A tracer methodology for identifying ambient flows in boreholes

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Abstract

Identifying flows into, out of and across boreholes is important for characterising aquifers, determining the depth at which water enters boreholes, and determining the locations and rates of outflow. This study demonstrates how Single Borehole Dilution Tests (SBDTs) carried out under natural head conditions provide a simple and cheap method of identifying vertical flow within boreholes and determining the location of in-flowing, out-flowing and cross-flowing fractures. Computer simulations were used to investigate the patterns in tracer profiles that arise from different combinations of flows. Field tracer tests were carried out using emplacements of a saline tracer throughout the saturated length of boreholes and also point emplacements at specific horizons. Results demonstrated that SBDTs can be used to identify flowing fractures at the top and bottom of sections of vertical flow, where there is a change in vertical flow rate within a borehole, and also where there are consistent decreases in tracer concentration at a particular depth. The technique enables identification of fractures that might be undetected by temperature and electrical conductance logging, and is a simple field test that can be carried out without pumping the borehole.

Introduction

Identification of actively flowing fractures in boreholes is an important component of aquifer characterisation. For example, understanding the spatial distribution of flow in an aquifer improves groundwater models and provides insight into contaminant transport. Identifying the major in-flowing fractures in boreholes enables improved understanding of the depth from which waters sampled for chemical analysis have originated. Knowledge of the location of major out-flowing fractures can improve the chances of success during larger scale tracer tests from boreholes because tracer emplacement can be targeted at the depth at which water is known to exit the borehole. Targeting sampling in monitoring boreholes during tracer tests at in-flowing fractures is also important. This paper describes ways of improving the Single Borehole Dilution Test (SBDT) to enable flowing fractures to be identified by integrating uniform and point emplacements and using forward simulations to aid interpretation of the field data. The techniques described can be applied to detect flows in boreholes which are undisturbed by pumping – termed *ambient* flows in the title of this article – but may also be employed in boreholes that are being actively pumped, or are affected by the pumping of a nearby well. Only ambient flows are discussed here.

Various borehole logging techniques (caliper, imaging, fluid temperature/electrical conductance, and flow logging) can be used to identify fractures but some of these are unable to distinguish between flowing fractures and hydrologically inactive fractures, and they may not identify all flowing fractures that are present. Caliper logs record the variation in borehole diameter with depth. Increases in borehole diameter often occur where a fracture is present, but the drilling process may also cause enlargements. Calipers consist of two or three prongs that measure the distance from a centralised point to the borehole wall, and may miss vertical fractures and voids which do not persist horizontally around the circumference. Fractures can be seen on borehole imaging logs where cameras are used to view the borehole walls. However, neither caliper nor imaging data demonstrate whether the fracture is actively flowing, and many hydrologically inactive fractures have been identified in boreholes (Price et al., 1977; Michalski and Klepp, 1990; Paillet, 1998, 2000; and Williams and Paillet 2002).

Borehole fluid logs may indicate flowing fractures where there is an abrupt change in electrical conductance and/or temperature (e.g. Tate et al., 1970; Price et al., 1977; Williams and Paillet, 2002; Schurch and Buckley 2002). However, the technique fails where flowing features share the same electrical conductance and temperature as the water column within the borehole (Michalski and Klepp, 1990). Price et al. (1982) point out that this technique is less likely to detect outflows than inflows because there is likely to be no difference between the temperature/electrical conductance of the water in the borehole and that of the water leaving. High sensitivity impeller flowmeters (e.g. Molz et al. 1989, 1994), or heat-pulse flow meters (e.g. Paillet et al., 1987; Morin et al., 1988) have proved the most successful logging method for identifying flowing fractures, although cross-flowing fractures where there is no change in vertical flow rate are difficult to identify.

The commonest use of single borehole dilution tests (SBDTs) involves emplacing tracer throughout the saturated length of the borehole, and monitoring the dilution of the tracer by groundwater entering and leaving the borehole (Ward et al., 1998; Williams et al. 2006; Pitrak et al., 2007). If there is no vertical flow and the water in the borehole is well mixed, the Darcian velocity in the aquifer can be derived from the decline in the average concentration. This should follow an exponential curve if the field situation satisfies the conditions stipulated above (Lewis et al., 1966).

Less commonly a ‘point emplacement’ is employed, in which a slug of tracer is introduced at a particular depth. If vertical flow is occurring, the tracer plume from a point emplacement moves up or down the borehole (Tate et al., 1970; Michalski and Klepp, 1990).

In fractured aquifers, where there is variability in hydraulic head between the fractures intercepted at different depths, vertical flow within the borehole is the norm (Michalski and Klepp, 1990; Church and Granato, 1996; Elci et al., 2001; Shapiro, 2002). Under those conditions, SBDTs are often conducted in a short interval of borehole that is isolated using packers (Palmer, 1993;

Shreiber et al., 1999; Novakowski et al., 2006). However, SBDTs in long open borehole sections can be used to identify the location of flowing fractures using the shapes of profiles of tracer concentration with depth measured at sequential times following tracer emplacement. The disadvantage of performing SBDTs in long sections of open borehole under ambient conditions is that the technique cannot identify which of the features have the highest transmissvity, or which would contribute most water when the borehole is pumped. Flow log interpretations often assume that the amount of inflow from each interval is proportional to transmissivity. In cases where there is strong pumping this is at least approximately the case. In situations with ambient flow or low pumping, this is the cause of serious error.

Since the 1990's, several authors have successfully used SBDTs to develop methods of determining the hydraulic properties of flowing fractures in boreholes (e.g. Tsang et al., 1990; Löw et al., 1994; Evans 1995; Brainerd and Robbins 2004; Dougherty and Tsang, 2005; West and Odling, 2007). These studies all involved analysis of results obtained under pumped conditions that disturbed the ambient head distributions and induced vertical flows. Most were undertaken in very low permeability strata in which aquifer water was replaced by de-ionised water, the borehole was pumped, and flowing fractures were identified where water with higher electrical conductance entered the borehole. This type of test cannot be carried out in high permeability strata because it is not generally possible to empty the borehole of aquifer water. No systematic account has been published of how flowing fractures can be identified from SBDTs.

This study considers two types of tracer dilution test: uniform and point emplacement. The overall objective was to investigate the applications of simple SBDTs carried out under natural gradient conditions, especially as a tool for qualitatively identifying flowing fractures and vertical flow in boreholes. Firstly we present computer simulations that show the patterns in tracer profiles that occur with different patterns of water flow into and out of a borehole. We then show how real tracer tests can be qualitatively interpreted using these simulations as a guide. We describe examples from a large field programme where both types of test were used. Uniform emplacements were performed first and, with the aid of the simulation results, used to plan the depths of subsequent point emplacements.

Simulation of single borehole dilution tests

Simulation Methods

A spreadsheet-based model was developed as an exploratory tool to investigate the patterns in tracer profiles during SBDTs. The principle of the model is that the borehole is divided into vertical segments and the user specifies an initial tracer concentration (C_o) and a (constant) horizontal inflow (Q_{IN}) and outflow (Q_{OUT}) for each segment. The sum of inflows over all segments $\sum Q_{IN}$ must be equal to $\sum Q_{OUT,}$ the sum of all outflows. Vertical flows within the borehole result from the existence of segments in which inflow and outflow are not equal. The model runs forward in time and predicts profiles of tracer concentration with depth. The code models vertical advection and dispersion within the borehole using the mathematical formulation given in Appendix A.

