Reconnaissance tracer tests in the Triassic sandstone aquifer north of Liverpool, UK

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Abstract

Three tracer tests were carried out by slug injection of fluorescein, amino-G-acid, and bromide at piezometers with 0.4 m long intake zones located 5 m distant from an 80 m deep pumping borehole. The piezometer intake zones were about 2 m (Tests 1 and 2) and 18 m below static water level, and the pumping borehole was sealed using a packer at about 11 m (Tests 1 and 2) and 19 m below static water level. Analytical expressions were used to interpret the data. Test 2 was unsuccessful.

Four pathways were discernible from the Test 1 tracer breakthrough curves. These pathways were interpreted as being due to three dominantly fracture routes and one dominantly intergranular flow route. The earliest (sharp) peak arrived after a few hours, and the last (broad) intergranular flow peak arrived after around 40 hours. Fluorescein was delayed slightly (retardation factor = 1.4) relative to the other tracers. In the deeper Test 3, three pathways were discernible, with concentration peaks at about 9, 25, and 78 hours. Fluorescein was delayed relative to amino-G-acid (retardation factors = 1.25 and 1.5) in the second and third pathways. As with the first test, the last peak was very broad, suggesting a variety of intergranular routes through the rock, and possibly the effect of diffusion.

The tests clearly demonstrate the importance and complexity of fracture flow over short distances in the Triassic sandstones, the complexity of the intergranular flow routes, and that different retardation factors can be associated with different pathways.

Keywords: dye tracers, sandstone

Relatively little is known of solute transport processes in the UK Triassic Sandstone aquifer systems. Most information has accumulated through observations made following pollution incidents: however, this information tends to be qualitative and poorly constrained. Tracer tests, which, in principle, are much more tightly constrained and can be interpreted quantitatively or at least semi-quantitatively, have been little used for testing the Sandstone. A recent survey (Ward *et al*. 1998) could find records of only three tracer tests in the UK Triassic Sandstones: the first was a forced gradient test using bacteriophage in Yorkshire (Ward *et al.* 1998); the second was a borehole to (dewatering) tunnel test, in Liverpool, using fluorescein (Barker *et al*. 1998); and the third was a forced gradient, borehole to borehole test using several tracers in the Merseyside aquifer (Green 1994). This paper concerns the last of these tests, together with subsequent testing undertaken at the same site (Hamilton 1995; Betts 1996). The work was carried out as MSc student projects on very small budgets, and thus compromises were made which limited the extent of subsequent interpretation. Nevertheless, even such *reconnaissance* tests can provide useful information on flow mechanisms.

Methods

Summary of tests

Three tracer tests were attempted at a disused railway cutting site at Haskayne in south Lancashire (SJ357089) (Fig. 1). All three were forced gradient tests involving injection of fluorescein, amino-G-acid, and bromide tracers at one of the piezometers in a piezometer nest (Borehole 2; Fig. 1), and recovery from above a packer in a pumping borehole 5 m away (Borehole 4; Fig. 1). Test 1 was undertaken from the piezometer intake at 6 m depth, with the recovery borehole packered at 15 m depth. Test 2 was a modified rerun of Test 1, but proved unsuccessful. Test 3 used the 20 m piezometer with the recovery borehole packered at 23.5 m depth. The following subsections provide the necessary detail on the site, tracers, and the methods employed.

Site details

The Haskayne Test Site (HTS) was developed during a Natural Environment Research Council (NERC) investigation of flows in open boreholes (Tellam *et al*. 1993). The site has four boreholes (Figs 1 & 2), two of which (numbers 2 and 4) were used in this study. Borehole 2, 80 m deep, was converted into a piezometer nest around 1980 by North West Water Authority (University of Birmingham, 1984); the 0.4 m long piezometer screens are at approximately 6, 20, 40, and 80 m below ground level, and are separated from each
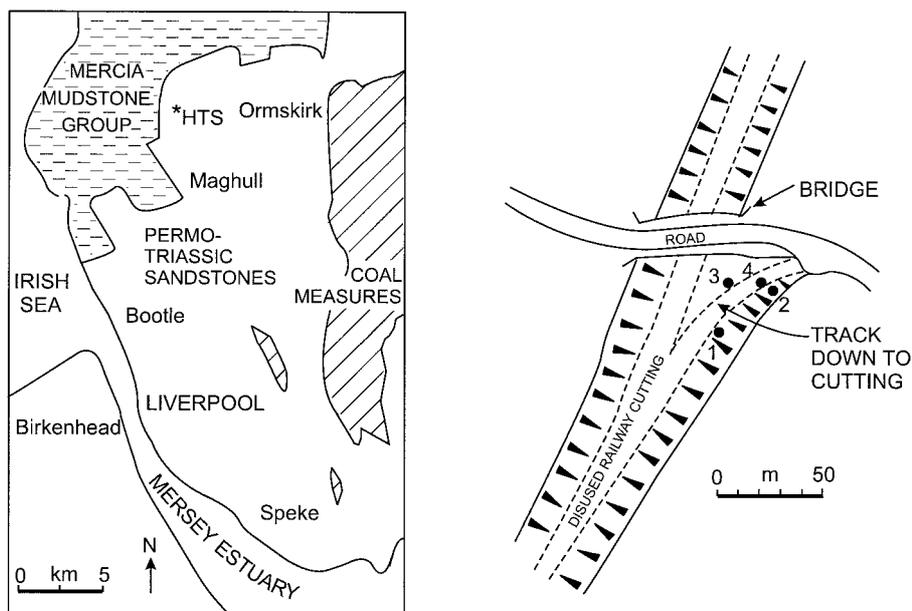
Fig. 1. (a) The location of the Haskayne Test Site (HTS) showing regional bedrock geology. (b) Plan of the site (numbers refer to borehole numbers).

other by grouting. As part of the NERC study, Boreholes 3 and 4 were drilled to 85 m depth. A 'Solinst' Waterloo multilevel sampler was fitted in Borehole 3. Borehole 4 was completed as an open hole of nominal 8 inches (0.2 m) diameter: solid casing is installed to 4 m bgl (below ground level). Pressure transducers and gas-drive samplers are installed in all piezometers and Waterloo ports.

The water level at the site is around 3–5 m bgl. The boreholes are all completed within the Ormskirk Sandstone Formation, the upper unit of the Sherwood Sandstone Group. The sequence consists of fine to medium-grained, 'bleached' sandstones, with three mudstones, totalling 2 m in thickness, at around 70 m bgl. There is a vertical downward head gradient of 3 m in 80 m at the site. Boulder Clay overlies the Sandstone, but this was mostly removed during the construction of the railway cutting.

