions will be injected and monitored until constant breakthrough is achieved. The flow will then be stopped. After a period of time, the cores will be flushed by virus-free water but in the direction opposite to that used during injection, the breakthrough again being recorded. The flushout phase may include a stepped increase in flow rate to examine velocity-dependent effects.

(iii) *field monitoring:* Field experiments cannot be undertaken using human viruses, and therefore the only way to gain information on their mobility is to monitor real systems. Previous sparse piezometer monitoring data on one piezometer system has indicated that virus concentrations may possibly vary seasonally in phase with expected variations in the general population (§3). If this can be confirmed, we will have a much more refined *in situ* measure of virus transport speeds in the vertical direction. Thus we intend to monitor the multi-level piezometer nest where the variation in virus populations has previously been observed: the monitoring will be ~ monthly over a period of around 1.5 years. To attempt to see whether any seasonal variation in virus populations is commonly found in deep groundwaters, we will also install virus traps on pumping wells, provided owners are willing for this to be done. Such data will also yield more information on the scale of the virus pollution, an issue irrespective of where any recovery well is located.

(iv) *modelling:* Numerical modelling will be an integral part of the project, for designing the field tests, for interpreting their results, and potentially for extrapolating to other cases. It is expected that a range of modelling approaches will be undertaken, using widely available groundwater flow and transport packages and also in-house software developed for previous virus and other studies.

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