Different flow scenarios were postulated and the numerical model was used to simulate the tracer profiles with depth that would result at increasing times after emplacement. Fractures and fissures were represented by short sections with relatively large values of Q_{IN} and Q_{OUT}. Diffuse flow was simulated by long borehole sections with relatively small and equal values of Q_{IN} and Q_{OUT}. These could be set to zero when our primary interest was in vertical flow.

Fig. 1 shows five different flow situations that can arise where a single fracture is intersected by a borehole. The presence of fractures where inflows and outflows are not equal will cause vertical flows to be set up along the length of the borehole. Such flows can be controlled by the model user by adjusting values of Q_{IN} and Q_{OUT} for individual segments. In Fig. 1 the arrows outside the borehole indicate the segments for which a flow rate is specified, with thicker arrows indicating higher flow rates. Many segments are specified to have no horizontal inflow or outflow (representing unfractured sections of strata in which the matrix permeability is negligible). Vertical flow occurs between individual segments and in Fig. 1 arrows inside the borehole depict upward flow because inflows at the bottom are larger than outflows, and the reverse occurs at the top. Different, simple combinations of these five basic types of flowing fracture were used to generate tracer concentration patterns, which can be used as a tool for identifying the flowing fractures in real boreholes.

The model was run with the following settings:

- The borehole length was set at 50 m and the segment length at 1 m (therefore C_o, Q_{IN} and Q_{OUT} were specified for 50 segments). C_B was set at 0 throughout.
- C_o was set at 100 for every segment except for simulations of point emplacements. For these C_o was set at 500 in three segments near the bottom of the borehole and 0 in all other segments.
- The diameter of the borehole was assumed to be 0.25 m.
- Simulated profiles were generated at regular time intervals, corresponding to profiles of tracer concentration that might be measured in the field.
- For most simulations involving vertical flow a dispersivity value of 0.5 m was used to represent the effects of dispersion on tracer as it was advected vertically within the borehole. (This value was derived from a point dilution test in a borehole with upward vertical flow. However, it is not clear how representative this single value is, or how the movement of water across the borehole might affect dispersivity.) Some simulations were also run with a higher dispersivity value of 3 m for comparison.

Results of SBDT simulations

The results of simulated profiles of tracer concentration with depth are presented for regular time intervals in Figs. 2 to 5. On the right of each simulation, the flow patterns are shown schematically. The vertical lines represent the length of the borehole. Arrows depict the locations of inflows (pointing towards the borehole), outflows (pointing away from the borehole), and the resulting vertical flow (up the borehole). Thicker arrows indicate higher flow rates.

Fig. 2 shows simulations of flow patterns with horizontal flow only. Fig. 2a is the straightforward case of uniform horizontal flow across the whole length of the borehole. Fig. 2b introduces a cross-flowing fracture with a locally higher flow rate (twice the rate that was applied to the rest of the borehole). This causes a distinctive nick in the profile at the depth of the fracture (Fig. 2b). If horizontal flow is stronger in the upper section of a borehole than below, in this case again twice as large, a boundary is apparent between sections of faster and slower dilution (Fig. 2c). These simulations demonstrate that, in the absence of vertical flow, nick points and boundaries remain in the same position in all profiles.

Simulations of upward vertical flow are presented in Fig. 3. The simplest occurrence of vertical flow is the case of a single inlet and a single outlet (Figs. 3a & 3b). In Fig. 3a as tracer exits from a fracture at the top of the borehole it is replaced by tracer-laden water from below. There is no decrease in tracer concentration at the top fracture before the arrival of new tracer-free water that entered the borehole though the bottom fracture. The profiles are characterised by a distinctive ‘front’ of freshwater that migrates up the borehole. In Fig. 3b identical parameters were used except the dispersivity was increased from 0.5 m to 3 m. This has the effect of spreading the freshwater front over a greater length of borehole.

Where vertical flow is occurring, a boundary is created at the entry and/or exit points because tracer dilution is much slower in the adjacent borehole section. For example, in Figs. 3a and 3b, Q_{IN} and Q_{OUT} were set to 0 for four metres at the bottom of the borehole, (representing impermeable strata) and the fracture inflow point is marked by a boundary. In all subsequent simulations (Figs. 3c-3i) the in-flowing fracture was positioned at the bottom of the borehole and therefore the boundary is absent.

In cases of vertical flow with two outlets (Fig. 3c), the rate of vertical flow is slowed as the tracer plume passes the first outlet, but there is no decrease in the tracer concentration at either outlet until they are reached by the tracer-free water entering through the in-flowing fracture at the bottom of the borehole. The intermediate out-flowing fracture produces a change in the rate at which the tracer-free front migrates up the borehole, as shown by the closer spacing of profiles in the upper part of Fig. 3c. In this simulation the outflows in both fractures are equal and therefore the rate of vertical flow is halved as the plume passes the first out-flowing fracture. A decrease in vertical flow rate therefore indicates the presence of an out-flowing fracture and represents Type 5 in Fig. 1.

Fig. 3d shows a situation in which vertical flow occurs from a single fracture at the bottom and leaves the borehole via a fracture at the top. However, in this case the upper fracture also has a cross-flow, i.e. an inflow on one side of the borehole and a larger outflow on the other. This produces an immediate reduction in tracer concentration that is apparent in the earliest simulated profile (Fig. 3d). However, the concentration in subsequent profiles remains at this reduced level while tracer-laden water from below moves up the borehole (profiles 1 to 4), until the arrival of the freshwater front at the outflow point causes further dilution (profiles 5 and 6).

Fig. 3e shows the results of a simulation with cross-flow in the middle of a section of vertical flow (Type 3 in Fig. 1). The cross-flowing fracture reduces the tracer concentration, creating a freshwater 'sub-front' that moves up the borehole (profiles 1 and 2), but concentrations do not reduce further until the main freshwater front has passed the cross-flowing fracture. As the main tracer front passes the cross-flowing fracture, a nick point (profile 3) and a small step (profile 4) are apparent. In this case the vertical flow rate is unaffected by the cross-flowing fracture because it has equal inflow and outflow. A superficially similar pattern occurs in the case of vertical flow with the inflow divided between two fractures (Fig. 3f), each of which are of Type 1 from Fig. 1. However this pattern is different in detail in that the vertical flow rate increases above the second in-flowing fracture. There is also a more pronounced nick as the main tracer front passes the second in-flowing fracture (profiles 4, 5 and 6). Fig. 3g shows that similar profiles are generated in the case of vertical flow with a cross-flowing fracture for which $Q_{IN} > Q_{OUT}$ (Type 2 in Fig. 1). If $Q_{OUT} > Q_{IN}$ (Type 4 in Fig. 1), the pattern differs from Figs. 3e, 3f and 3g because the vertical flow rate is reduced above the cross-flowing fracture (Fig. 3h). Increasing the dispersivity from 0.5 m to 3 m has the effect of creating smoother profiles in which the sub-front apparent in Figs. 3e to 3h is removed. For example Fig. 3i shows the results of a simulation with identical parameters to Fig. 3f except the dispersivity is increased to 3 m.

