The dipole flow and reactive tracer test for aquifer parameter estimation

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ABSTRACT
Effective and efficient groundwater remediation requires site-specific knowledge of physical, chemical and biological aquifer properties. The dipole flow and reactive tracer test (DFRTT) is a single well test proposed as a cost-effective alternative to current aquifer parameter estimation methods. A steady-state dipole flow field is created by circulating groundwater between chambers isolated by the dipole tool. A tracer is released into the injection chamber and the breakthrough curve at the extraction chamber is interpreted with the DFRTT specific model. This paper describes the construction of a prototype dipole tool and results from ongoing field trials.

RÉSUMÉ
La remédiation efficace des eaux souterraine contaminée exige la connaissance site-spécifique des propriétés physiques, chimiques et biologiques d'un aquifère. Le flux de dipôle et test de traceur chimique réactif (DFRTT) est proposé comme une alternative aux méthodologies aux courant pour estimer les paramètres d'aquifère. Le champ de flux constant d'un dipôle est créé en circulant l'eau souterraine entre les chambres qui sont isolées par l'outil de dipôle. Un traceur est relâché dans la chambre d'injection et les concentrations observées dans la chambre d'extraction sont interprété avec le modèle spécifique de DFRTT. Ce papier décrit la construction de l'outil de dipôle prototype et les résultats des essais pratiques préliminaires.

1 INTRODUCTION

The effective and efficient remediation of impacted groundwater sites requires site specific information regarding the physical, chemical and biological properties of the aquifer (e.g., hydraulic conductivity, porosity, ion exchange capacity, redox capacity, and biodegradation potential). *Ex situ* measurement techniques involve the removal of aquifer material from the impacted site for analysis. Although these materials can be tested to determine aquifer properties such as hydraulic conductivity, porosity, and biodegradation potential, *ex situ* techniques may not be representative due to loss of sample integrity during collection, transport and experimental setup. *In situ* techniques are presently available for estimating aquifer physical and geologic characteristics (e.g. hydraulic conductivity, storativity, porosity, and fracture zones). However, few *in situ* methods can be used to estimate biological and chemical properties. The main advantage to choosing an *in situ* technique over an *ex situ* technique is the opportunity to perform *in situ* techniques over multiple depths and locations across an impacted site while minimizing disturbance to the aquifer sample. Recent work with partitioning inter-well tracer tests and push-pull tests indicate *in situ* approaches present an opportunity to identify additional aquifer parameters.

A multi-well *in situ* technique to estimate NAPL saturations is termed the partitioning inter-well tracer test (PITT). A PITT consists of the simultaneous injection of several tracers with different partitioning coefficients at one or more injection wells and the subsequent measurement of tracer concentrations at one or more monitoring wells (Jin et al. 1995). If NAPLs are present in the subsurface, the partitioning tracers lag behind the non-partitioning tracers. The extent of the separation of the breakthrough curves (BTCs) is a function of the NAPL saturation. PITTs are often conducted prior to and post remediation to quantify the effectiveness of the remediation activities.

The push pull test is an *in situ* technique which consists of the injection of a series of tracers at a monitoring well ("push") followed by the extraction of the tracers from the same well ("pull") (Istok et al. 1997). Depending on the application of the push-pull test, the injection and extraction of the tracers may be separated by a lag period to allow reactions to occur in the aquifer. Push-pull tests have been used to quantify microbial metabolic activities (Istok et al. 1997) and in situ reaction rate coefficients (Haggerty et al. 1998) in petroleum contaminated aquifers. Push-pull tests have also recently been used to estimate the natural oxidant demand of an aquifer (Mumford et al. 2004), and TCE degradation rates and permanganate consumption rates (Ko and Ji 2007). One of the major disadvantages to using the push-pull test to estimate aquifer properties is the need to determine groundwater velocity direction and magnitude during the test as they are responsible for transporting the injected solution down-gradient of the monitoring well (drifting).