Near ground surface the groundwater composition is dominated by calcium and sulphate, with moderate chloride concentrations. At depth the waters are calcium and bicarbonate dominated, and have lower chloride concentrations. All waters are calcite-saturated, with neutral pHs, and very low nitrate concentrations. The waters are moderately reducing, with high Fe concentrations. Pumped water compositions from the site were classified by Tellam (1996) as being of Type 2, a mix of deeper older waters and induced recharge through the drift deposits.

Pumping tests, laboratory tests on core material from Borehole 3, and multilayer modelling have indicated that most of the sandstones at the site have a bulk hydraulic conductivity of 1–5 m/d (Fig. 2) and a porosity of around 0.2 (Segar 1993). CCTV, calliper, and core logging indicate fractures to be common, as shown on Figure 2.

Information on the Haskayne site is given by Segar (1993), and Jones & Lerner (1995) (the latter paper refers to Haskayne as 'Plex Moss', and the borehole which was used for most of the experiments described was Borehole 4).

Choice and analysis of tracers

It was decided to use low reactivity tracers, and the Environment Agency approved the use of bromide (as KBr), sodium fluorescein, and amino-G-acid. An Orion specific ion electrode was used to analyse for Br. Background concentrations are around 0.7 mg/l Br. Fluorescein and amino-G-acid concentrations were determined by fluorimetry (Perkin Elmer 204-A fluorescence spectrophotometer). The fluorimeter measurements were found to be reproducible to within less than 2.5%. pH values were checked, and modified, using KOH, to lie between 7 and 10 (Smart & Laidlaw 1977). The spectrophotometer was zeroed using a pre-tracer test groundwater sample, as the natural groundwater fluoresces, albeit at low intensities. Any sediment in the samples appeared to have negligible affect on the fluorescence measured, as unshaken and shaken samples gave indistinguishable results. To avoid photodegradation, samples and tracer solutions were stored in the dark, and exposure to sunlight was minimized.

Previous studies had indicated that no reaction of fluorescein, amino-G-acid, and Br with Triassic Sandstone could be detected (Bashar 1997). Batch experiments were carried out to confirm this for the fluorescent dyes using heavily crushed core material from Borehole 3 at Haskayne. The results indicated less
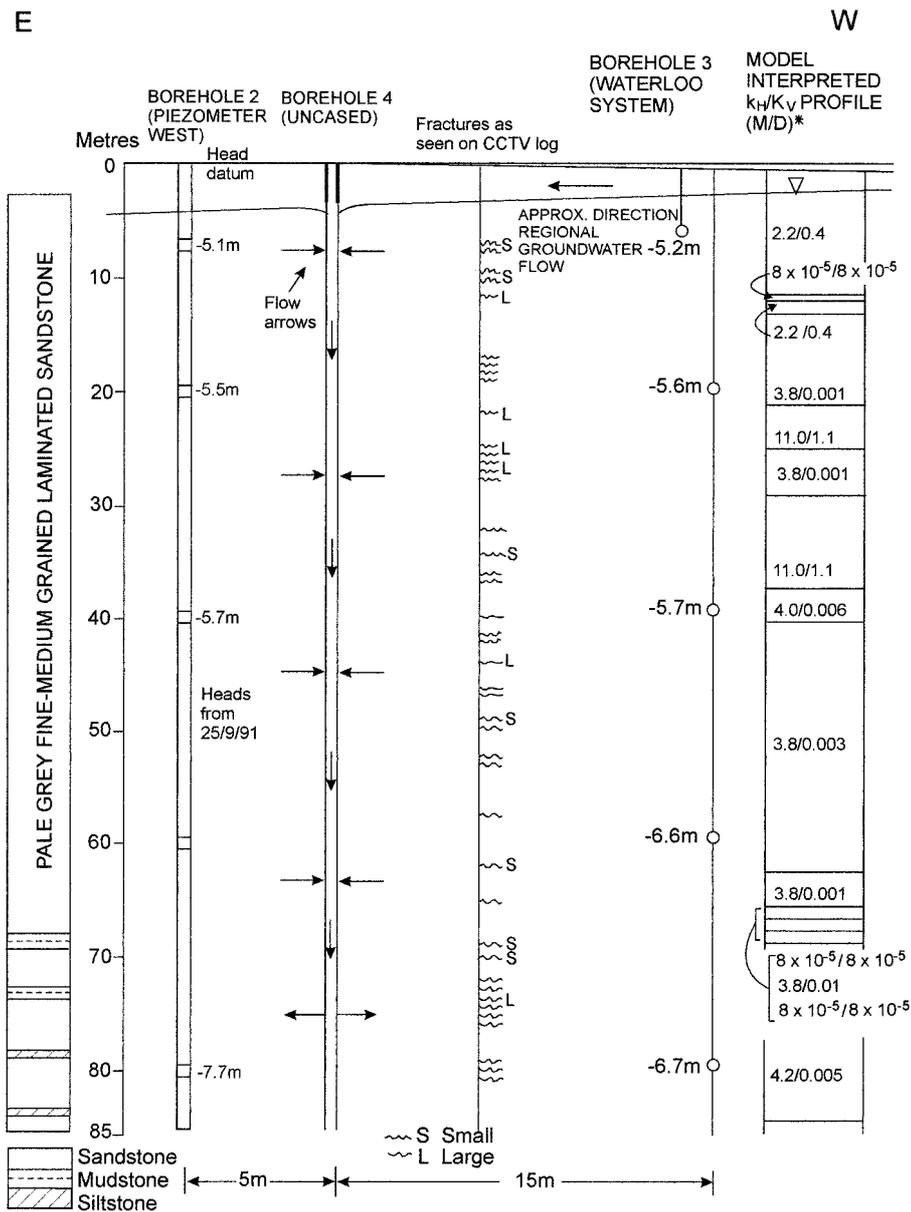
Fig. 2. Hydrogeological features of the HTS (modified from Segar, 1993).

than 3% sorption, but insufficient time was available to repeat the experiments with a sufficiently large number of samples to improve the experimental resolution. Sample bottles and peristaltic tubing have an undetectable effect on measured fluorescence when using 10^{-4} g/l fluorescein and 10^{-3} g/l amino-G-acid.

Tracer Test 1

Borehole 4 was chosen as the abstraction well. Preliminary testing and calculations indicated that tracer dilution factors and flushing times would be too great for the tests to be conducted by pumping from the whole depth of the open borehole. Hence a gas-inflatable packer was used to seal the borehole at about 15 mbgl: static water level was at 3.4 mbgl. The packer increased the drawdown from 0.7 m to 2.9 m when pumping at 0.7 l/s. Pumping at this rate gives an expected average tracer residence time of around 60 hours. The pumped water was discharged in the cutting at a distance of 50 m from the pumping borehole.