Table 1 summarises the effects that different types of flowing fracture may have on the tracer concentration in the borehole during a SBDT with uniform emplacement of tracer. The first column indicates the type of flow contributed by the fracture, which is envisaged to be located within a section of borehole in which there is uni-directional vertical flow. Column 2 indicates the effect of the fracture's contribution on the vertical volumetric flow rate within the borehole – for a uniform diameter this will translate directly into a change of velocity which will be reflected in the rate of migration of "fronts" or "sub-fronts", as described above and illustrated in Fig. 3. Column 3 of Table 1 indicates the effect on the concentration of tracer in the borehole just down-flow of the fracture itself.

The effects produced by a flowing fracture within a section of borehole with vertical flow are similar for the vertical migration of plumes produced by point emplacement SBDTs. To illustrate this, a point dilution test was simulated for a borehole intersected by three fractures. Upwards vertical flow occurred between the lowest and the uppermost fracture while located between them was an in-flowing Type 1 fracture (Fig. 4). The point emplacement was positioned just above the bottom in-flowing fracture. It is clear in Fig. 4a that as the tracer plume passes the middle fracture its rate of migration is increased. Thus the peaks of concentration profiles below the middle fracture (profiles 1 to 4 in Fig. 4a) are closer together than those above it (profiles 5, 6, and 7). However, as illustrated in Fig. 4b and noted in Table 1, the total amount of tracer in the borehole does not decrease as the plume passes the in-flowing fracture. A decrease in tracer amount in the borehole only occurs when the plume reaches the out-flowing fracture at the top (profile 7). In contrast, if there is an out-flowing fracture within a section of vertical flow, the flow rate decreases, as shown by the spacings of profiles in Fig. 5a. The total tracer amount also decreases as the tracer plume passes the fracture (profiles 3 and 4 in Fig. 5b). (Note that in the simulations summarised by Figs. 4b and 5b the average tracer concentration over the entire borehole has been used as a surrogate for the total mass of tracer still present. This substitution is valid if the borehole has uniform diameter.)

Examples from Field Experiments in the English Chalk

Study area

Field data were obtained from the Pang and Lambourn drainage areas in Southern England. All boreholes tested are within the Cretaceous Chalk which is a fine-grained very pure porous limestone typically composed of ~98% calcium carbonate. The Chalk contains fairly frequent marl layers, flint layers and hard-grounds that are known to localise flow (Allen et al., 1997). The Chalk is mildly karstic with groundwater flow predominantly through fractures which are frequently enlarged by dissolution to form fissures or small conduits. Primary porosity is typically ~30 to 45% (Allen et al., 1997) but the permeability of the primary pore network, usually termed the “matrix”, is very low. Matrix permeability measured in unfractured cores is several orders of magnitude lower than overall permeability and solutionally enlarged fractures are largely responsible for the transmissivity of the Chalk (Price et al., 1982). Flows into and out of boreholes are predominantly via fractures.

Field Methods

SBDTs were carried out in uncased boreholes using common salt as a tracer that can be easily monitored by measuring the electrical conductance of the borehole water. For uniform emplacements a weighted hosepipe was lowered to the bottom of the borehole and filled to the depth of the water table with a solution of approximately 120 g/l NaCl. Where borehole casing extended below the water table, clean water was used to fill the section of hosepipe within the casing. The hosepipe was removed leaving a uniform distribution of tracer in the uncased part of the water column. The relatively high density of the saline solution may cause some sinking of the tracer in the borehole, and the first profiles taken after emplacement have small-scale irregularities due to imperfect mixing, but these are smoothed in later profiles and do not affect the identification of flowing fractures. For point emplacement experiments a container filled with salt and with a triggered seal was lowered to the desired emplacement depth. A weight dropped down the line triggered the release of the tracer.

Fluid electrical conductance profiles were obtained before emplacement and at intervals afterwards using a Solinst Levelogger LTC probe, model 3001, programmed to record depth and specific electrical conductance at 2-second intervals as it was lowered down the borehole. Data were downloaded via a cable link to a laptop computer, enabling real-time monitoring of tracer in the field. Electrical conductance measurements were accurate to ±0.01 $mS.cm^{-1}$ and depth measurements to ±10 cm (Maurice, 2009).

Results

Fifty uniform- and point-emplacement SBDTs were carried out in 25 boreholes in the study area (Maurice, 2009). Results from three boreholes named Barracks, Bagnor and Frilsham C are presented here to illustrate how flowing fractures were identified using the principles illustrated by the simulations presented above. The three boreholes differ in that one (Barracks) contains a section with upwards flow, a second (Frilsham C) has a section with downwards flow, whereas the third (Bagnor) has divergent flow, upwards and downwards, from a fracture where there is a strong inflow. Figs. 6a, 7a and 8a show profiles of electrical conductance following uniform emplacements whereas profiles taken after point emplacements appear in Figs. 6b, 7b and 8b. The emplacement took a variable time and the interval that elapsed before the first profile was also variable, but normally only a few minutes. Numbers on the profiles refer to the time in hours since the first profile after emplacement. 'BG' indicates a background electrical conductance profile. Horizontal grey dashed lines indicate the inferred location of flowing fractures and dotted arrows the direction of inferred vertical flow. (No time interpolation of the profile data has been performed as trials showed negligible difference between recorded profiles that took 5-10 minutes to obtain and values interpolated for a single time.)

At Barracks (Fig. 6b) the point emplacement SBDT demonstrates upward flow from 45 m AOD (above Ordnance Datum). The location of an in-flowing fracture at 45 m AOD is clear from both the uniform and point emplacements because both show a clear boundary below which tracer concentrations do not change, indicating zero flow. An out-flowing fracture is present at the top of the vertical flow section at about 114 m AOD. The vertical flow between them was first inferred from the upward movement of the tracer-free front following the uniform emplacement (Fig. 6a), and confirmed later by the point emplacement (Fig. 6b). The point-emplacement data indicate that there is an additional out-flowing fracture at about 80 m AOD above which the tracer plume slows and loses mass. It is apparent from Fig. 6b that the tracer plume was diluted and reduced in size between the profiles taken at 6.9 and 23.4 hours. Fig. 9 plots the average tracer concentration against time and shows a decrease from 0.03 to 0.006 $mS.cm^{-1}$ indicating substantial tracer loss as the plume passed the fracture. The point emplacement data also indicate a decrease in upward velocity (based on the movement of peak concentration) from an average of 2.8 $m.h^{-1}$ to an average of 0.8 $m.h^{-1}$ as the plume passed this fracture (Table 2). The combination of decrease in flow rate and tracer loss suggests this is an out-flowing fracture belonging either to Type 4 or Type 5 (see Fig. 1 and Table 1). There is little change in the tracer concentration at 80 m AOD following the uniform emplacement, which has similarities to the simulation in Fig. 3c suggesting that it may be a Type 5 fracture with outflow only.