1.1 The dipole flow test (DFT)

The dipole flow test (DFT) is a single-well test initially proposed by Kabala (1993) to determine the vertical distributions of the horizontal hydraulic conductivity (K_r), vertical conductivity (K_z) and the specific storativity (S_s) in the vicinity of a test borehole. Kabala's (1993) test setup consisted of three inflatable packers isolating two chambers in a cased well (Figure 1). The characteristic dimensions of the dipole probe are the chamber length (2Δ) and the distance from the center of the probe to the chamber center (the dipole shoulder – L) (Figure 1). A submersible pump located in the central packer pumps water at a constant rate from the aquifer into one chamber and transfers the water to the other chamber where it returns to the aquifer. Pressure transducers located in the upper and lower chambers monitor the pressure changes. The transient chamber pressure changes (drawup and drawdown) were matched to type curves with a Newton-Raphson algorithm to estimate the unknown aquifer parameters (K_r, K_z and S_s).

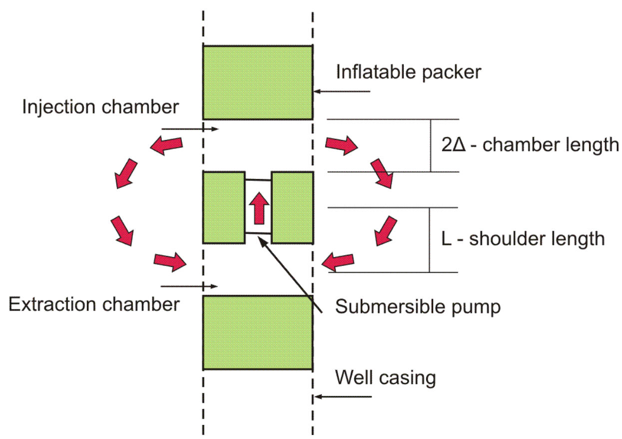

Figure 1. Schematic of the dipole probe and flow test where the arrows indicate flow direction. Adapted from Kabala (1993).

Zlotnik and Zurbuchen (1998) constructed and field tested a dipole probe with three configurations in a naturally developed well installed in an unconfined sand and gravel aquifer. The DFTs were conducted in 0.3 m increments along a 10 m well screen to determine the vertical profile of the horizontal hydraulic conductivity. The K_r profile obtained with the DFTs showed similar trends to the K profile obtained by grain size analysis of disturbed soil cores (Zlotnik and Zurbuchen 1998). In the analysis, Zlotnik and Zurbuchen used steady-state chamber pressure changes and assumed the aquifer to be isotropic to calculate the K_r values.

To expand the range of the dipole probe, the DFT was field tested in filter-packed wells constructed in a heterogeneous highly permeable aquifer (Zlotnik et al. 2001). Analysis of the specific drawdown data from the upper and lower chambers provided estimates of K_r in the immediate vicinity of the chambers. The results of the DFT analysis were consistent with K_r values estimated by permeameters, sieve analyses, flowmeters and pump tests (Zlotnik et al. 2001).

1.2 The dipole flow test with a tracer (DFTT)

Sutton et al. (2000) combined the DFT with a tracer test to determine dispersivity (α) as well as K_r and K_z. Once the dipole flow field reached steady-state, a conservative tracer was released into the injection chamber and the BTC was monitored in the extraction chamber. A recirculation mode was used where the extracted solution was re-injected into the injection chamber. Aquifer dispersivity was estimated by fitting a type curve to the ratio of the BTC time to front (arrival of 5% of the peak) and the time to peak concentration. Aquifer anisotropy was estimated based on a linear relationship with the BTC time to peak concentration as the dependant variable.

Sutton et al. (2000) field tested the DFTT in 0.11 m (4.5 in) naturally developed and filter-packed wells installed in a layered sand and silt aquifer. The DFTT prototype and test setup consisted of a 0.812 m central packer, two 0.61 m packers, 0.86 m chambers, a submersible pump, 12.7 mm diameter tubing, a fluorometer and pressure transducers. Tracer BTCs obtained by Sutton et al. (2000) in naturally developed wells exhibited numerous concentrations peaks. The authors attributed the initial peak as a small well skin effect and the highest peak as the aquifer peak. The BTC for the DFTT conducted in a well with an artificial filter pack had a much faster peak concentration arrival time due to preferential flow through the filter pack.