The tracer injection point was chosen to be the 6 m depth piezometer in Borehole 2. The tracer solution was injected using a funnel and tube connected to the gas inlet of the sampler already installed in the piezometer (Fig. 3). The piezometer screen is set between 5.7 and 6.1 m below the top of the casing, and when the test was carried out the static and pumped water levels were
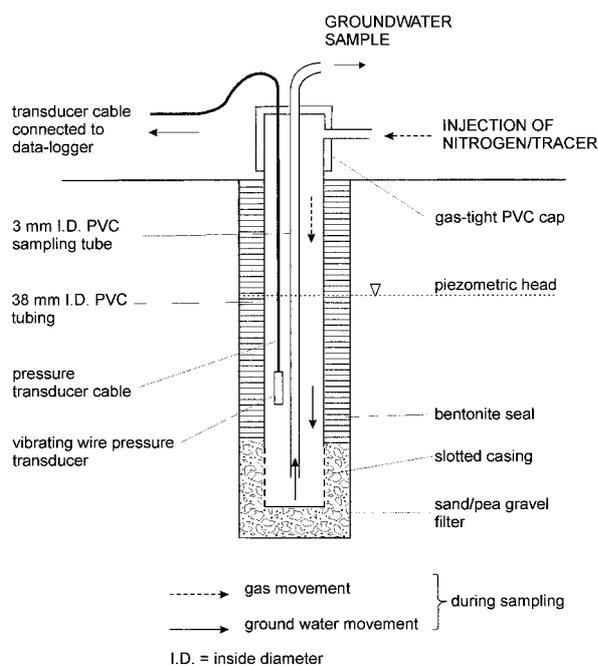
Fig. 3. A cross section of a piezometer in Borehole 2.

at about 2.5 and 2 m higher than the top of the screen, respectively. Although this injection method is far from ideal, it was thought to be the only practicable method at the time.

The tracer concentrations used in Test 1 were: 2 g/l fluorescein; 2 g/l amino-G-acid; and 12 g/l potassium bromide. Six litres of the tracer mixture were injected into the gas port of the piezometer once steady-state had been achieved in the pumping borehole.

The test was conducted from 9–13 August 1994. Samples were taken from the pumped discharge every 15 minutes for the first 3.5 hours and at 30 minute intervals thereafter to 73.5 hours. It was not possible to monitor concentrations in the injection piezometer. During the test, heads were monitored in the pumped borehole and in the injection borehole at the 20, 40, and 80 m piezometers. Steady-state was achieved in the pumping well within 10–20 minutes.

Analysis of these data, and similar data obtained during Test 2, indicated a hydraulic conductivity of about 1 m/d, similar to the value of 2.2 m/d estimated by Segar (1993) on the basis of detailed modelling of a pumping test at the site. The value also agrees with the value of 1.3 m/d obtained using a Bouwer & Rice (1976) interpretation of a slug test carried out during Test 2.

Apart from a rise of about 20 cm after about 30 hours caused by a temporary partial deflation of the packer, the head in the test well remained almost constant throughout the test. Heads in the piezometer nest showed a variation of up to 20 cm on 9 August, but thereafter varied by at most 5 cm.

Tracer Tests 2 and 3

Tracer Test 2 (4–7 August 1995), using recirculated injection in the 6 m piezometer, failed due to greater dilution than expected.

Tracer Test 3 was designed to test solute movement from the 20 m piezometer in Borehole 2 towards Borehole 4, when abstracting from Borehole 4 from above a packer set at 23.5 m bgl. The test was carried out between 4 and 6 August 1996.

Samples were taken from the 20 m and 6 m piezometers, and from the water surface and 10 m depth in Borehole 4 prior to the test to determine the background tracer concentrations. It was found that, at the water surface in Borehole 4, concentrations of the tracers were 1.5×10^{-2} mg/l fluorescein, 6.3×10^{-2} mg/l amino-G-acid, and 1 mg/l Br.

A slug test in the 20 m piezometer indicated recovery within about 120 s, corresponding to a hydraulic conductivity of a little under 1 m/d.

The tracer solution contained 20 g/l KBr, 3 g/l fluorescein, and 3 g/l amino-G-acid. Aluminium oxide colloids were also added to the solution, but no breakthrough was detected.

The tracer solution was injected before abstraction began. This procedure avoided the use of a positive head during the test itself, and as steady-state was rapidly achieved, any effects due to the unsteady-state phase of pumping are likely to be small. The piezometer head was removed and a weighted length of 4 mm ID plastic tubing was lowered to the base of the piezometer, 10 litres of tracer solution were poured into the tubing, followed by one litre of groundwater. When the piezometer started to overflow, the injection hose was withdrawn and three litres of water bailed out of the top of the piezometer.

The slow acceptance of the tracer solution by the piezometer is probably due to the clogging of the piezometer screen by the aluminium oxide colloids in the tracer solution. Consequently, the injection signal is unknown in detail, and is a variable which requires interpretation. A slight but continuous drop in head in the 20 m piezometer during the test indicates that a small positive head might have existed between the piezometer and aquifer.