At Frilsham C the point emplacement data demonstrate downward flow from above 50 m AOD to 20 m AOD (Fig. 7b). Six fractures are clearly indicated by the presence of nick points in the profiles following the uniform emplacement (Fig. 7a). These nicks persist through multiple profiles despite the downward flow of water in the borehole. The point emplacement results indicate that as the tracer plume moved down the borehole there was a progressive increase in flow velocity (based on the movement of the peak tracer concentration) (see Table 3). The velocity was low between 1.3 and 1.8 hours because by then the front of the plume had reached the out-flowing fracture near the bottom of the borehole. The combination of the increase in the velocity shown by the point-emplacement plume and the nick points observed in the uniform-emplacement profiles indicates that the fractures within the vertical flow section are inflow dominated and belong either to Type 1 or Type 2 in Fig. 1 and Table 1. The point emplacement results suggest they are Type 1 (inflow only) because there is little loss of tracer until the plume reaches the fracture at the bottom of the borehole (cf. Fig. 4). This is supported by the similarity between the stationary nicks in the profiles in Fig. 7a and the simulation in Fig. 3i.

At Bagnor borehole point emplacements demonstrate both upward and downward flow (Fig. 8b). The distinctive nick at 59.5 m AOD in the uniform emplacement electrical conductance profiles (Fig. 8a) pinpoints the location of the in-flowing fracture generating these vertical flows. Out-flowing fractures are inferred to exist at the top of the upward flowing section, and at the base of the downward flowing section at 56.5 m AOD where there is a distinctive boundary. There are many additional small-scale nicks in the uniform emplacement electrical conductance profiles between 60 and 70 m AOD. These structures resemble the effects of additional fractures, and might be an indication that fractures with small flows occur in the borehole within this section. However they are not stable like the large nick at 59.5 m AOD, but appear to migrate with the vertical flow, so are not interpreted as fractures.

Identifying flowing fractures from SBDTs

Many of the simulated features shown in Figs. 2-5 were observed in the field data (e.g. nick-points, boundaries, freshwater fronts moving up or down a borehole, and changes in velocity within sections of vertical flow). The combination of computer simulations and uniform and point emplacement field experiments suggest that flowing fractures can be identified from SBDT results using four criteria:

1) The top and bottom of vertical flow sections

Vertical flow is more obvious from point emplacement SBDTs, but the uniform emplacement field data and computer simulations both indicate that vertical flow causes a freshwater front to move up or down the borehole. Fractures can be identified at the top and bottom of the vertical flow section, and the location may be pinpointed by a nick point or boundary.

2) Nick-points

Cross-flowing and in-flowing fractures cause a decrease in tracer concentration at the fracture location, which may produce distinctive nick-points in electrical conductance profiles during both uniform and point emplacement SBDTs. However, flowing fractures can only be conclusively identified if the nick points are consistently present in multiple profiles (e.g. Frilsham C, Fig. 7a). The large number of small-scale nick-points in the profiles from Bagnor borehole (Fig. 8a), suggest that additional flowing fractures that could not be conclusively identified may be present and in this case it is possible that not all flowing fractures were detected by SBDTs.

3) Tracer loss during point emplacement tests
Out-flowing fractures within sections of vertical flow can be identified from point emplacements by tracer loss within the section that is not caused by out-flow into the fracture at the down-flow end (e.g. Barracks, Fig. 6b). However, if the tracer plume is spread out over a section of borehole that contains two or more in-flowing fractures then interpretation can be difficult (e.g. Frilsham C, Fig. 7b). Combined plots of the position of the peak concentration alongside the total tracer amount in the borehole (or average tracer concentration as a surrogate in boreholes with uniform diameter) provide a useful means of indicating where tracer loss is occurring (e.g. Fig. 9).

4) Changes in vertical flow rate
As suggested by computer simulations, changes in vertical flow velocity can be detected from the movements of fronts in uniform-emplacement SBDTs (e.g. in Fig. 6a the freshwater front moves up the borehole faster in the first 7.7 hours than between profiles at 19.8 and 21.1 hours). The movement of peak tracer concentrations following point emplacements can provide clearer indications of changes in vertical velocity. Values calculated from successive profiles can be quite variable (e.g. Barracks, Table 2). However, at both Barracks and Frilsham C (Tables 2 and 3), substantial differences in the rate of tracer peak migration strongly suggest the presence of flowing fractures within sections of vertical flow.

Background fluid electrical conductivity and temperature logs can only identify features which involve a change in the conductivity or temperature, which does not usually occur when water is leaving a borehole. The background conductivity profile from Frilsham C (Figure 7) is remarkably uniform which might indicate that there were no active fractures in the borehole. However the SBDTs clearly show 6 flowing fractures. This shows that flowing fractures that would be overlooked using fluid electrical conductance and temperature logs can be identified using the SBDTs.
Hydraulics within the natural system can also conspire to ‘hide’ features that may be very productive in a pumped borehole. For a fracture to flow under ambient conditions there must be a head gradient between it and the borehole. The head within the borehole will be determined by the head in the most transmissive feature. If there are other features with a similar natural head, they will not flow significantly and therefore may not be identified by SBDTs or other flow logging techniques.

Future improvements

Point emplacement SBDTs could be improved by using caliper data to determine variations in borehole diameter enabling tracer loss to be calculated more accurately. Results might also be improved if the effect of the time taken to lower the electrical conductance probe down the borehole were taken into account (e.g. Evans, 1995). A further improvement would be to produce best-fit modelled tracer profiles of the field data to determine values of inflow and outflow at each fracture, which would also demonstrate which of the five flow types shown in Fig. 1 occur. However, these modifications were not undertaken in the current study because flowing fractures could be identified without them and the estimated values of inflows and outflows are difficult to interpret in terms of the hydrogeology of the surrounding aquifer because they are not natural features but owe their existence to the presence of the borehole and the effect of the ambient head distribution. The qualitative interpretations used here can locate horizons which form sources or sinks for flows within the borehole that have been induced by vertical differences in head within the surrounding aquifer.

Prior to modelling profiles of field data to determine values of inflows and outflows it would be useful to establish a representative dispersivity value for inclusion in the model. The patterns in the profiles following the uniform emplacement in Frilsham C (Fig. 7a) are similar to the simulation of an in-flowing fracture within a borehole with high dispersivity of 3m (Fig. 3i). The freshwater ‘sub-fronts’ seen in the simulations with low dispersivity of 0.5m (Figs. 3e-h) were not observed in any field data (Maurice, 2009). This suggests that the higher value may be nearer the true dispersivities in the boreholes studied.

A further improvement would be to determine how much downward movement of the saline tracer occurs due to the density difference between the tracer and the aquifer water. This could be particularly important if point dilution tests were used for detecting low rates of vertical flow in boreholes. This could be a useful application of point emplacement SBDTs because heat pulse flowmeters have a range of ~ 4 to 370 $m.h^{-1}$ (Morin et al., 1988) and therefore point dilution SBDTs may detect lower flows in boreholes (e.g. the upward flow of 0.8 $m.h^{-1}$ in Barrcaks borehole, Table 2). In this situation, a tracer with a similar density to water (e.g. a fluorescent dye which can be monitored using an *in situ* fluorometer) might provide a good alternative tracer.