1.3 The skin effect

The skin effect is the preferential flow of water through the disturbed zone around the well casing (either an artificial filter pack or a naturally developed filter) which may cause errors in interpreting the results of a single-borehole test (Kabala and Xiang 1992). Since the DFT induces a predominantly vertical flow field, the short-circuiting through the disturbed zone may be more pronounced in the DFT than in other single-borehole tests (Kabala 1993). Xiang and Kabala (1997) investigated numerically the effect of the disturbed zone on the estimate of anisotropy ratios and found the estimated anisotropy ratio ($a^2 = K_r/K_z$) decreased with increasing hydraulic conductivity ratio between the disturbed zone (K_s) and the aquifer (K_s/K_r).

Peursem et al. (1999) used a numerical model to quantify the effect of a higher K_s near the well and observed the presence of the higher K_s reduced the radial extent of the streamlines. The effect was more pronounced for short distances between the injection and extraction chambers. Aquifer anisotropy was also found to increase the short-circuiting through the skin zone due to the increased vertical resistance to flow in the aquifer (Peursem et al. 1999).

Zlotnik et al. (2001) found slight evidence of the skin effect in the results of DFTs in 14 filter-packed wells in a heterogeneous highly permeable aquifer. Seven of the wells were installed with geotextile rings to prevent short-circuiting. The mean K_r was 7.0 x10^{-3} m/s and 4.0 x10^{-3} m/s for wells with geotextile rings and without geotextile rings, respectively. Zlotnik et al. (2001) note aquifer heterogeneity was not considered in the experimental design so definite conclusions about the skin effect could not be made; however, K_r estimates collected from pumping tests generally agreed with the overall estimates for K_r from DFTs so the skin effect does not appear to have greatly influenced the aquifer properties captured by the DFTs.

2 THE DIPOLE FLOW AND REACTIVE TRACER TEST (DFRTT)

The proposed dipole flow and reactive tracer test (DFRTT) is an extension of the DFTT; however, in place of a single non-reactive (conservative) tracer, a suite of non-reactive and reactive tracers (i.e. sorbing, degrading, biodegrading, etc.) are released into the injection chamber. The concentrations of the tracers are monitored in the extraction chamber to develop BTCs. The difference between the BTCs of the non-reactive tracers and reactive tracers is attributed to aquifer processes (e.g. sorption, biodegradation). The tracer BTCs are analyzed with the DFRTT interpretation model (Thomson et al. 2005) to estimate the desired aquifer parameters. A brief summary of the DFRTT model is provided in Section 3.

2.1 Prototype construction

The prototype dipole probe consists of three rubber inflatable packers separated by two chambers (**Error! Reference source not found.**). The inflatable packers were constructed at the University of Waterloo with rubber sleeves and brass end caps. The rubber is sealed to the end caps with fishing line and silicone. The packers are separated by adjustable spacer rods to create the injection and extraction chambers. The characteristic dimensions of the Waterloo prototype dipole probe are L = 0.22 m and Δ = 0.079 m.

A 3.18 mm (1/8 in) HDPE inflation line connects the packers to a valve and pressure gage at ground surface. Two vented pressure transducers (Huba Control Type 680 with range 0 – 2.5 bar) are mounted in the packers and connect to the chambers with 6.35 mm (¼ in) stainless steel tubing. The changes in current measured by the transducers are recorded by a data logger (Hobo Micro Station Data Logger) and used to determine the changes in pressure in the chambers.

2.2 Surface equipment for tracer tests

The surface equipment controls and monitors the injection and extraction streams (
Figure 3). The peristaltic pump (Masterflex modular drive with standard pump head) draws water from the extraction chamber through the 6.35 mm (1/4 in) ID HDPE extraction line and feeds the extracted stream to the fluorometer (Turner Designs 10AU Field Fluorometer). A three-way valve acts as a sampling port for the extraction stream. An acrylic flow-through cell (constructed by the University of Waterloo) with ports for four probes provides in-line monitoring of the extraction stream. The four in-line probes monitor dissolved oxygen, pH, electrical conductivity, and oxidation reduction potential and record the data on a field notebook computer. A syringe pump