Once the head in the piezometer had apparently stabilized after injection of the tracer, the pumping from Borehole 4 was started. Heads in Borehole 4 and in the 6 m and 20 m piezometers of Borehole 2 were monitored throughout the test: steady-state was achieved in 120 minutes, and the pumping rate remained constant at 0.8 l/s. Samples were taken every 15 minutes for the first 24 hours, then every 30 minutes. Periodically samples
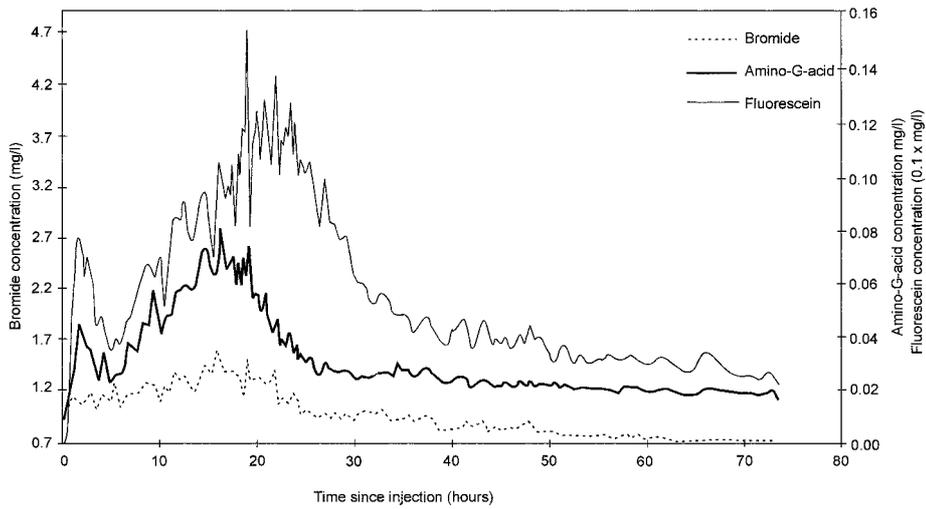
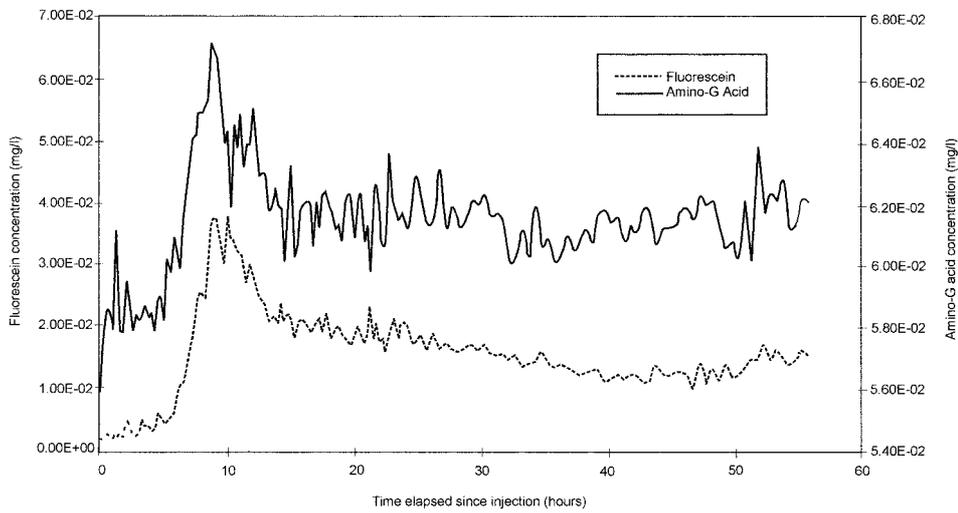**Fig. 4.** Tracer breakthrough curves for Test 1.

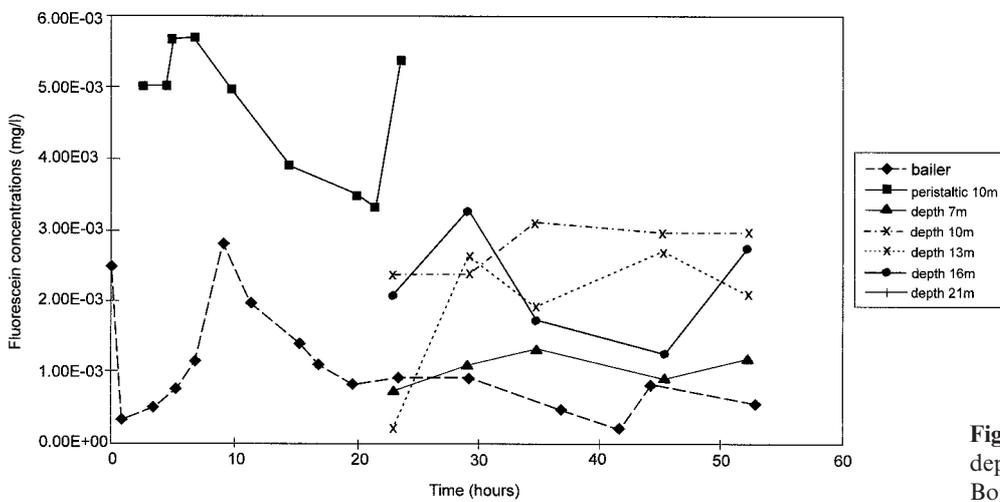**Fig. 5.** Tracer breakthrough curves for Test 3.

Fig. 6. Variation with time and depth of fluorescein in Test 3 in Borehole 4.

were also taken from the water surface and various other depths in Borehole 4. All samples were analysed as described in the accounts of Test 1, both in random order and subsequently in time-sequence. The Br concentrations were all too low for the specific ion electrode to produce consistent results.

Results

Figures 4 and 5 show the results from Tests 1 (6 m bgl injection level) and 3 (20 m bgl injection level). Figure 6 shows how tracer concentrations vary with time and depth in the abstraction borehole during Test 3.

Analysis

Preliminary qualitative assessment

From Figures 4 and 5, it is clear that at both 6 and 20 m levels several fairly distinct pathways are present between injection and recovery points. Taking average total intergranular porosities for the two depths (Segar 1993), the calculated average breakthrough times were 60 hours for the 6 m test and 80 hours for the 20 m test. As the main concentration peaks are as early as a few hours, it is likely that there are some faster than average pathways, and it is probable that these are fractures. The last, broad peak probably represents intergranular flow breakthrough.

In Test 1, and possibly in Test 3, the fluorescein breakthrough is retarded relative to the amino-G-acid and bromide breakthroughs, suggesting that sorption is occurring. This is also suggested by the fact that the fluorescein concentrations in the pumped water are much lower than amino-G-acid concentrations, despite the fact that the tracers were injected at the same concentration. As amino-G-acid and Br breakthrough curves coincide, it is likely that neither is sorbed to the sandstone. Some degradation of fluorescein may also be occurring.

Tracer recovery is low, with fluorescein recovery being less than amino-G-acid recovery. The total mass of fluorescein recovered during Test 1 as a percentage of the injected mass was 11%; for amino-G-acid, the recovery was 50%.

The total mass of fluorescein recovered during the period of Test 3 was 9% of the total mass injected, compared with 35% for amino-G-acid. If background concentrations from pumping tests are subtracted, these figures become 8% and 17% respectively. If the breakthrough curve is extrapolated using the model described below, 27% of the fluorescein mass and 43% of the amino-G-acid mass above presumed background would have been recovered had pumping continued longer. The low amino-G-acid recovery is probably caused by non-ideal injection conditions, and by diffusion into zones of less mobile water.

