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DETERMINING AND MAPPING DNAPL SATURATION VALUES FROM NONINVASIVE GPR MEASUREMENTS

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ABSTRACT

With the possible application to fluid-flow modeling, saturation values of dense nonaqueous phase liquids (DNAPLs) may be determined and mapped through the use of measurements acquired by noninvasive ground penetrating radar (GPR). In 1991, a controlled injection of perchloroethylene (PCE), a common DNAPL, was performed by the University of Waterloo into an isolated, water-saturated, sandy aquifer at Canadian Forces Base Borden. One of the geophysical techniques employed by the U. S. Geological Survey to monitor the location and migration of the subsequent plume was 500-MHz surface GPR acquired on a one meter grid spacing across the nine meter by nine meter cell over a period of 340 hours. This paper describes how full-waveform GPR modeling of these data for relative dielectric permittivity versus depth may be used to calculate and map spatial distributions of DNAPL saturation over time using recursive solutions of the Bruggeman-Hanai-Sen (BHS) mixing formula.

INTRODUCTION

Dense nonaqueous phase liquids (DNAPLs) comprise one of the largest classes of groundwater contamination (Lucius and others, 1992; Pankow and others, 1996). Sources of subsurface DNAPL contamination include seepage from insufficiently lined landfills, improper disposal, leakage from storage or processing equipment such as tanks, and accidental spills. Relatively small concentrations of solvent liquids, on the order of parts per billion, have the capacity to contaminate widespread amounts of groundwater to unacceptable levels. Concentrations of contaminants at a site are commonly monitored by analyzing groundwater samples obtained from wells located throughout the site. The irregular and unpredictable migration patterns of the contaminants make mapping the extent of the contamination difficult with point measurements. In addition, if an invasive well does intersect a pool of contaminant, it has the undesirable potential of re-mobilizing an otherwise stable system.

One possible complement to this monitoring approach is the use of surface ground penetrating radar (GPR); a noninvasive geophysical method sensitive to contrasts in subsurface electromagnetic properties, including relative dielectric permittivity. If DNAPL is introduced to a water-saturated, sandy aquifer, for instance, the DNAPL exhibits electrical properties distinctly different from the water it displaces in the pore space, and the DNAPL-saturated sand may appear as a reflector on a radar scan (Redman and others, 1991). The main advantage of the use of GPR is its ability to continuously and noninvasively sample 3D data over time, rather than at discrete point locations, with a better resolution-to-cost ratio than other geophysical methods.

The main application of GPR explored in this paper is the use of full-waveform GPR modeling to determine and map changes in DNAPL saturation values over time and space. Results of GPR modeling include the ability to resolve relative dielectric permittivity (RDP) versus depth, which may then be used to calculate pre-spill porosity and post-spill DNAPL saturation values. This process, outlined in figure 1 and discussed in detail below, may then be useful in developing conceptual models of layering and deriving porosity and saturation input values for use in other applications such as fluid-flow modeling.