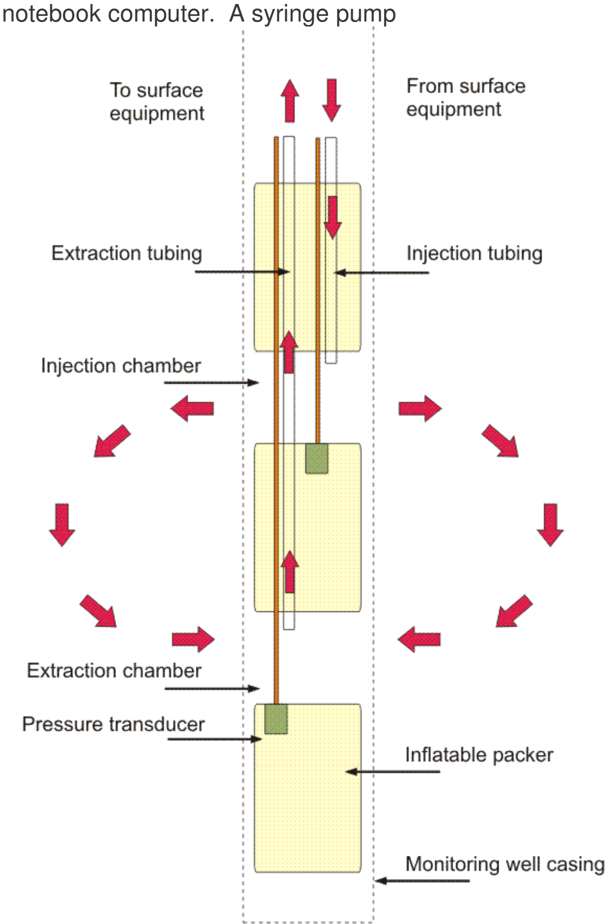

Figure 2. Schematic of the Waterloo prototype dipole probe and reactive tracer test setup (arrows indicate tracer flow direction). Scale is exaggerated 3x in the horizontal direction.

(Cole-Parmer Programmable Compact Syringe Pump) injects the tracer solutions into the extracted solution through a three-way valve. The tracer solution is mixed into the extracted solution with a static inline mixer (Cole-Parmer) and sampled via a three-way valve before being injected into the injection chamber of the dipole probe.

2.3 Potential reactive tracers

Numerous studies have been conducted regarding the use of tracers for identifying physical, chemical and biological properties of an aquifer (Davis et al. 1985; Smart and Laidlaw 1977). Potential tracers were chosen based on commercial availability, safety, required residence time and feasibility. In most field situations bromide or a fluorescent dye can be used as a non-reactive (conservative) tracer. The retardation of sorbing tracer can be used to estimate the reactive surface area of the solid phase. To estimate degradation properties, methanol or acetate can be used due to their rapid decay rates. The extent of the reaction can be calculated by: a decrease in the recovery of the electron donor (methanol or acetate), a decrease in the recovery of the electron acceptors (e.g. O_2, NO_3^-, NO_2^-, SO_4^{2-}, CO_2), or an increase in the recovery of the reduced electron acceptors (e.g. CO_2, NO_2^-, N_2O, Fe^{2+}, Mn^{2+}, HS^- (McKnight et al. 2003). A summary of potential DFRTT tracers is provided by Thomson et al. (2005).

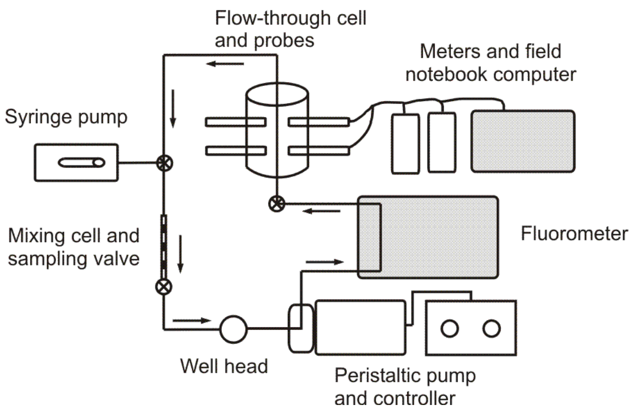

Figure 3. Schematic of surface equipment for controlling and monitoring dipole flow and reactive tracer tests.

