

Impact of Dissolution of Dense Non-Aqueous Phase Liquids (DNAPLs) on Groundwater Remediation

Charles J. Newell, Ph.D, P.E.; John A. Connor, P.E.; Dale K. Wilson; and Thomas E. McHugh

ABSTRACT

A modeling study and an in-situ field test have been performed at a Superfund site to estimate the intensity of remediation required to reach groundwater clean-up standards in a shallow aquifer affected by DNAPLs (dense non-aqueous phase liquids). A previous pilot recovery test conducted in 1989 (Connor, Newell, and Wilson, 1989) had demonstrated that the mobile fraction of the DNAPL fluids could be removed from the water-bearing stratum using enhanced oil recovery technologies. However, a significant percentage of the DNAPL mass would remain immobilized within the aquifer matrix, possibly acting as a continued source of organic constituent release to groundwater due to dissolution of soluble DNAPL components. To quantify the effect of DNAPL dissolution on the aquifer remediation program now being planned for the site, a modeling study and in-situ field test were designed to simulate the performance of the full-scale groundwater recovery system.

To obtain a preliminary estimate of the DNAPL dissolution rate, an existing dissolution relationship (Borden and Kao, 1989) was applied using field data previously collected from the site. The model assumed equilibrium partitioning of soluble organics between water and DNAPL, and required estimates of the mass of DNAPL in the aquifer and the chemical composition of the DNAPL itself.

Using the model results, the field test was designed to simulate the actual hydraulic conditions that might be expected during a full-scale pumping and waterflooding program for DNAPL-affected areas. One injection well and one production well, spaced 11 feet apart, were used to flush fresh water through the test area. During the 30-day test period, groundwater samples were collected from 4 observation wells and analyzed for organic indicator constituents. During the test, 14 - 43 pore volumes of fresh water were drawn through the test area, resulting in significant reductions in the concentrations of key organic constituents (i.e., > 85%).

The test results were analyzed to determine the number of pore volumes required to achieve the specified groundwater recovery standards, ranging from 2.4 to 39 mg/l for two of the key dissolved organics indicator parameters. Pore volumes, or the number of times the groundwater in a given volume of aquifer is replaced by fresh water, is an important indicator of the remediation intensity required at a site. A large number of pore volumes, for example, indicate that either a large number of recovery wells or an extended clean-up period will be required. At this site, the field test showed that approximately 50 to 100 pore volumes of fresh water may be required to achieve the groundwater recovery standards in DNAPL-affected areas. These empirical results are in good agreement with modeling predictions, which indicated that roughly a 50 pore volume flush would be required to adequately reduce dissolution products from the residual DNAPL. These data indicate the significance of the DNAPL dissolution phenomena to groundwater remediation design.

Due to the effects of DNAPL dissolution, restoration of groundwater to drinking water standards (organic constituents in the low ppb range) may prove infeasible at many DNAPL-affected sites. A general management strategy, consisting long-term containment of organics in the DNAPL zone and restoration of groundwater affected by dissolved plumes in DNAPL-free areas, is proposed.

PROJECT BACKGROUND

Impact of DNAPL on Groundwater Remediation Efforts

The presence of DNAPL in aquifers can greatly increase the scope and complexity of groundwater remediation efforts. Under saturated conditions, DNAPL fluids migrate as a continuous separate phase under the influence of capillary, viscous, and gravity forces. However, once the source of the DNAPL has been eliminated, the continuous phase hydrocarbon mass breaks up, trapping some of the hydrocarbon fluid as "blobs" or "ganglia" within the aquifer pores. The fraction of residual DNAPL trapped in an aquifer, i.e. the residual saturation, has been shown to be a function of the ratio of the capillary forces and viscous forces (i.e., groundwater velocity) acting on the oil (see Hunt et. al., 1988 and Wilson and Conrad, 1984). The ultimate degree of DNAPL recovery from aquifers will be limited by the effect of capillary forces acting on the viscous hydrocarbon fluid. Even under relatively intense hydraulic gradients imposed by groundwater recovery systems, 30-90% of the initial DNAPL mass is likely to remain immobilized within the pores and fractures of the aquifer media.

The water-soluble fraction of this residual DNAPL will serve as a long-term source of dissolved organic release to local groundwater. The dissolution rate is a function of initial mass of trapped DNAPL in the aquifer, the fraction of the residual DNAPL mass composed of soluble constituents, and the rate at which fresh water can be drawn through the DNAPL-affected area (see Miller et. al., 1990). Reported complications which hinder the remediation process include 1) the presence of aquifer heterogeneities, which shield DNAPL "ganglia" from flushing effects during remediation, and 2) possible "bounce-back" effects, where constituent concentrations increase after the system has been shut off. While permanent clean-up to low-ppb drinking water standards may be impossible to achieve, containment of DNAPL-generated plumes is feasible using conventional pump-and treat approaches, and significant percentage reductions in soluble constituent concentrations (i.e. > 90%) have been realized at many sites.