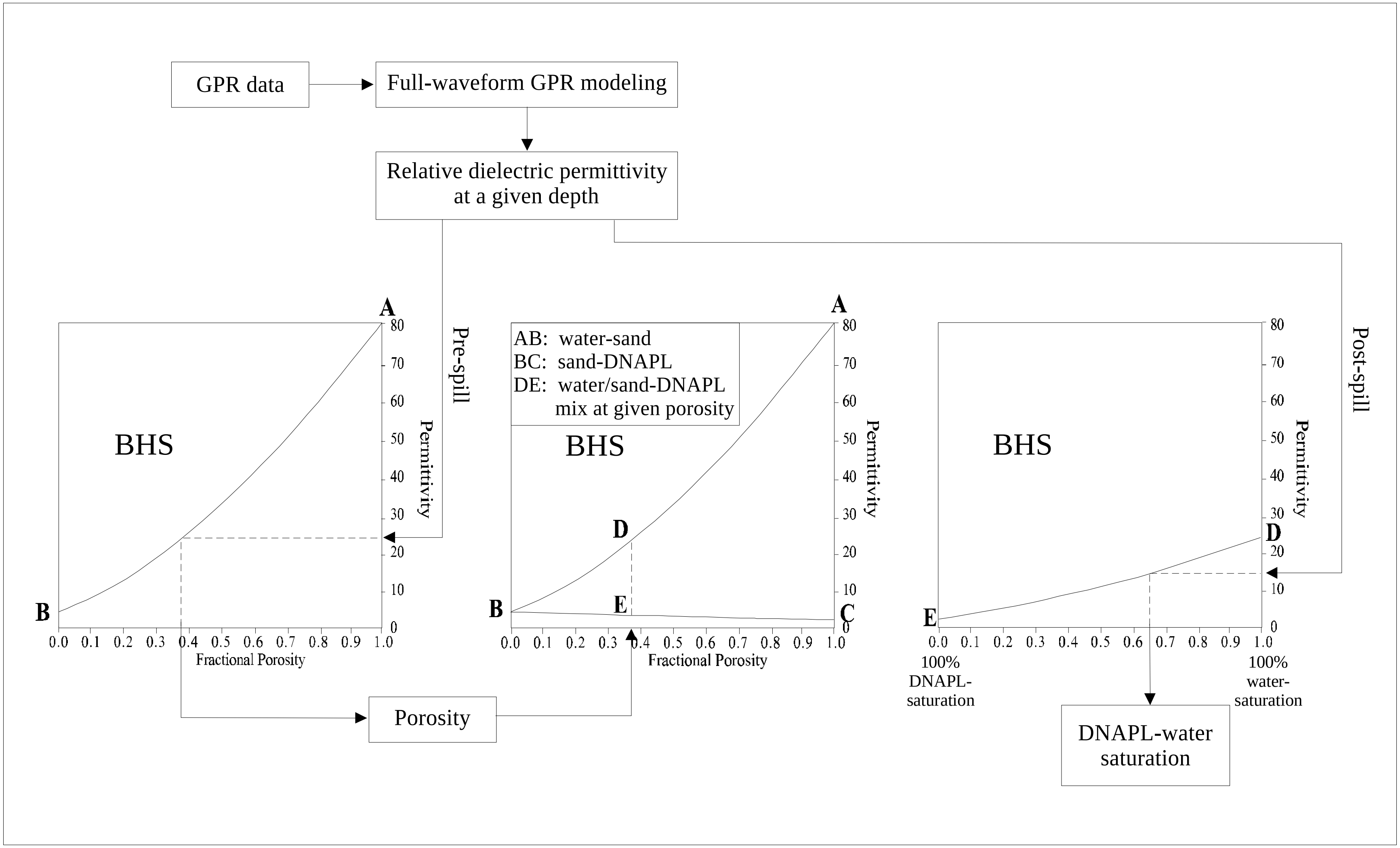


Figure 1: Flow-chart of determining DNAPL-water saturation values from noninvasive GPR measurements.

GPR DATA

The GPR data used in this study were acquired in 1991 at Canadian Forces Base Borden by the University of Waterloo in conjunction with the U. S. Geological Survey. Brewster and others (1995) provide a general description of the experiment and the various geophysical methods used to monitor the migration of DNAPL from the intentional injection of PCE into an isolated cell within the saturated zone of the natural sandy Borden aquifer. Of the various geophysical data available, the 500-MHz GPR data presented in Sander and Olhoeft (1994) are used in this study.

As described by Brewster and others (1995), the Borden cell was 9 x 9 x 3.3 m deep, isolated on the four sides by double steel sheet piling and underlain by an aquitard of clay size particles (Bauman, 1989). The sand in the natural aquifer consists of fine to medium grained particles with silt lenses present, deposited in a progradational foreshore environment (Bohla, 1986). The cell is considered to have been fully water saturated with the water table artificially maintained at 15 cm beneath the ground surface. The ground surface of the cell was smoothed prior to data acquisition, with surveying data available (Sander and Olhoeft, 1994) for topographic correction.

Approximately 770 liters of PCE over a period of 70 hours were injected under constant head into the center of the cell with an outlet located 0.6 m below the ground surface. Sander and others (1992) describe data acquisition and processing. Using a GSSI SIR-7 radar system, surface GPR data were acquired over a total period of 340 hours measured from the time the injection began. Data presented in this report were acquired within the first 22 hours, by which time the GPR data show that the PCE formed a second and third layer within the cell. Continuous surface data were collected along a grid of lines spaced 1 m apart and are later horizontally corrected by rubbersheeting and vertically corrected for topographic variations and velocity. For this report, other processing of the data included binning and smoothing.

A great deal of qualitative information on the migration behavior of the DNAPL in the Borden cell may be ascertained from visual inspection of the GPR profiles over time and is provided by Sander and others (1992) as well as by Sander (1994). Additional interpretation is also provided by Brewster and others (1995) and Greenhouse and others (1993). Figure 2 demonstrates how an accumulation of DNAPL is seen as a bright reflector in the GPR record. Comparing pre- to post-spill images and traces helps determine which features are pre-existent and which are due to the migration of the DNAPL. The most prevalent feature governing DNAPL flow above 2 m is the soil horizon occurring at approximately 1 m in depth, seen as an increasingly bright reflector as the horizon fills with DNAPL over time. This horizon bows slightly upward just under the injection point and dips in the form of a paleochannel trending roughly parallel to the southeast edge of the cell. For more quantitative information on porosity, DNAPL pool thickness, and fluid saturation, full-waveform GPR modeling is required. Sander (1994) describes initial attempts at such modeling, and provides a framework for the research presented here.