3 INTERPRETATION MODEL

To estimate the aquifer properties of interest, a robust DFRTT-specific model was developed for the interpretation of tracer BTCs. Two assumptions underlie the model: 1) the physical and geochemical properties of the aquifer are homogeneous in the vicinity of the test well, and 2) the effects of ambient ground water flow on the dipole flow field are minimal. These assumptions allow for symmetry around the test well to be exploited. The conditions under which both of these assumptions are valid have been explored through the use of high resolution three-dimensional flow and reactive transport modelling.

The developed DFRTT model consists of a steady-state groundwater flow component and a reactive transport component. The backbone of the DFRTT model is the flow field which transports the various tracers from the injection to the extraction chamber. Depending on the nature of the available site information, the user has the option of calculating the dipole flow field by using either a stream function formulation or a hydraulic head formulation.

The reactive transport component of the DFRTT model accounts for well-bore mixing, advection, dispersion, diffusion, and various reactions with the solid phase (aquifer material) such as sorption, decay, and ion exchange. Further details of the DFRTT model are summarized in Thomson et al. (2005).

4 PRELIMINARY FIELD RESULTS

The field site for the preliminary field tests is located in an abandoned sand pit at Canadian Forces Base Borden (CFB Borden), approximately 80 km northwest of Toronto, Ontario, Canada. The site is underlain by an unconfined aquifer of glacio-lacustrine deposits of fine to medium sand. Although the aquifer is relatively homogeneous, distinct horizontal bedding features have been observed (Mackay et al. 1986). The sand is underlain by silts and clays approximately 9 m below ground surface (bgs) (MacFarlane et al. 1983).

Six 51 mm (2 in) PVC monitoring wells were installed at CFB Borden in June 2007. The wells comprise a 3 m screen (0.010 slot) located 2.5 – 5.5 m bgs. The wells were installed by jetting the casings into the sandy aquifer material. Four wells were installed with naturally developed filter packs while the remaining two wells were installed with 46 mm filter packs (grade 0 sand). All monitoring wells were developed by repeatedly surging and pumping the wells.

4.1 Hydraulic test results

DFTs were conducted in the monitoring wells at CFB Borden to determine high resolution vertical profiles of radial hydraulic conductivity. The DFTs were conducted at 3 flow rates at each 0.10 m increment from 3.0 – 4.2 m bgs. The changes in pressure in the chambers were recorded and used to estimate K_r with the relationship derived by Zlotnik and Ledder (1996) as given by

$$K_r = \frac{Q}{2\pi(\Delta h)\Delta}\ln\left(\frac{4a\Delta\Phi(\lambda)}{er_w}\right), \text{ with} \qquad [1]$$

$$\Phi(\lambda) = \left(\frac{\lambda^2}{\lambda^2-1}\right)^{\lambda/2}\left(\frac{\lambda-1}{\lambda+1}\right)^{1/2} \text{ and } \lambda = \frac{L}{\Delta}, \qquad [2]$$

where Q is the flow rate, Δh is the sum of the drawdown and drawup in the respective chambers, *a* is the anisotropy ratio $(K_r/K_z)^{0.5}$, e = 2.718…, and r_w is the well radius. The function Φ(λ) increases from 0.5 to 1.0 as λ increases and *a* must either be assumed or known prior to the test.

The DFT estimates for K_r across the tested depths ranged from 1.6 $\times10^{-5}$ – 2.7 $\times10^{-5}$ m/s (Figure 4) with a mean value of 2.2 $\times10^{-5}$ m/s and standard deviation of 3.8 $\times10^{-6}$ m/s. The overall trend of K_r showed increasing K_r values with depth. As previously observed in field DFTs (Zlotnik and Zurbuchen 2003; Zlotnik et al. 2001), the drawups and drawdowns in the dipole chambers were not always similar for a given DFT. However the differences between the drawups and drawdowns were considered to be small enough for the estimation of K_r.

To benchmark the DFT, double-packer tests were conducted in the monitoring wells (Hvorslev 1951). While the dipole flow and double-packer tests are not directly comparable as they test different portions of the aquifer (the DFT tests a larger portion of the aquifer) and induce different flow patterns around the monitoring well (the double-packer test induces primarily horizontal flow), the overall trends of increasing K_r with depth are similar (Figure 4).