All pumped water tracer concentrations in Tests 1, 2, and 3 show minor fluctuations (Figs 4 & 5). A proportion of the minor peaks and troughs are formed by several samples, and all these fluctuations were reproducible irrespective of the order of sample analysis. Differences in sediment content, groundwater chemistry, and bottle contamination were shown by various tests to be incapable of producing the observed fluctuations. It is conceivable that each peak represents a discrete flow path: however, it seems likely that tracers passing through *c.* 50 pathways in such a small vertical interval would result in discrete peaks at the sampling well. Hence it is assumed that the minor peaks arise through variable mixing in and around the pumped well. This implies turbulent flow in a system with strong concentration gradients. A calculation of the Reynold's Number for the pumping borehole indicates that conditions are likely to be on the point of turbulence, and probably turbulent in the vicinity of the pump itself. Similarly, calculations suggest that turbulent flow may be occurring within the fractures immediately around the borehole. It is clear from the breakthrough curves and from the depth plots shown in Figure 6 that concentrations vary considerably with depth.

Semi-quantitative interpretation: approach

Given the complexity of the sandstone system and the problems experienced in injecting the tracers, a rigorous quantitative interpretation is not possible. However, a semi-quantitative analysis is possible, and instructive.

The radial flow tracer transport solution of Moench (1989) was used to investigate the tracer test breakthrough curves. Although the solution is not ideally suited to the tests carried out in the present study, it allows the construction of a self-consistent description of the results. The calibrated parameters of this approximate model are believed to be indicative of the transport parameters of the aquifer at the scale tested. Moench (1989) supplies a Laplace transform solution to the standard partial differential equation for radial flow with advection-dispersion. The solution requires numerical inversion, and this was achieved using a code written by Noy (1993).

Moench (1989) assumes that: a vertical pumped well fully penetrates a horizontal, homogeneous (but dispersive) isotropic aquifer; a steady-state, horizontal, radially convergent flow field is established prior to tracer injection; the tracer is introduced into the aquifer via a fully penetrating well without disturbing the flow field; the injection well diameter is small with regard to the distance to the pumped well; the tracer is either continuously injected, or (as in the present case) injected as a slug which is progressively diluted by through flow; the tracer is transported in the aquifer by radial

advection towards the pumped well and by Fickian mechanical dispersion; the tracer concentration is sufficiently small that density effects can be neglected; and the tracer is either unreactive, or subject to linear reversible sorption.

The model predictions were fitted by trial and error to the data. As described above, the test breakthrough curves were characterized by several peaks in the tracer breakthrough curves. The decision was made to model the minimum number of pulses which would produce an adequate representation of the breakthrough curves. Each major pulse was modelled separately, and the predicted concentrations combined to provide the pumped well concentrations. This approach assumes that there is negligible diffusional interchange with slower moving water. In each case, the earlier pulses are better constrained, as the fits for the later pulses include the sum of the errors in fitting the earlier pulses. Once a fit was obtained, sensitivity analysis was used to determine how stable it was. Undoubtedly the final models, as is usually the case in environmental modelling, are not unique. T.C. Atkinson (personal communication, 2001) has found that the results can be sensitive to the order in which the pulses are considered.

The same hydraulic constants were used to fit all the different tracer breakthrough curves associated with a particular concentration pulse in a test. The hydraulic and other parameters which were varied in order to get an adequate representation were:

(i) flow rate in each pathway;
(ii) initial concentration at the injection point for each pathway;
(iii) dispersivity for each pathway;
(iv) thickness for each pathway;
(v) porosity for each pathway;
(vi) tracer decay rate at the injection point; and
(vii) retardation factor for each pathway.

The constraints on each parameter and the reasons for varying them are discussed below.

The summed flow rate for each pathway (parameter (i)) must be a realistic proportion of the total pumping rate for the geometry and hydrogeology of the test concerned, and must satisfy the constraint of the masses of tracer recovered. Parameter (ii) is considered a calibration parameter because the injection methods may well result in spatially varying initial tracer distributions, and hence a spatially varying injection zone decay function. The sum of the thicknesses for each pathway (parameter (iv)) must add up to not more than the saturated depth at the pumping well, and not less than the thickness of the injection piezometer screen length. However, there is little control over the choice of the product $d\varphi$, where d is the thickness of a particular pathway, and φ is its kinematic porosity. Porosities must, of course, lie between 0 and 1. For the peaks thought to be associated with fractures, the porosities

were set to 1, thus ignoring the possibility of fracture fill material.

The tracer decay rate (parameter (vi)) describes the rate of decay of concentration in the injection well due to groundwater flow towards the well. The rate will be exponential:

$$C = C_0 \exp(-bt)$$

where C is concentration at the time t, C_o is initial concentration, and b is the decay constant. This decay equation was incorporated into Moench's (1989) slug injection option. When modelling the field data, the decay rate was kept at the same value for all pathways. In Test 1 the tracer was injected under a positive head gradient, and the assumption of passive dilution from lateral groundwater flow through the piezometer is not ideal. In both Tests 1 and 3, the fluorescein was delayed relative to the amino-G-acid, and it was assumed that the delay was due to linear sorption onto the aquifer (parameter (vii)). It was also found necessary when modelling to reduce the initial concentration of the fluorescein in the injection piezometer relative to the amino-G-acid (see discussion of Test 1 interpretation).

In the tests analysed here, the *well mixing factor* was very small, and flux-averaged results approximate resident concentrations (see Moench 1989, p 443).

Semi-quantitative interpretation: Test 1

Although not strictly meeting all the assumptions listed above, Test 1 was interpreted using the Moench (1989) solution.

The results of fitting the model to the field data are shown in Figures 7 (fluorescein) and 8 (amino-G-acid), and the model parameters are listed in Table 1.

The modelling supports the hypothesis that there are four main pathways through the system. Attempting to match the data using only three pathways produced a clearly poorer fit.

It appears that, although the first three 'pulses' (pulses 1–3) are much faster than the fourth, they carry significantly less flow (Table 1). The flow reaching the pumping borehole from all directions over the vertical 0.4 m interval of the injection zone amounts to about 10% of the total flow, roughly as expected, suggesting the injection interval may be typical of the volume of the aquifer above the packer. Pulses 1–3 probably represent fracture flow pathways. CCTV logs (Fig. 2) indicate that there are four small and one large fracture in the borehole wall above the packer level. Pulse 4 probably represents the intergranular flow pathways.