ONE-DIMENSIONAL FULL-WAVEFORM GPR MODELING TO DETERMINE RELATIVE DIELECTRIC PERMITTIVITY VERSUS DEPTH

One-dimensional full-waveform GPR modeling can provide information on geologic layers and their associated electromagnetic properties. GPR modeling entails the calculation of changes in the transmitted and reflected waves as functions of electromagnetic properties such as RDP, electrical conductivity, and magnetic permeability, as well as layer thickness and depth as the pulse is propagated through user-defined layering. Solutions are non-unique, but may be constrained by the user with prior knowledge of the medium. In this case, ranges of conductivity and RDP were available from many of the cited references. The GPR full-waveform modeling software applied to the Borden data in this research is a module of GRORADAR™ version 8.99 (Olhoeft, 1998), which is an extension of GPRMODEL by Powers and others (1992).

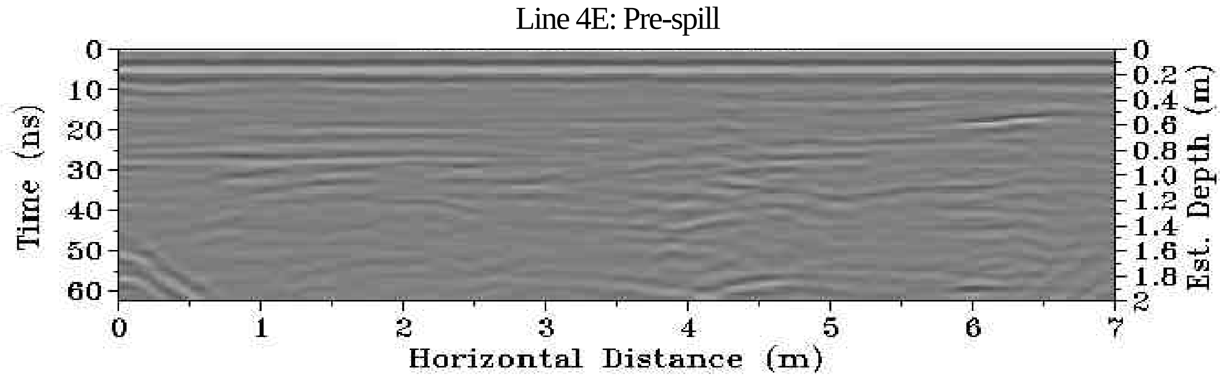


Figure 2a: Pre-spill radar image along line 4E, located 4 m from, and parallel to, the southwest edge of the cell. In this image, the horizontal distance 0 m corresponds to 1 m inward from the northwest edge of the cell. A single value of RDP=25 was used to provide the estimated depth scale.

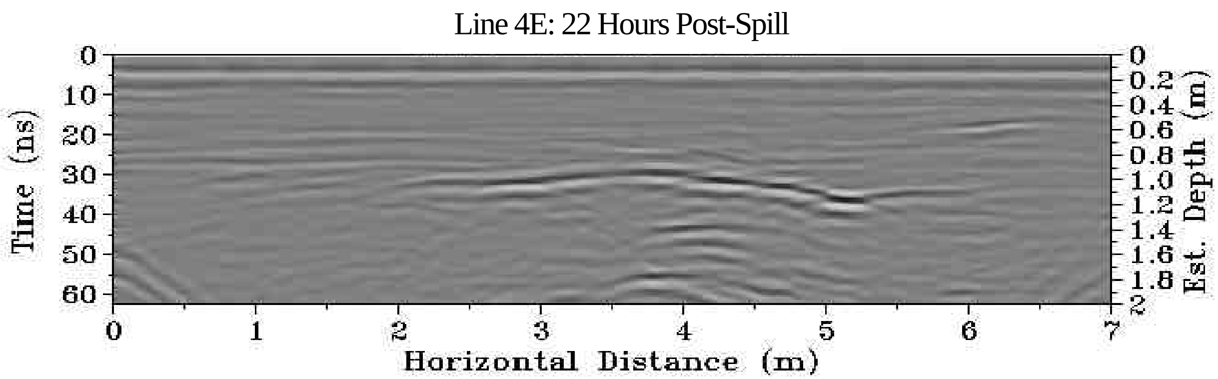


Figure 2b: Radar image in same location as that in Figure 2a, measured 22 hours post-spill. DNAPL, identified as the bright reflector not seen in the pre-spill image, has migrated laterally and begun to fill the paleochannel located at roughly 5 m horizontal distance and 1.2 m in depth.