Conclusions

The results of this study demonstrate that simple qualitative interpretation of uniform emplacement SBDTs can be used to identify actively flowing fractures in boreholes from:

- Nick points or steps in multiple electrical conductance profiles.
- Sharp boundaries between zones of faster and slower dilution.
- At the top and bottom of a vertical flow interval inferred from the movement of a freshwater ‘front’ up or down the borehole

If point dilution data are available flowing fractures can be confirmed or identified at:

- The top and bottom of a section in which vertical flow is occurring (often indicated by tracer loss)

- Depths within sections of vertical flow at which there is tracer loss and/or a change in flow velocity.

To optimise the information obtained from SBDTs, a uniform emplacement SBDT should be undertaken first to determine the nature of flows throughout the saturated length of the borehole. Point emplacement SBDTs, targeted by the uniform-emplacement data, can then clarify uncertainties.

There are many useful applications of combined uniform and point emplacement SBDTs under natural gradient conditions, for example:

- Actively flowing fractures can be identified enabling investigations of the spatial distribution of flow in aquifers. As in any study of flow in boreholes that are not directly pumped, it is important to remember that where vertical flow is occurring, it is driven by the head differences between different levels in the aquifer that are intersected by the borehole. Therefore actual flows in the aquifer in the absence of a borehole will differ from those detected by SBDTs.
- Flowing fractures identified from SBDTs can be compared to image logs to reveal whether flow is through horizontal, inclined or vertical features, and in karst aquifers whether flow is through solutional features or unmodified fractures.
- The occurrence of vertical flow in boreholes is clearly demonstrated, and an estimate of the vertical flow rate can be obtained from the rate of tracer migration following point emplacement tests.
- The main in-flowing fractures are apparent enabling clearer understanding of the depth in the aquifer at which the water present in boreholes originated.
- If larger scale tracer tests are planned (e.g. borehole-to-borehole tests), SBDTs can be used to increase the likelihood of success. SBDTs in the emplacement borehole will demonstrate whether tracer will leave the borehole, and indicate the depth(s) at which tracer should be emplaced. SBDTs carried out in proposed monitoring boreholes enable sampling to be targeted at the depth at which flow enters or passes through the borehole.

The greatest advantage of a SBDT carried out under non-pumped conditions is that it is a simple cheap test that can be carried out with minimum equipment by a single person, and provides a considerable amount of information. If there is no tracer dilution the test indicates that flows in the borehole are very slow. In boreholes with stronger flows the tests demonstrate whether upflow and downflow are occuring and the location of inflows, outflows and crossflows. The principles of identifying flows described here could also be applied to tests carried out under pumped conditions.

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Appendix A. Mathematical formulation of the model

The formulation of the simulation model of a SBDT is outlined here.

The vertical volumetric flow rate in the borehole, $Q(z)$, is determined by the distribution of flux in, $q_{IN}(z)$, and flux out, $q_{OUT}(z)$, per unit depth:

$$\frac{dQ(z)}{dz} = q_{IN}(z) - q_{OUT}(z) \qquad \text{(A1)}$$

and the boundary conditions:

$$Q(0) = Q(L) = 0 \qquad \text{(A2)}$$

representing zero flow through the top and bottom of the open section of the borehole, of length L:

We assume perfect mixing across the borehole so at any depth we have a single concentration $c(z,t)$. This is assumed to be governed by the advection-dispersion equation in the form:

$$\pi r_w^2 \frac{\partial c(z,t)}{\partial t} + \frac{\partial Q(z)c(z,t)}{\partial z} = \pi r_w^2 \frac{\partial}{\partial z}\left[D(z)\frac{\partial c(z,t)}{\partial z}\right] + q_{IN}(z)c_b - q_{OUT}(z)c(z,t) \qquad \text{(A3)}$$

(From left to right, the terms represent: rate of change of mass, net vertical advective flux, vertical dispersive flux, lateral flux in, and lateral flux out.) r_w is the radius of the borehole. c_b is the background concentration of water entering the borehole.

$D(z)$ represents a dispersion coefficient which is considered a function of $Q(z)$ and hence of z. This has been assumed to take the form:

$$D(z) = \alpha \left| v(z) \right|^P \quad \text{where} \quad v(z) = \frac{Q(z)}{\pi r_w^2} \qquad \text{(A4)}$$

So α can be regarded as a 'generalized dispersivity'; this will have dimensions dependent on the power, P.

(We regard the formulation of Equation (A4) the least certain part of the model. An attempt was made to determine the value of P from the point dilution data but we found the data inadequate for this purpose. It does however seem likely that, assuming the form of (A4) is correct, that the value of P will lie in the range 1 to 2).

The code based on the above equations assumed $q_{IN}(z)$ and flux $q_{OUT}(z)$ to be piecewise constant with depth, so $Q(z)$ was determined analytically, from Equation (A1), to be a piecewise linear function of depth. Equation (A3) was then solved by a fully-implicit finite-difference method with time and depth intervals Δt and Δz , respectively. To help ensure stability, the code generated warnings if the conditions $2D(z)\Delta t/\Delta z^2<1$ and $v(z)\Delta t/\Delta z<1$ were not met at all depths at all times.

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Figure 1: Schematic of five different types of flow in boreholes with vertical flow

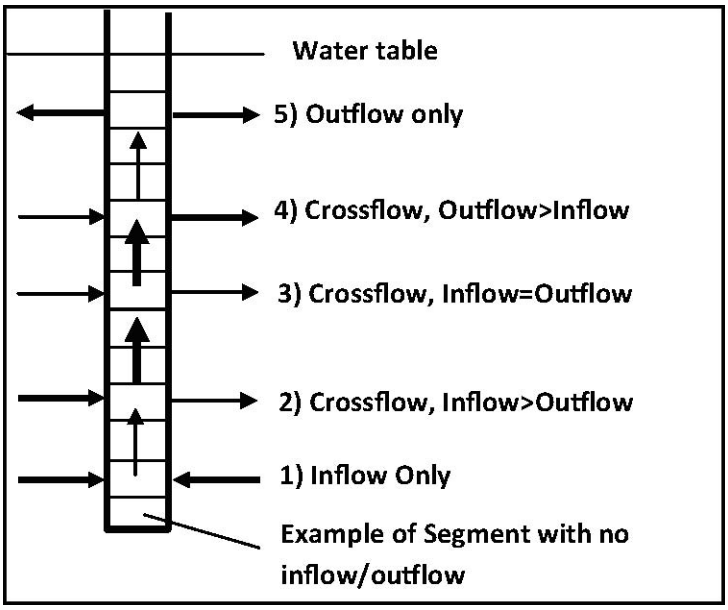

Figure 2: Simulations of SBDTs in boreholes: (a) with uniform diffuse horizontal flow; (b) with a zone of stronger horizontal flow creating a nick; (c) with a boundary between an upper layer with a uniformly high flow rate across the borehole and a lower layer with a uniform lesser flow rate. Numbers are sequential profiles simulated at regular time intervals.