The initial fluorescein concentration assumed for the analysis is significantly lower than that assumed for the amino-G-acid: a concentration ratio of 5.25 (amino-G-acid/fluorescein) produces adequate fits for all four
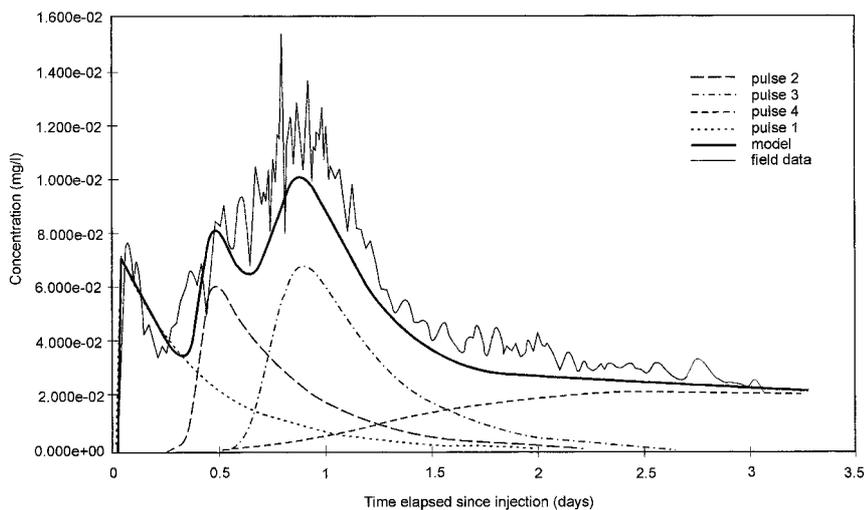
Fig. 7. Curve match for the four pathway model for the fluorescein breakthrough of Test 1. The calculated breakthrough curves for each pathway are also shown.
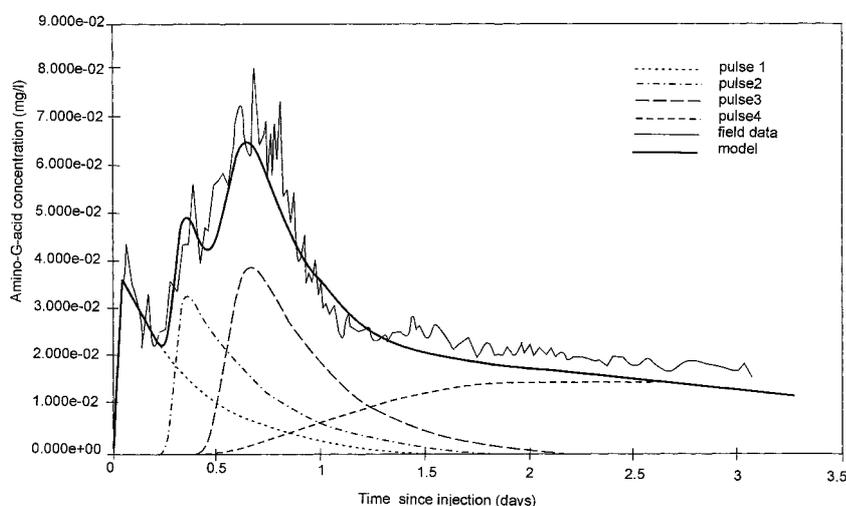

Fig. 8. Curve match for the four pathway model for the amino-G-acid breakthrough of Test 1. The calculated breakthrough curves for each pathway are also shown.

pulses, but a better fit for Pulse 3 would have been achieved using a factor of 4.4. It is possible that this may represent considerable uptake by the gravel pack material of the more reactive fluorescein. However, the low concentration of fluorescein in all three tracer experiments suggests that degradation reactions may be important in the slightly reducing groundwaters. Smart & Laidlaw (1977) consider biodegradation to be a 'significant cause of dye loss' in bacterially active systems. Drilling at the site using fluids with a polymer additive instigated a period of sulphate reduction (Barker 1996), indicating that bacterial activity can be rapidly established in these low salinity groundwaters.

The fracture apertures interpreted from the breakthrough times for pulses 1–3 range from 0.2 to 7 mm. These apertures imply, using the parallel plate model, transmissivities of 0.6 m^2/d to 2.4 x 10^4 m^2/d: the former is rather low, the latter far too high, and the smallest aperture corresponds to the earliest breakthrough. It is possible that the thickness suggested by the model is made up from several fractures, or that the 'fracture' pathways consist of a combination of fractures and intergranular flow zones (including fracture fill material). The total thickness of contributing aquifer is about the same as the piezometer screen length. The porosity used for Pulse 4 is that obtained by laboratory analysis by Segar (1993) (22%).

The interpreted dispersivity values appear reasonable, though sensitivity analysis indicates that of all the calibration parameters, the interpretations are least sensitive to this parameter. The dispersivity interpreted for the intergranular flow pathways of Pulse 4 is unrealistically large, implying a forced fit of model to data. Bashar (1997) has found a similar problem in rapid flow laboratory-scale experiments, where a large 'tail' in the breakthrough curves cannot be adequately represented by a one-domain model, but needs a multidomain interpretation incorporating the effects of layering in the samples. The sandstone at the HTS has bed thicknesses in the range from centimetres to over a metre.

The tracer decay rate implies, using the standard point dilution equation (e.g. Freeze & Cherry 1979), that the flux past the piezometer is about 0.03 m/d, an order of magnitude smaller than that predicted by perfect radial

Table 1. *Model parameters used in interpreting Test 1*

Model Parameters	Pulse 1	Pulse 2	Pulse 3	Pulse 4
Flow rate (m³/s)	8.0×10^{-6}	8.5×10^{-6}	1.2×10^{-5}	4.0×10^{-5}
Flow rate (% total pumping rate)	1.1	1.1	1.6	5.3
Flow rate (% flow carrying tracer)	11.6	12.4	17.5	58.4
Thickness (m) (if fracture)	2.0×10^{-4}	2.8×10^{-3}	7.4×10^{-3}	
Thickness (m) (if layer)	0.10	0.16	0.20	0.80
Dispersivity (m)	0.02	0.02	0.03	2.0
Porosity (if fracture)	1.0	1.0	1.0	1.0
Porosity (if layer)	2.0×10^{-3}	1.8×10^{-2}	3.7×10^{-2}	2.2×10^{-1}
Travel distance (m)	5	5	5	5
Amino-G-Acid				
Initial Conc. (mg/l)	21.0	22.6	32.0	107.0
Retardation factor	1.0	1.0	1.0	1.0
Tracer conc. decay rate at injection point (/s)	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}
Fluorescein				
Initial Conc (mg/l)	4.0	4.3	6.1	20.3
Retardation factor	1.4	1.4	1.4	1.4
Tracer conc. decay rate at injection point (/s)	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}

flow towards the pumping borehole. However, the value is calculated using a rather simple model, is constrained only by the concentrations measured in the piezometer at the start of the test and the amount of tracer recovered at the end of the test, and ignores the effects of more complex pathways.

The retardation factor for fluorescein, 1.4, implies a K_d value of around 0.04 l/kg, taking porosity to be 22% (Segar 1993) and the bulk rock density to be 2332 kg/m³. This K_d is below the detection limit of the batch method used for the preliminary tracer experiments described above.