To pattern the effects as DNAPL was injected into the cell, model values of RDP, electrical conductivity, and depth were varied to indicate DNAPL displacing water in the pore spaces. As PCE has a much lower RDP (2.3) than water (80), and slightly lower than the dry sand of the aquifer (4.5), it is expected that the bulk permittivity of a water-saturated layer will decrease with the infiltration of DNAPL (Lucius and others, 1992). Magnetic permeability was assumed to be that of free space and did not vary with time. The measured electrical conductivity of the Borden water was approximately 50 mS/m (Redman, 1991), while the dry sand and the DNAPL have conductivity values less than 1 mS/m. The measured electrical conductivity of the water-saturated sand was 9-10 mS/m. Therefore, in the models, the electrical conductivity decreases incrementally in a range of 9.5 to 0.25 mS/m as the bulk RDP decreases from 25 to 9 to model the effects of the more conductive and higher permittivity water being displaced by the resistive and lower permittivity DNAPL. It is also expected that the apparent thickness of a given layer (corresponding to the depth) will vary as migrating DNAPL encounters a layer of lower permeability, spreads laterally, then thickens upward into the higher permeability horizon (see figure 6 to observe this thickening over time). A Ricker wavelet with a center frequency of 273 MHz (approximating the output of a 500 MHz antenna after downloading due to ground coupling) was used as the starting model wavelet, and a gain of 6.0 dB was applied to all model traces.

While the true layering of coarse and fine-grained units within the cell is likely complex and locally variable, in modeling one tries to use the simplest models to match the data. Though a three-layer model adequately described the portion of the cell modeled by Sander (1994), further modeling throughout the cell indicated the necessity for at least a five-layer model for a good match with broad consistency. GPR modeling of data over a 4 x 4 m portion of the cell at a 1 m spacing surrounding the injection point led to the five-layer conceptual model describing the cell in terms of RDP versus depth over time. Figure 3 shows an example of five-layer model results at a node point located 5 m along line 4E measured from the northwest edge of the cell at times 0, 14, and 22 hours post-spill (see Table 1 for pre-spill conditions). As expected, the amplitude of the field trace increases with the introduction of DNAPL into the more permeable zone located at approximately 1 m in depth. The zone above these layers is held constant at a relative permittivity of 25, the background for the cell (Sander and others, 1992), because comparison of the traces indicates that this zone does not change appreciably within the first 22 hours. Further layers may be indicated in the zone below the three intermediate layers, but were not modeled at this time and were assumed to remain roughly constant at a relative permittivity of 25 within the first 22 hours.

DETERMINING POROSITY AND DNAPL SATURATION VALUES: THE BHS MIXING FORMULA

The relationship of porosity to the complex dielectric permittivity of two materials may be described by the Bruggeman-Hanai-Sen (BHS) formula (Sen and others, 1981):

$$\varphi = \frac{(\varepsilon^*_{matrix} - \varepsilon^*_{comp})\,(\varepsilon^*_{fluid} / \varepsilon^*_{comp})^C}{(\varepsilon^*_{matrix} - \varepsilon^*_{fluid})}$$

where:

- φ = fractional porosity
- ε^*_{matrix} = complex relative dielectric permittivity of the matrix
- ε^*_{fluid} = complex relative dielectric permittivity of the fluid
- ε^*_{comp} = complex relative dielectric permittivity of the composite
- C = shape factor (1/3 for spherical grains).

The BHS is a volumetric mixing formula describing a physical mixture assuming no interaction between the matrix and the fluid and no scattering (e.g. long wavelength compared to pore and particle sizes). These assumptions are valid for the quartz silica sand of the Borden aquifer, which does not react with water or PCE. In addition, PCE does not react with water.

The first step in applying the BHS formula to the GPR model results is to determine the porosity of the pre-spill, water-saturated Borden sand (figure 1) at five main soil horizons of the cell where variations in the pre-spill radar data are assumed to be due to variations in porosity. In this step, ε^*_{matrix} refers to the relative permittivity of the dry Borden sand (ε^*_s) at a given depth horizon (approximately 4.5); ε^*_{fluid} is the relative permittivity of the Borden water (ε^*_w) (approximately 80 with a conductivity of 50 mS/m); and ε^*_{comp} refers to the relative permittivity of the sand-water composite ($\varepsilon^*_{s\text{-}water}$) modeled from the pre-spill GPR data at each horizon (variable from approximately 19 to 27). Assuming spherical matrix particles and full saturation of the aquifer, the fractional porosity of the pre-spill water-saturated sand is calculated for every GPR model location (figure 1, curve A-B). Table 1 summarizes the results of these pre-spill fractional porosity calculations, and figure 4 shows the pre-spill porosity distribution in the modeled area of the cell for layer II. Depth to bottom of a given layer varies according to location within the cell.