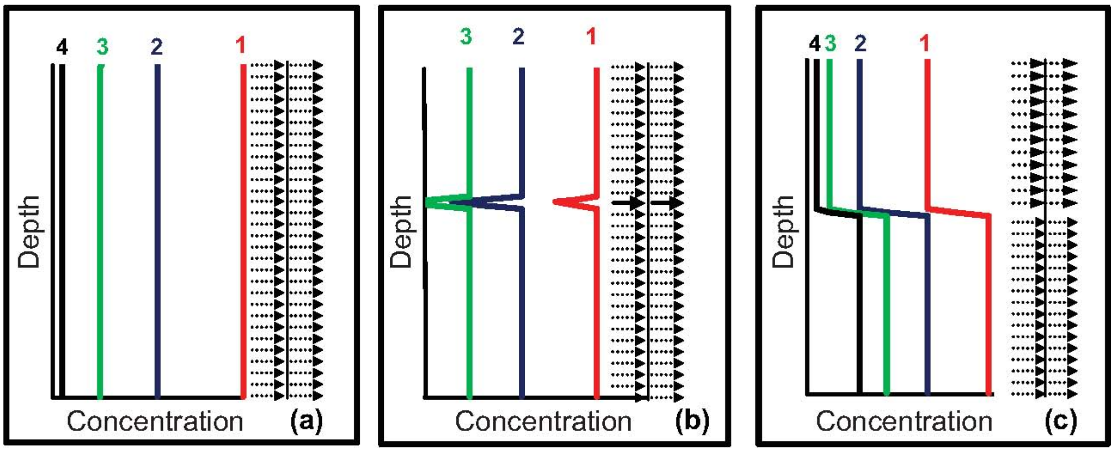

Figure 3: Simulations of SBDTs in boreholes with upward vertical flow. Numbers are sequential profiles simulated at regular time intervals.

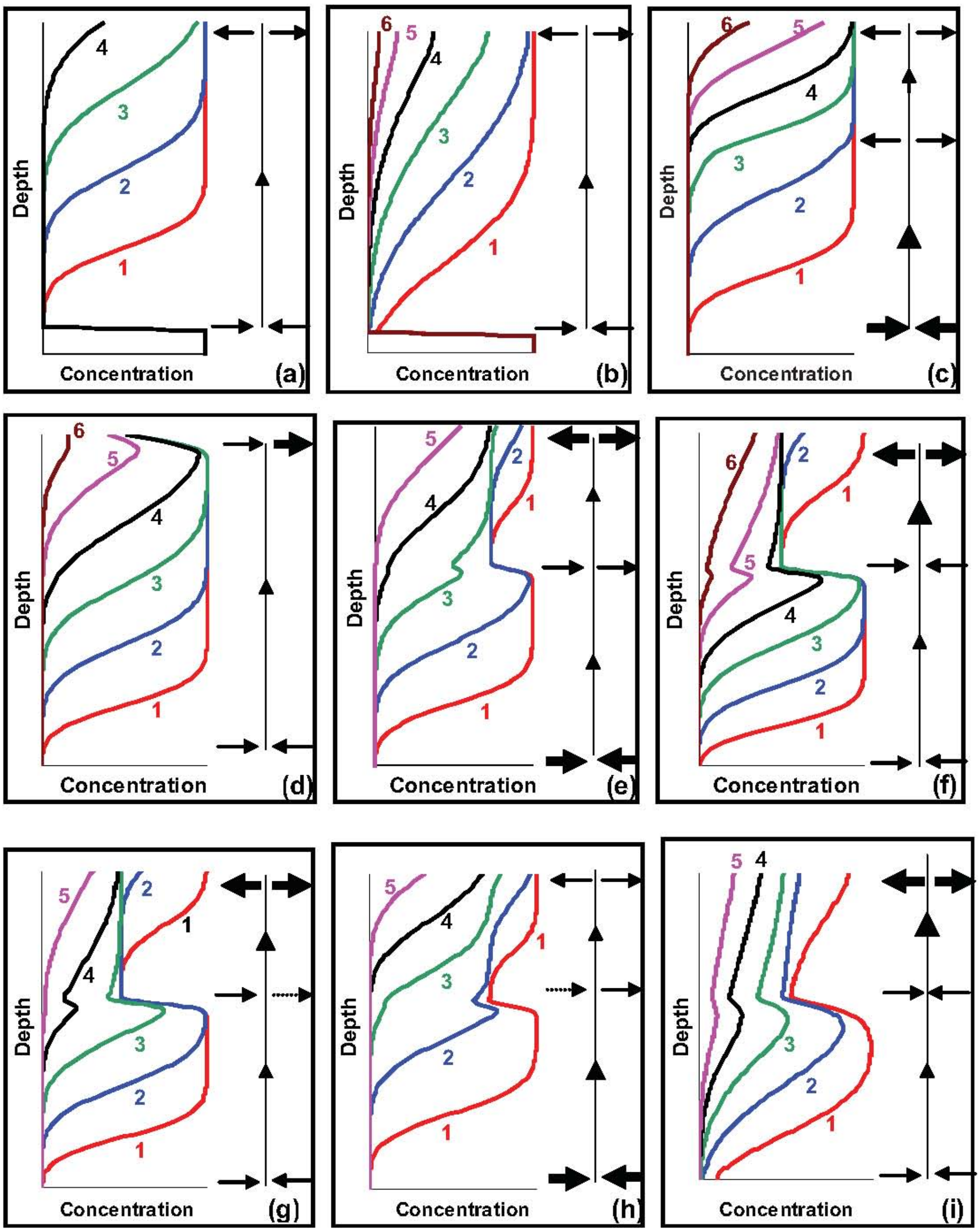

Figure 4: Simulation of a point emplacement SBDT in a borehole containing an in-flowing fracture within a section of vertical flow. (a) Concentration profiles at equally spaced times after emplacement. (b) The average tracer concentration in each profile plotted against time.

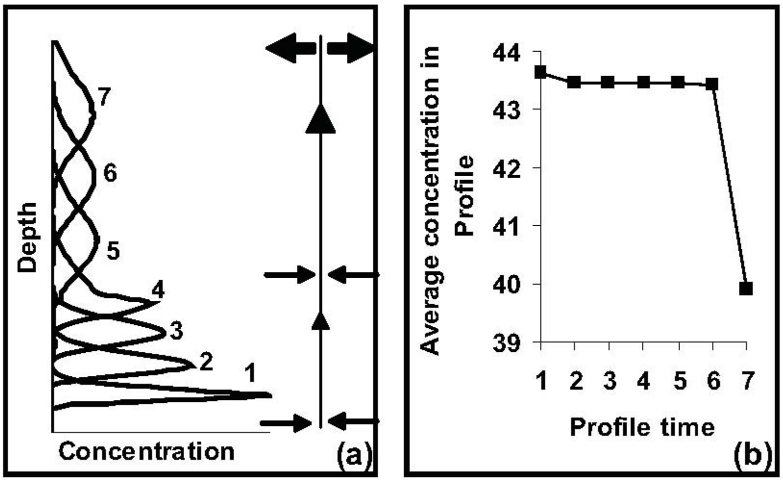

Figure 5: Simulation of a point emplacement SBDT in a borehole containing an out-flowing fracture within a section of vertical flow. (a) Concentration profiles at equally spaced times after emplacement of tracer. (b) The average tracer concentration in each profile plotted against time.