In order to provide a mean hydraulic conductivity for the entire screened area, slug tests were also conducted at CFB Borden. Following the Bouwer and Rice method (Bouwer 1989; Bouwer and Rice 1976; Butler et al. 1996), the mean K_r was estimated to be 2.0 $\times 10^{-5}$ m/s (9.3 $\times 10^{-7}$ m/s standard deviation) which is consistent with the DFT estimates.

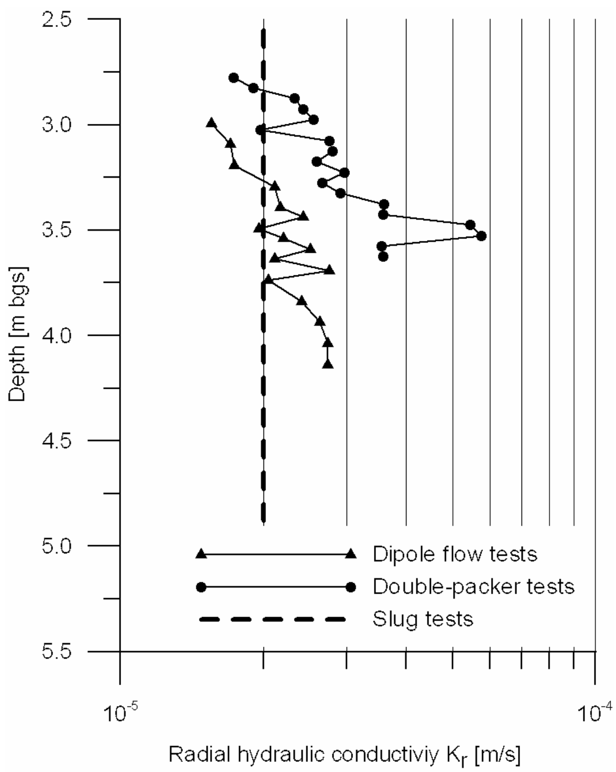

Figure 4. Hydraulic conductivity estimates for monitoring well S07-6 (screened 2.5 – 5.5 mbgs) as determined by DFTs, double-packer tests and Bouwer and Rice method slug tests.

4.2 Tracer test results

Between June and December 2007, 22 tracer tests were conducted in the monitoring wells installed at CFB Borden. A typical DFRTT was conducted at flow rate 550 mL/min with a two minute tracer injection period. Tracer concentrations were then monitored in the extracted solution for approximately 240 min.

The DFRTT BTCs are characterized by two concentration peaks followed by a long tail (Figure 5). The first peak is caused by tracer circulation through a small skin or disturbed zone near the well casing. The second peak is tracer movement through the undisturbed aquifer. The long tail of the BTC is due to the recirculation of the tracer. Tests conducted without tracer recirculation will have lower concentration tails. The tracer concentrations are normalized by the injected tracer concentration (C_o).

The magnitude of the individual concentration peaks of the BTC is determined by the relative conductivities of

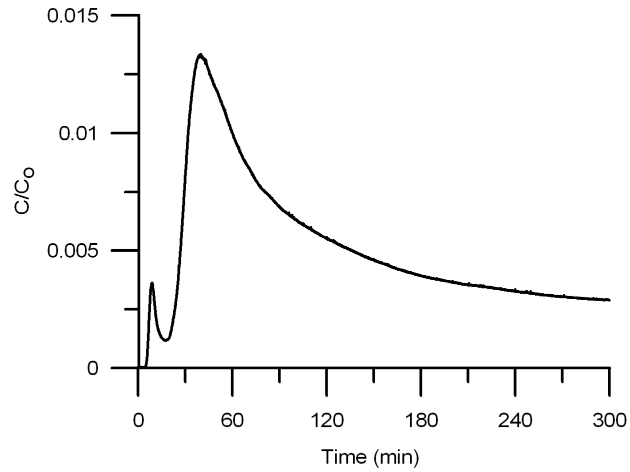

Figure 5. Conservative tracer BTC (scaled by injected concentration C_o) at 4.4 m bgs in monitoring well S07-6 at CFB Borden on December 5, 2007.