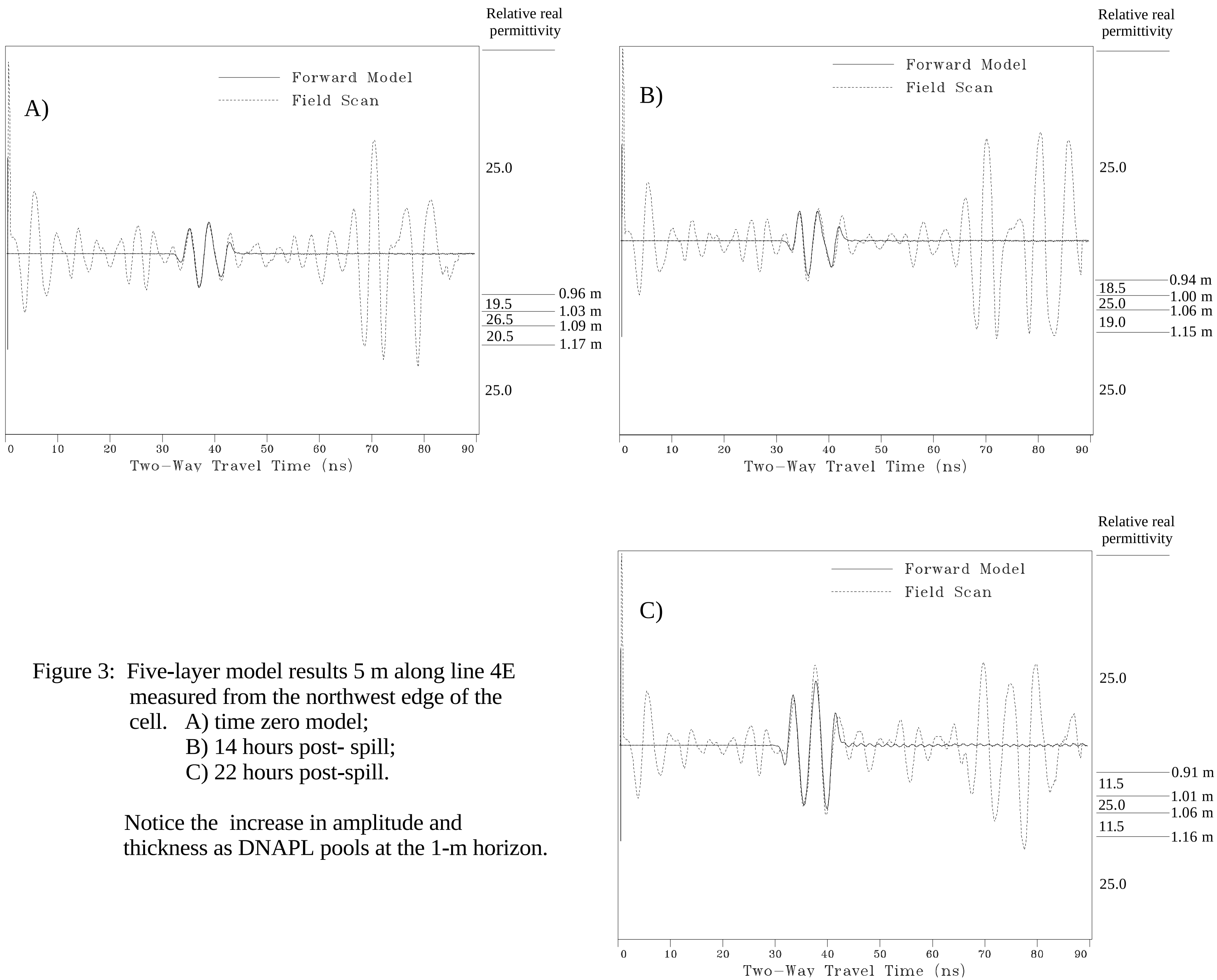


Figure 3: Five-layer model results 5 m along line 4E measured from the northwest edge of the cell. A) time zero model; B) 14 hours post- spill; C) 22 hours post-spill.

Notice the increase in amplitude and thickness as DNAPL pools at the 1-m horizon.