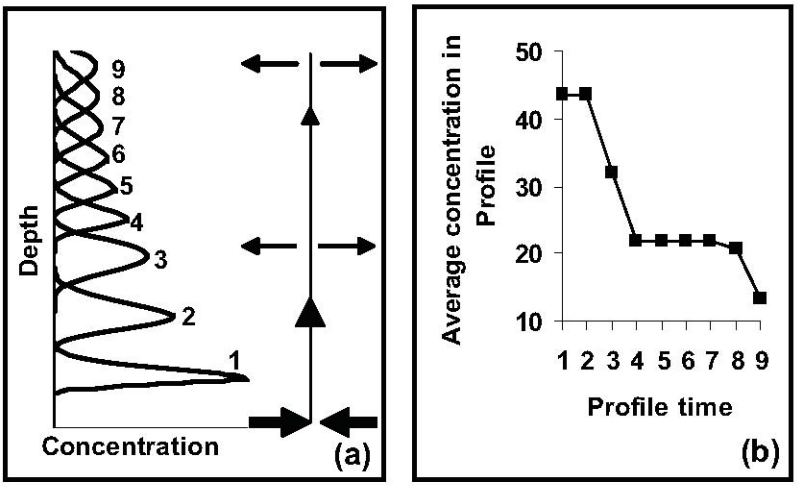

Figure 6: Results of (a) uniform emplacement between 52 and 115 m AOD at Barracks borehole and (b) a point emplacement at 54 m AOD.

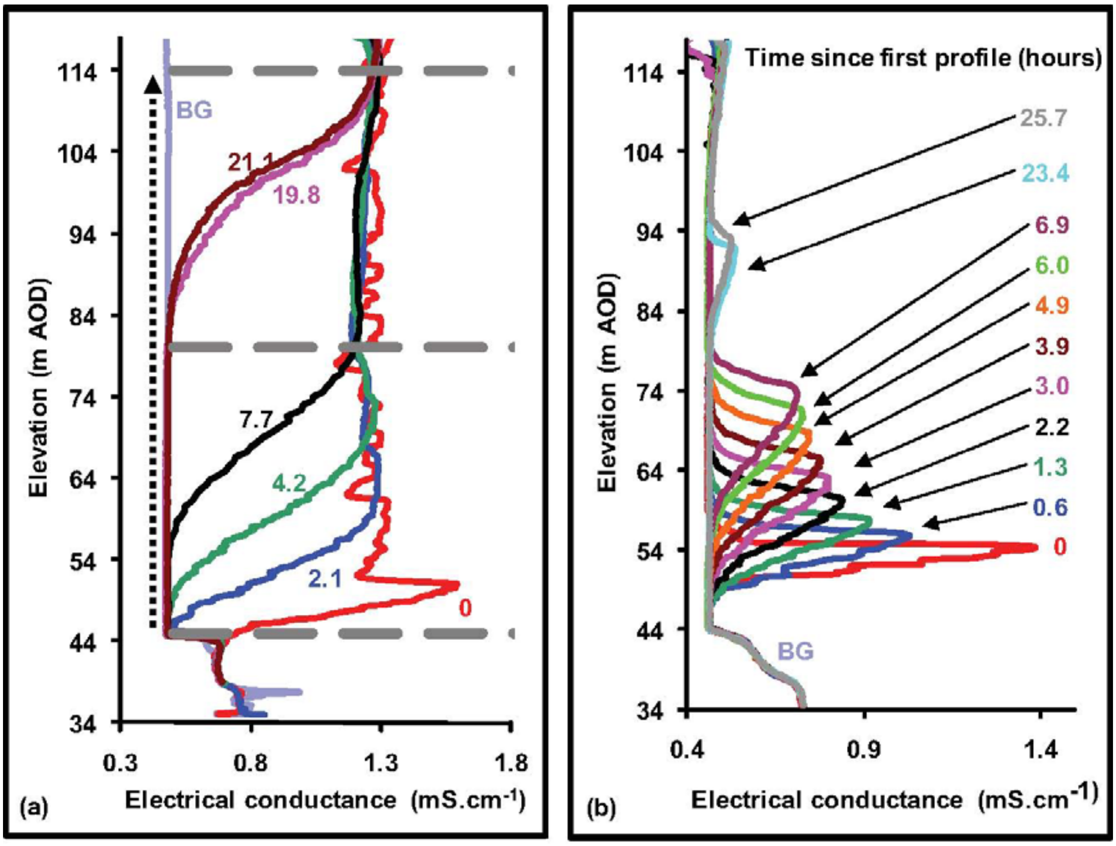

Figure 7: Results of (a) uniform emplacement between 18 and 52 m AOD at borehole Frilsham C and (b) point emplacement at 51.3 m AOD .

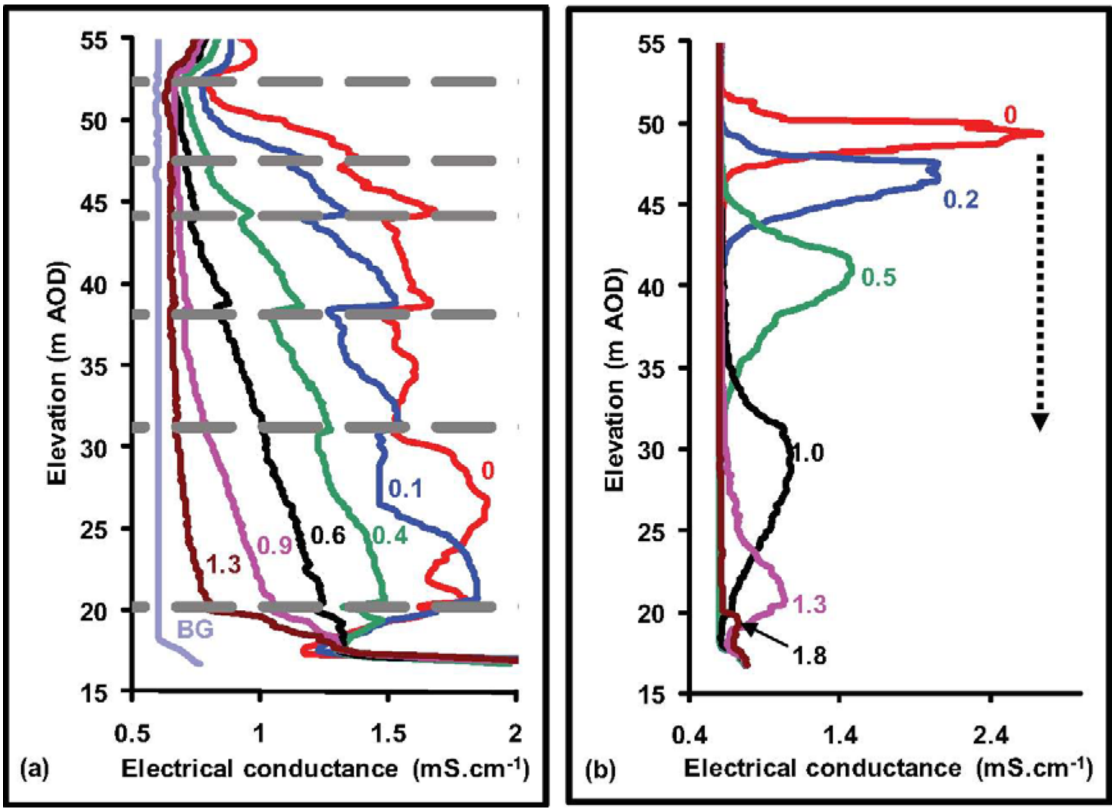

Figure 8: Results of (a) uniform emplacement between 55.5 and 70 m AOD at Bagnor borehole and (b) point emplacements at 63 m AOD (indicating upward flow) and 59 m AOD (indicating downward flow).