Semi-quantitative interpretation: Test 3

The quantitative analysis of Test 3 was carried out in an identical manner to that of Test 1.

Before the breakthrough curves could be analysed, certain decisions had to be made concerning the background concentrations. Figure 5 indicates that the apparent background concentration of amino-G-acid is much larger than that of fluorescein. This may be due to biodegradation of fluorescein within the aquifer as proposed above. To account for the background concentrations of the two tracers, they were initially estimated as the minimum concentration measured: however, this resulted in fluorescein peaks much greater than the amino-G-acid peaks, despite the known greater propensity for sorption of fluorescein. Hence it was decided to assume a background concentration for the fluorescein equal to the minimum concentration measured (2 µg/l), and then to assume a background concentration for the amino-G-acid equal to the difference in peak height between the first, unretarded, fluorescein pulse and the first amino-G-acid pulse. This procedure normalizes the data so that the first main peak for the amino-G-acid was the same height as that of the fluorescein. As the

figures below indicate, it is clear that this approach is not really appropriate for the early amino-G-acid data, implying that any fluorescein degradation was not uniform. No attempt has been made to scale the initial concentrations of tracers by a constant factor as was done in Test 1. The initial conditions of this test are hence only crudely represented.

Assuming that before pumping began, 7 litres of tracer were forced horizontally into the aquifer around the screened depth of the piezometer, the tracer would have occupied a volume of the aquifer 0.14 m in radius and 0.4 m deep at the start of the test.

The results of applying the model to the modified field data are shown in Figures 9 and 10. A minimum of three pathways are needed to adequately model the data. The model parameters are listed in Table 2. The experiment ended before the final pulse was completed, and the interpretation of this pulse is thus even more uncertain.

Flow reaching the pumping borehole from all directions over the vertical 0.4 m interval represented by the piezometer injection point is interpreted to amount to 6% of the abstraction rate, about three times greater than expected from a homogeneous system. As for Test 1, most tracer travels in the slowest pulse.

If the two fastest pulses are interpreted as being due to fracture flow, the fracture apertures are unreasonably large, as for Pulse 3 in Test 1. The same explanations may apply here. The interpreted total thickness of the pathways is around 1 m, two and a half times the length of the injection point, hence implying a good deal of lateral spreading: this may reflect some 'bridging' flow between injection point and the main flow paths, especially during the tracer injection.

Dispersivities are similar to those interpreted for Test 1. Again, the slowest pulse has a large interpreted dispersivity, which may imply more complex spreading processes than those included in the rather simple
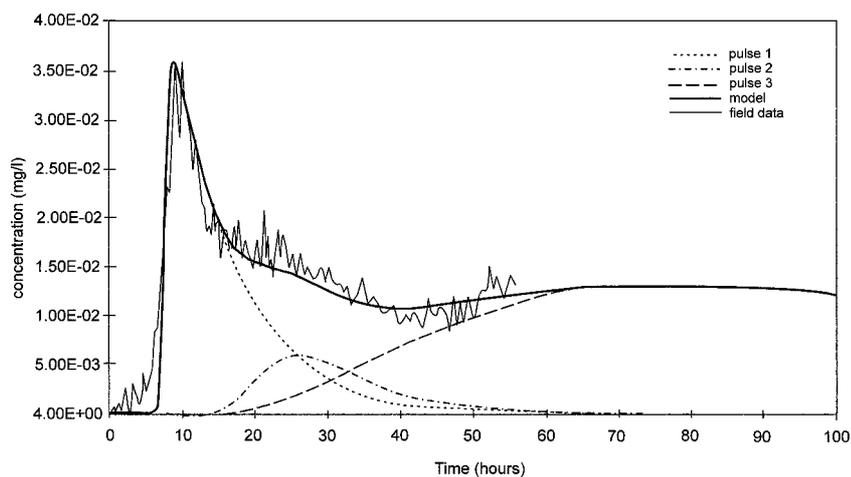
Fig. 9. Curve match for the three pathway model for the fluorescein breakthrough of Test 3. The calculated breakthrough curves for each pathway are also shown.
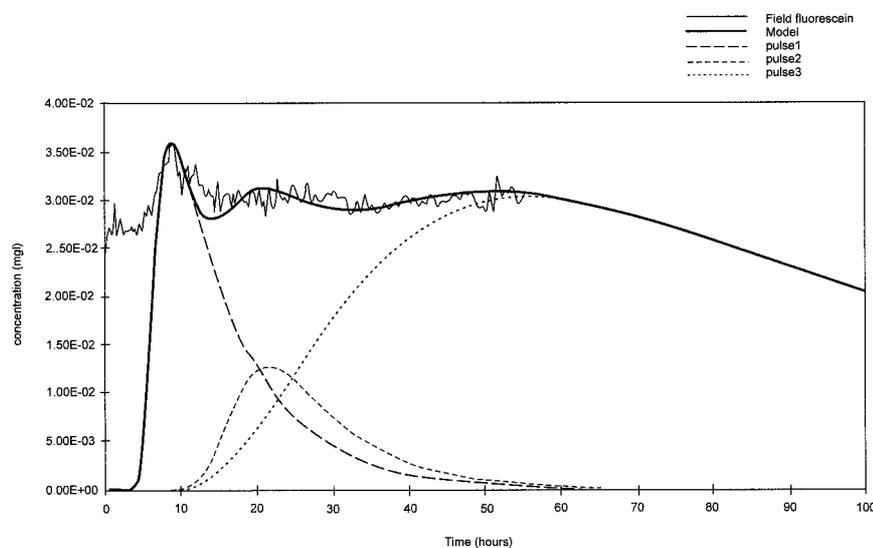

Fig. 10. Curve match for the three pathway model for the amino-G-acid breakthrough of Test 3. The calculated breakthrough curves for each pathway are also shown.

model. The actual value of dispersivity should not therefore be used in other contexts.

The retardation factor for the first fluorescein pulse is very close to one. For the subsequent pulses, the retardation factor was 1.25 and 1.5, similar to the 1.4 value obtained in Test 1. Consequently the implied K_d value, using Segar's (1993) laboratory-determined average porosity value of 0.19 and a density of 2332 kg/m^3, is similar to that implied by Test 1 (0.038 l/kg for Test 1, 0.041 l/kg for Test 3).