Table 1: Conceptual model of pre-spill cell conditions

	Dielectric Permittivity	Depth to Bottom (m)	Description	Fractional Porosity (%)
I	25	0.63 – 1.00	average cell layer	40
II	19 – 23	0.70 – 1.05	finer than average	31 – 37
III	22 – 27	0.74 – 1.10	coarser than average	35 – 41
IV	20 – 23	0.89 – 1.17	finer than average	33 – 37
V	23 – 25	∞	average cell layer	37 – 40

Once the injection of DNAPL begins, the aquifer becomes a three-phase system of sand, water, and DNAPL. Assuming fluid type, movement, and replacement does not change the soil porosity, and that sand is always the matrix, another iteration of the BHS is applied to determine ε^*_{comp}, which now refers to the relative permittivity of the sand-DNAPL composite ($\varepsilon^*_{s\text{-}DNAPL}$) (figure 1, curve B-C). At a given porosity determined from the pre-spill BHS water-sand curve (figure 1, curve A-B), $\varepsilon^*_{s\text{-}water}$ and $\varepsilon^*_{s\text{-}DNAPL}$ define the end members of ε^*_{matrix} and ε^*_{fluid}, respectively, for additional iterations of the BHS (figure 1, curve D-E). The new ε^*_{comp} of the sand-water-DNAPL composite ($\varepsilon^*_{s\text{-}water\text{-}DNAPL}$) is determined from modeling the GPR response as DNAPL is injected into the cell and displaces water, assuming the cell is still fully saturated. Variations in the values of the post-spill composite $\varepsilon^*_{s\text{-}water\text{-}DNAPL}$ are now assumed to be due to the introduction of DNAPL rather than to variations in porosity and solving for 1-ϕ is then equivalent to solving for DNAPL saturation (figure 1, final BHS plot). Figures 5a and 5b show the spatial distribution of calculated PCE saturation for the uppermost of the intermediate three layers.

CONCLUSIONS

Within the first 22 hours, DNAPL flow in the modeled portion of the Borden cell appears to have been governed by initial pre-spill fractional porosity and geometry of the layering. The injection point to the cell was located approximately above a peak in the gentle slope of the 1 m horizon allowing for injected DNAPL to flow "downhill" to either side of the peak. Zones of initially lower porosity, to either side of the peak, exhibit the first increase in PCE saturation post-spill (figure 4 and figures 5a and 5b). By 22 hours, DNAPL has begun to fill the small channel to the southeast of the injection point and thickened upward (figure 2, figures 6a-6c). Based on the calculations of their initial porosity, layers II and IV may be described as finer than the average cell layer, acting as further lateral control for the DNAPL flow path (table 1 and figure 2). As DNAPL migrated through the cell, it appears to have filled and thickened primarily within these layers (figure 3). In the first 22 hours, layer III did not exhibit any appreciable increase in saturation or thickness, though layers II and IV thickened into the intermediate layer (figure 4).

For input data to applications such as 3D, multiphase, fluid-flow, modeling programs, quantitative values of DNAPL saturation versus time and position are required, and this information is available from the modeling. The general description of DNAPL migration given in the preceding paragraph is a result of modeling the GPR data from a grid of locations over time. Simply viewing the GPR data of the cell in a 3D sense, and watching the changes in the data over time as the volume of injected DNAPL increased, leads to this same general understanding of the DNAPL migration pathways (Sander and Olhoeft, 1994), but without the quantitative information. The match between the two general descriptions of DNAPL migration pathways confirms that the quantitative DNAPL saturation values produced by the modeling method are also realistic results.

Figure 4: Contours are spatial distribution of calculated fractional porosity layer II, pre-spill;

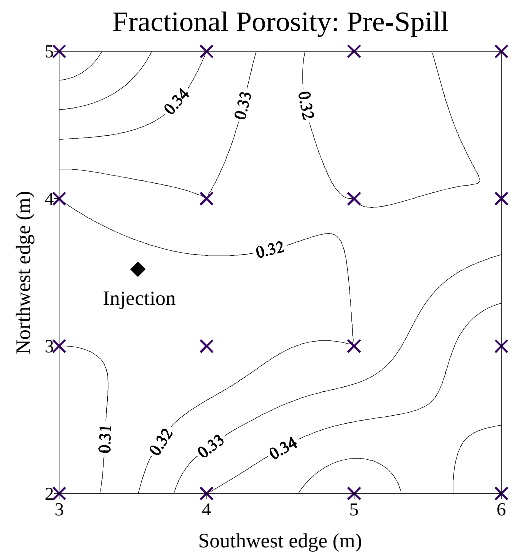


Figure 5a: Contours are spatial distribution of calculated fractional PCE saturation layer II, 14 hours post-spill;