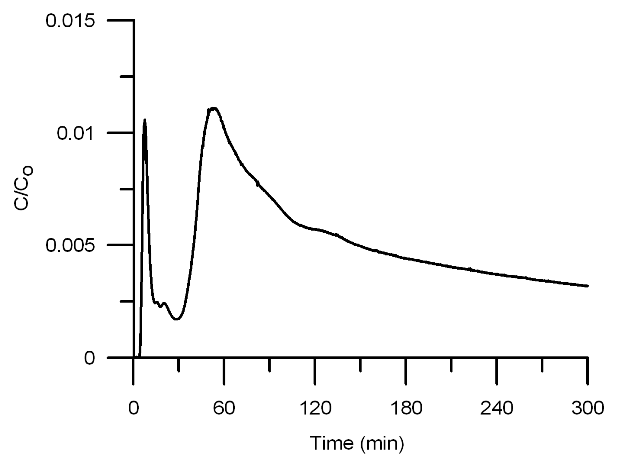

Figure 6. Conservative tracer BTC (scaled by injected concentration C_o) at 5.0 m bgs in monitoring well S07-6 at CFB Borden on December 13, 2007.

the zones. BTCs from tests conducted in areas with limited disturbed zones will exhibit low skin peaks

(Figure 5). In contrast,

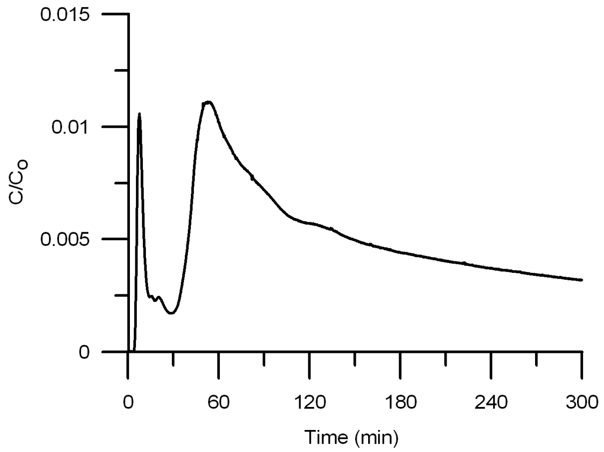

Figure 6 shows a BTC with a more prominent skin peak indicating a more pronounced disturbed zone in the vicinity of the test location. The conservative tracer tests shown in Figure 5 and

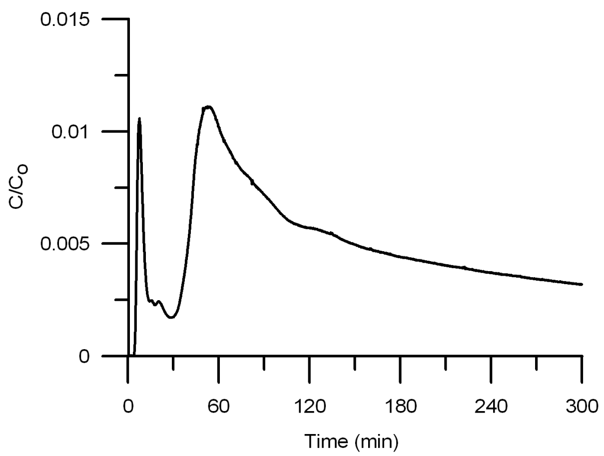

Figure 6 were conducted in the same monitoring well at different depths, 4.4 and 5.0 mgs, respectively.

For tests conducted at approximately 550 mL/min flow rates in monitoring wells without artificial filter packs, the time to the peak concentration ranged from 13 to 100 min. This is an indication of some of the variability within the aquifer. DFRTTs conducted in filter-packed wells exhibited much faster times to peak concentrations and much higher normalized peak concentrations (data not shown).

Tracer tests conducted in the same well at the same depth at the field site have shown good repeatability between tests (data not shown). Good test repeatability is demonstrated by similar peak tracer concentrations and similar times to peak concentrations.

5 PRELIMINARY MODEL RESULTS

Once the tracer BTCs are collected in the field, they are interpreted with the DFRTT numerical model. While the modelling and parameter estimation efforts are in their early stages, this paper presents some preliminary results.