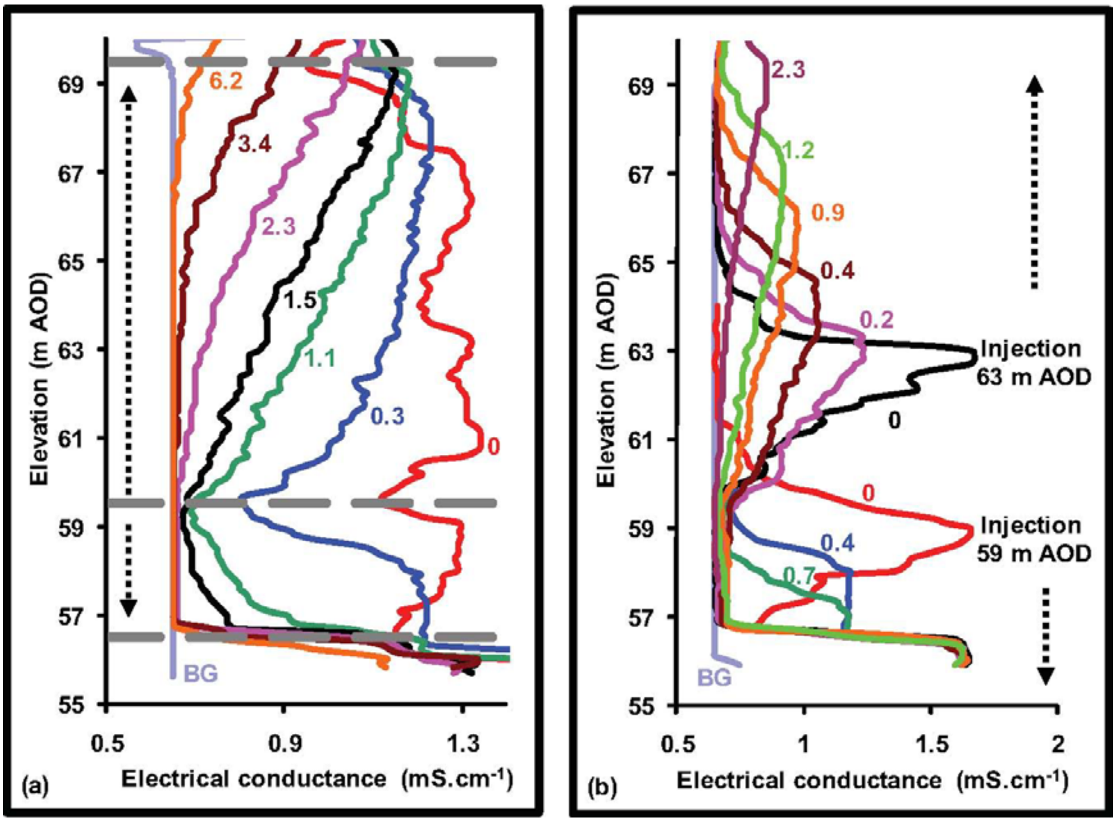

Figure 9: Combined plots showing change in average tracer concentration and upward migration of the tracer peak from electrical conductance profiles obtained following the point emplacement at 54 m AOD in Barracks

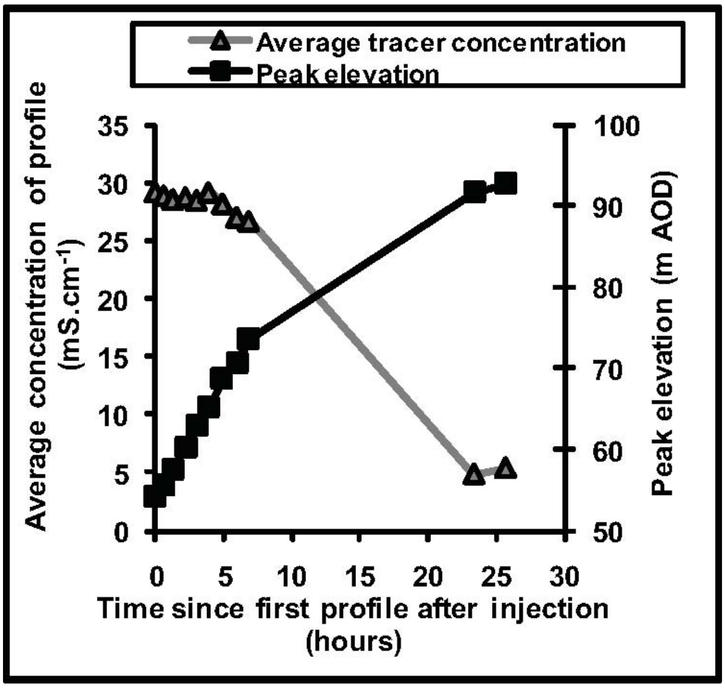

Table 1: Changes in vertical flow rate and tracer concentration as tracer passes different types of flowing fractures within a section of vertical flow

Flow type defined in Fig. 1	Effect on vertical flow rate	Effect on tracer concentration just down-flow of the fracture during uniform emplacement SBDTs	Change in total tracer mass in the section of borehole with vertical flow, during point emplacement SBDTs
1) Inflow only	Increased	Decreased	No change
2) Crossflow, Inflow> Outflow	Increased	Decreased	Decreased
3) Crossflow, Inflow = Outflow	None	Decreased	Decreased
4) Crossflow Outflow > Inflow	Decreased	Decreased	Decreased
5) Outflow only	Decreased	No change	Decreased

Table 2: Upward flow velocities in Barracks borehole

Time interval between profiles (hours after first profile)	Flow velocity ($m.h^{-1}$)	
0-0.6	2.3	Average flow velocity below fracture = 2.8 $m.h^{-1}$
0.6-1.3	2.8	
1.3-2.2	2.9	
2.2-3.0	3.4	
3.0-3.9	2.4	
3.9-4.9	3.4	
4.9-6.0	1.9	
6.0-6.9	3.3	
6.9-23.4	1.1	Flow velocity above fracture = 0.8 $m.h^{-1}$
23.4-25.7	0.5	

Table 3: Downward flow velocities in Frilsham C borehole

Time interval between profiles (hours after first profile)	Flow velocity ($m.h^{-1}$)
0-0.2	14.7
0.2-0.5	17.3
0.5-1.0	25.7
1.0-1.3	26.9
1.3-1.8	3.0