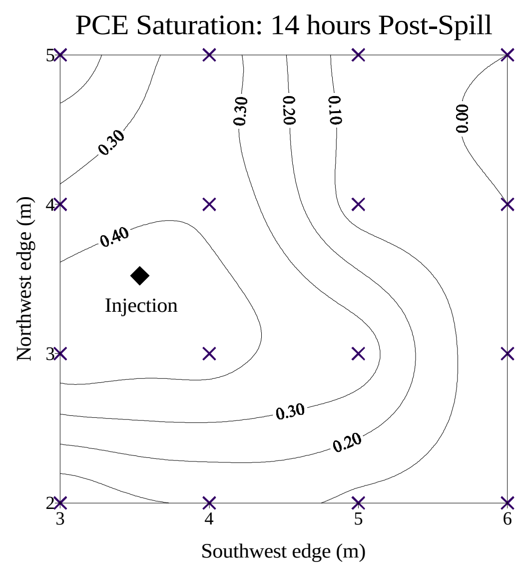
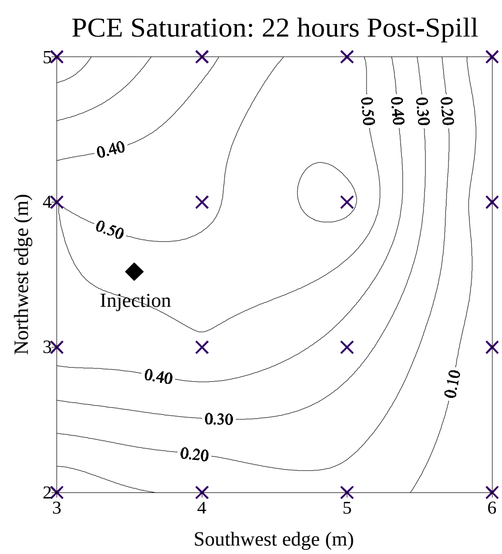


Figure5b: Contours are spatial distribution of calculated fractional PCE saturation layer II, 22 hours post-spill.



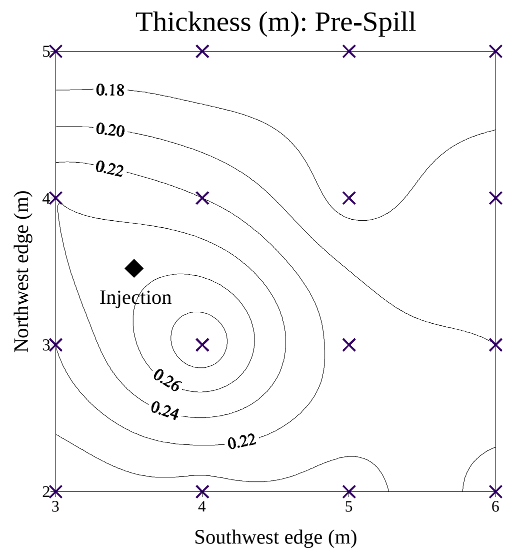


Figure 6a: Contours are spatial distribution of combined layer thickness (m) layers II, III, IV, pre-spill;

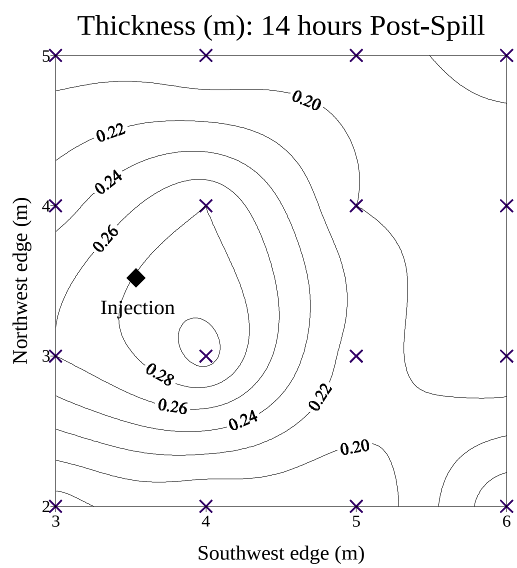


Figure 6b: Contours are spatial distribution of combined layer thickness (m) layers II, III, IV, 14 hours post-spill;