Figure 7 shows the field data from a conservative tracer test (December 5, 2007 test as shown in Figure 5) and the best model fit to date. A good model fit to the field data is achieved for the skin peak however only the time to aquifer peak and not the magnitude of the aquifer peak are fitted by the DFRTT model. The model estimates a narrow skin zone along the well casing (K_s = 8.6 x10^{-5} m/s) with a higher conductivity than the aquifer (K_r = 2.7 x10^{-5} m/s). The estimates of Kr from the DFRTT model are consistent with those obtained from the DFT. The aquifer was estimated as slightly anisotropic (K_r/K_z = 1.1) and longitudinal dispersivity (α_L) was estimated to be 0.003 m.

Results from the DFRTT model suggest the model BTCs are sensitive to the distance between the extraction and injection chambers (2L). The relative height of the skin and aquifer peaks is sensitive to the ratio of the skin and aquifer hydraulic conductivities (K_s/K_r) (**Error! Reference source not found.**).

6 CONCLUSIONS

The effective and efficient remediation of impacted groundwater sites requires site specific information regarding the physical, chemical and biological properties of the aquifer. The DFRTT is being developed as an aquifer assessment tool which can be tailored to estimate the desired aquifer parameters.

The vertical profiles of K_r estimated by the dipole tool are similar to those obtained by other hydraulic conductivity estimation methods. At the time of writing, 22 tracer tests have been completed with the dipole probe at CFB Borden. The tracer tests are being interpreted with the DFRTT model to estimate aquifer parameters. Field work planned for 2008 field season includes additional tracer tests at CFB Borden to determine optimal test setup for different parameters. Following the CFB Borden field trials, DFRTTs will be conducted at well-documented contaminated sites in Ontario.

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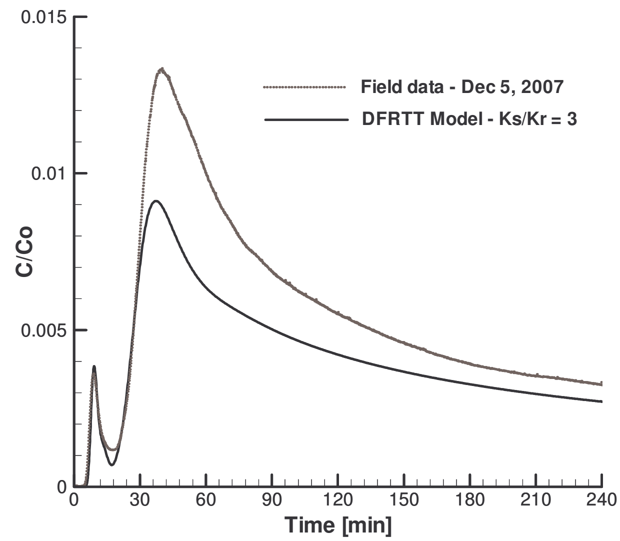

Figure 7. DFRTT model interpretation for December 5, 2007 conservative tracer test at 4.4 m bgs in monitoring well S07-6 at CFB Borden.

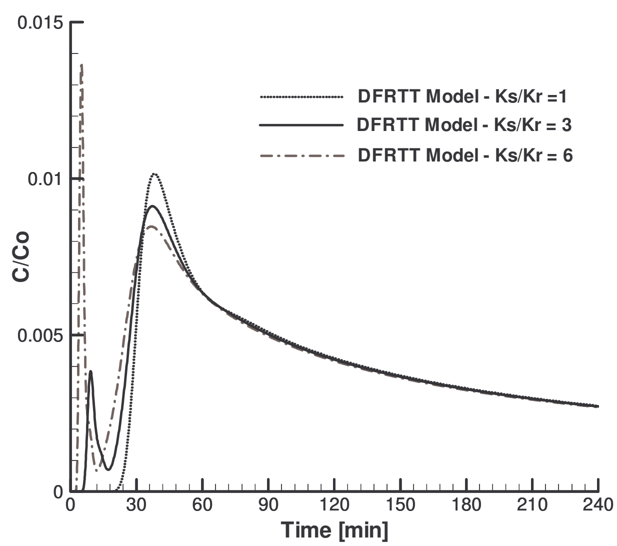

Figure 8. Sensitivity of DFRTT model interpretation to K_s/K_r (K_s/K_r = 1 (no skin), 3 and K_s/K_r = 6) for December 5, 2007 conservative tracer test at 4.4 m bgs in monitoring well S07-6 at CFB Borden.

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