The injection decay constant used was based on that used for Test 1. The sensitivity of the model to the decay constant and other parameters, each varied independently, was investigated. Typically parameter values need to be changed by more than 5% before the predicted breakthrough curves lie outside the fluctuation range of the field data. Thickness, porosity, injection well decay factor, and retardation factor are the most sensitive parameters, and dispersivity, flow rate, initial concentration at injection, and injection well radius, are the least sensitive. The sensitivity analysis is more complex in the zones where pulses overlap.

The model interpretation suggests two possible fracture pathways. CCTV logging indicates the presence of an apparently large fracture at 22 m depth, 1.5 m above the packer seal during the test (Fig. 2). Interpretation of separation pumping carried out by the Danish Geological Survey (Segar 1993) indicates that 16.5% of the total inflow to the unpackered borehole occurred at around this depth. The fracture is unlikely to run through the screened section of the piezometer but may be hydraulically connected to it. In addition, 2.5 inch (0.064 m) diameter core from the site contains about 28 fractures per metre at around 20 m depth, but it is not easy to distinguish drilling artefacts from natural fractures, and examination of in situ rock and degraded 36 inch (0.9 m) core from the site suggests this figure to be far too high as an estimate of natural fracture frequency. CCTV logging also indicates four moderately sized fractures at 17–19 m depth (Fig. 2). Hence the geological evidence is unclear; however, it confirms that fracturing is frequent enough that two fractures are likely to intersect or run close to the piezometer injection zone. The third pulse can be explained as intergranular flow

Table 2. *Model parameters used in interpreting Test 3*

Model Parameters	Pulse 1	Pulse 2	Pulse 3
Flow rate (m^3/s)	9.8×10^{-6}	7.4×10^{-6}	3.4×10^{-5}
Flow rate (% total pumping rate)	1.23	0.93	4.25
Flow rate (% flow carrying tracer)	19.1	14.5	66.4
Thickness (m) (if fracture)	3.0×10^{-3}	6.0×10^{-3}	
Thickness (m) (if layer)	0.20	0.2	0.96
Dispersivity (m)	0.01	0.09	2.0
Porosity (if fracture)	1.0	1.0	
Porosity (if layer)	6.0×10^{-2}	6.0×10^{-2}	1.8×10^{-1}
Travel distance (m)	5	5	5
Amino-G-Acid			
Initial Conc. (mg/l)	2.8	1.38	22.0
Retardation factor	1.0	1.0	1.0
Tracer conc. decay rate at injection point (/s)	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}
Fluorescein			
Initial Conc (mg/l)	2.8	0.7	14.0
Retardation factor	1.0	1.25	1.5
Tracer conc. decay rate at injection point (/s)	3.0×10^{-5}	3.0×10^{-5}	3.0×10^{-5}

through beds of different permeability, and may well include the effects of vertical flow across bed boundaries and diffusion.

Discussion and conclusions

It is clear that at shallow levels at the Haskayne site there are very rapid flow pathways through the rock, at least over small horizontal distances, which allow transport of a few percent of the tracer, and slower pathways through which the bulk of the tracer moves. The fast routes may represent single fractures, groups of fractures, or, less likely, beds of high intergranular permeability. In the Permo-Triassic sandstones of Lancashire, Cheshire, and Cumbria, there is good aquifer test and geophysical evidence for the hydraulic importance of fractures at least in the potentially disturbed zone immediately surrounding the test boreholes (e.g. Brereton & Skinner 1974; Walthall & Ingram 1984; Price *et al.* 1982). The slower, presumed dominantly intergranular pathways, give rise to very broad peaks, suggesting very heterogeneous permeability distributions as expected from laboratory permeability measurements (e.g. Campbell 1983; Lovelock 1977). Similar broad peaks occur in laboratory column experiments on the sandstone, and can be quantitatively described assuming lateral diffusion into lower permeability layers (Bashar 1997).

The flows in the fastest pathways are 10 to 40 times faster than suggested by calculations performed assuming a homogenous system. The tracer tests indicate that these fast pathways are present to at least 20 m bgl. There is qualitative evidence that they exist to deeper levels at the site. When Borehole 3 was drilled, the amount of water injected during drilling would have been enough to displace the groundwater to a radius of 1 m from the borehole had the rock been homogeneous.

However, within 24 hours of the drilling, the water in all four piezometers (7, 20, 40, 80 m) in Borehole 2, 15 m distant from Borehole 3, was contaminated by drilling fluid. This suggests that the fast routes are present to at least 80 m depth and that they are very frequent: the piezometer open zones are only 0.4 m in length. CCTV logging, calliper logging, and packer testing in the region indicate that fractures decrease in frequency below *c.* 200 m depth (Brassington & Walthall 1985; University of Birmingham 1981), but no fracture frequency/depth correlations have been seen above *c.* 100m depth (Jeffcoat 2002).

The region around a borehole may be atypical of the aquifer due to the development of fracture permeability by pumping. Observations in Runcorn, on the southern bank of the Mersey Estuary opposite Widnes (Fig. 1), suggest that at least some fractures are filled with sediment (G. Weathall, pers. comm.), and the general relationship between higher pumping rates and higher pumping test transmissivities in the region (University of Birmingham 1981) suggests that aquifer development can occur. It is therefore possible that, remote from pumping wells, limited fracture flushing occurs and the preferential pathways are not present to the same extent.

Barker *et al.* (1998) report a tracer test in which fluorescein was injected in an observation borehole and recovered in the Liverpool Loop Line rail tunnel. As the tunnel locally drains the aquifer, the test was effectively forced-gradient in nature. Breakthrough occurred at 7 of the 8 sites sampled in the tunnel. The greatest linear distance between the injection point and a breakthrough point was *c.* 280 m, and the average linear velocity over this distance was *c.* 140 m/day. Although again fracture flushing cannot be ruled out, this result suggests that solutes can travel substantial distances through fractures in the sandstones at least in response to artificially large head gradients. However, over the timescales

associated with flow under natural regional head gradients, diffusion into the matrix will be a very significant factor.

Sorption of fluorescein occurred during the Haskayne tests, but not always to the same extent in each pathway, thus indicating a relationship between hydraulic and geochemical properties which may be of importance in contaminant migration. In addition to sorption, fluorescein appears to be removed relative to amino-G-acid, probably by degradation.

With greater resources and the benefit of hindsight, the field procedures could have been improved, allowing greater confidence in the interpretations. However, it is unclear, even then, whether at a site such as Haskayne, with piezometers and closely-spaced boreholes, the interpretation could be any more than reconnaissance in nature. Nevertheless, the results of the tests described here and those of Barker *et al.* (1998) indicate that a small proportion of solutes in the Triassic Sandstones may move much more rapidly than the average flows, that these fast transport pathways are common in at least NW England, and that they are found over a range of length scales up to at least 280 m.

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