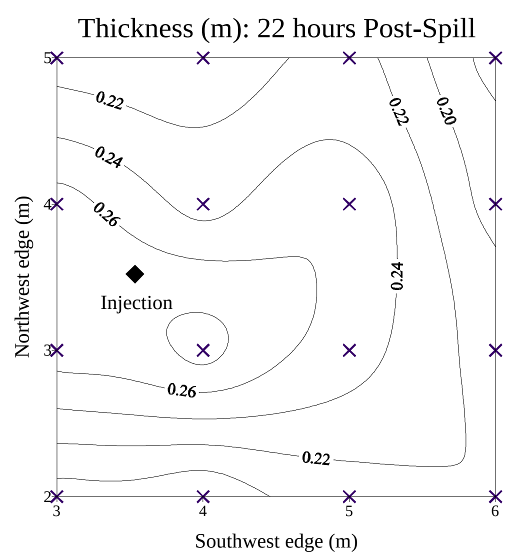


Figure 6c: Contours are spatial distribution of combined layer thickness (m) layers II, III, IV, 22 hours post-spill.

Results show the successful use of full-waveform modeling of continuous GPR data followed by an iterative application of the BHS mixing formula to determine pre-spill porosity and DNAPL saturation values over time and space. A possible application of results such as these is for use as input parameters to fluid-flow modeling programs. Recommendations for further work include the modeling of a finer set of grid points over a larger area of the cell, with the addition of deeper layers to fully describe the cell.

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REFERENCES

Bauman, P., 1989. A detailed geophysical investigation of a shallow sandy aquifer: MSc Thesis, University of Waterloo, Waterloo, Ontario, Canada, 238 p.

Bohla, J., Jr., 1986. A sedimentological investigation of a progradational foreshore sequence: C.F.B. Borden. M.Sc. thesis, Univ. of Waterloo, Waterloo, Ontario, Canada.

Brewster, M. L., Annan, A. P., Greenhouse, J. P., Kueper, B. H., Olhoeft, G. R., Redman, J. D. and Sander, K. A., 1995. Observed migration of a controlled DNAPL release by geophysical methods: Ground Water, v. 33, p. 977-987.

Greenhouse, J., Brewster, M., Schneider, G., Redman, D., Annan, P., Olhoeft, G., Lucius, J. E., Sander, K., Mazzella, A., 1993. Geophysics and Solvents: The Borden experiment: Geophysics: The Leading Edge of Exploration, v. 12, n. 4, p. 261-267.

Lucius, J. E., Olhoeft, G. R., Hill, P. L., and Duke, S. K., 1992. Properties and hazards of 108 selected substances – 1992 edition: U. S. Geological Survey Open File Report 90-527, 554 p.

Olhoeft, G. R., 1998. GRORADAR™: Acquisition, processing, modeling, and display of ground penetrating radar data: ver. 4.0, software distributed on CD-ROM at GPR'98, 7th Int'l. Conf. On Ground Penetrating Radar, May 27-30, 1998, The Univ. of Kansas, Lawrence, KS, USA. (1999 version 8.99, http://www.g-p-r.com).

Pankow, J. F., Feenstra, S., Cherry, J. A., Ryan, M. C., 1996. Dense chlorinated solvents in groundwater, background and history of the problem *in* Dense Chlorinated Solvents and other DNAPLs in Groundwater; History, Behavior, and Remediation, Pankow, J. F., Cherry, J. A., eds. Waterloo Press, Portland, OR, United States, 1996, p. 1-52.

Powers, M. H., Duke, S. K., Huffman, A. C., and Olhoeft, G. R., 1992. GPRMODEL: One dimensional full waveform forward modeling of ground penetrating radar, U. S. Geological Survey Open File Report 92-532, 22 p. plus floppy disk.

Redman, J. D., Kueper, B.H., and Annan, A. P., 1991. Dielectric stratigraphy of a DNAPL spill and implications for detection with ground penetrating radar: Ground Water Management n. 5, Proc. of the Fifth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, May 13-16, Las Vegas, NV, p. 1017-1030.

Sander, K. A., Olhoeft, G. R., and Lucius, J. E., 1992. Surface and borehole radar monitoring of a DNAPL spill in 3D versus frequency, look angle and time: Proc. of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, R.. S. Bell, ed., April 26-29, 1992, p. 455-469.

Sander, K. A., 1994. Characterization of DNAPL Movement in Saturated Porous media Using Ground Penetrating Radar, Colorado School of Mines Master's Thesis, ER-4336, 258p.

Sander, K. A., and Olhoeft, G. R., 1994. 500-MHz ground penetrating radar data collected during an intentional spill of tetrachloroethylene at Canadian Forces Base Borden in 1991, U.S.G.S. Digital Data Series DDS-25, CD-ROM.

Sen, P. N., Scala, C., and Cohen, M. H., 1981. A self-similar model for sedimentary rocks with application to the dielectric constant of fused glass beads: Geophysics, v. 46, p. 781-795.