Background Information

Hydrogeologic site investigations conducted during the period of 1984 to 1988 found dense non-aqueous phase liquids (DNAPLs) to be present within the near-surface Transmissive Zone underlying the Motco Superfund Site in La Marque, Texas. Subsequently, a DNAPL recovery pilot study was conducted during the period of March-June, 1989, to determine local hydrogeologic conditions and evaluate the effectiveness of pumping wells for removing free-flowing DNAPL from these near-surface strata (see Connor, Newell, and Wilson, 1989). The results of these previous investigations are summarized below.

Site Stratigraphy

During the 1989 pilot study, cone penetrometer testing was used successfully to characterize the base topography and lateral continuity of the Transmissive Zone strata underlying the Motco Site. A total of 73 cone penetrometer logs and 15 soil borings were completed at the site in March-April, 1989. In conjunction with information from previous studies, these data indicated that near surface stratigraphy, in order of increasing depth, consisted of:

- 1) A surface deposit of low to high plasticity clay, extending to approximately 25 feet below ground surface,
- 2) A silty sand layer, designated as stratum TZ-2, extending from approximately 25 to 35 feet below grade,
- 3) A high-plasticity clay layer of variable thickness, termed the TZ-2/TZ-3 clay stratum,
- 4) A zone of interbedded silt and silty clay layers, designated as stratum TZ-3, extending from approximately 40 to 50 feet below grade.

These units are designated as the Transmissive Zone (TZ) at the Motco Site. A stiff, high-plasticity clay layer, termed the UC-1 Clay, forms the base of the Transmissive Zone. An idealized geologic cross-section is shown in Figure 1.

Delineation of DNAPL Plume

Soil cores were collected at selected locations to define the distribution of DNAPL in the TZ unit. In addition, inspection of grout returns discharged from cone penetrometer test holes proved an effective indicator of the presence or absence of DNAPL in the strata penetrated by the cone tool. Information from the cone penetrometer tests and soil boring was used to develop the DNAPL plume map presented in Figure 2. Visual evidence of DNAPL saturation in the TZ-2 sand was limited to the area in the immediate vicinity of the pits located at the site. DNAPL in TZ-3, however, extended over a much wider area and appeared to have migrated a distance of up to 300 feet from the eastern edge of the Motco pits (see Figure 2 and Connor, Newell, and Wilson, 1989).

DNAPL Migration

The distribution of DNAPL fluids within the Transmissive Zone strata suggest the principal factors in DNAPL migration to be the downward fluid density gradient and the secondary porosity features of the fine-grained sediments underlying the site. DNAPL has seeped downward from the source pits, migrating laterally via fractures, partings, and other secondary porosity features of the TZ-3 silt stratum, in general accordance with the surface topography of the underlying UC-1 Clay, a low permeability, massive clay deposit (see Figure 3).

Removal of DNAPL

The 1989 pilot test demonstrated the feasibility of recovering DNAPL and compared the relative performance of three oil recovery technologies: pumping-only, vacuum-enhanced pumping, and vacuum-enhanced pumping augmented by waterflooding. The pumping only scheme was based on groundwater withdrawal from a single recovery well screened in both the TZ-2 and TZ-3 units. For the

vacuum-enhanced pumping scheme, a downhole pump was augmented by a wellbore vacuum to increase the available drawdown and maximum yield of the recovery well. For the waterflooding scheme, a freshwater injection well was operated at a distance of 100 ft from the pumping well to increase the hydraulic gradient. A three-week testing program demonstrated that some DNAPL could be removed by pumping alone, but that waterflooding and vacuum-enhanced recovery greatly increased DNAPL recovery rates (see Connor, Newell, and Wilson, 1989).

Groundwater Remediation Design Standards

As the Transmissive Zone is classified as a saline aquifer, drinking water standards are not applicable and health-based standards were developed using a one-dimensional solute transport model. Of the seven indicator constituents, Bis (2-chloroethyl) ether (BIS) and 1,2-Dichloroethane (1,2-DCA) were found to be critical to the remediation effort at Motco. To protect potential users of nearby surface water and the deeper drinking water aquifers, the following groundwater recovery standards for the Transmissive Zone were derived: 2.4 mg/l for BIS and 39 mg/l for 1,2-DCA. The standards for these two chemicals determine the intensity of groundwater flushing required to remediate the TZ unit at Motco.

APPLICATION OF DNAPL DISSOLUTION MODEL

Objectives and Description of Model

To estimate the volume of rinse water required to meet the groundwater recovery standards specified for the Motco site, a mathematical model developed by Borden and Kao (1989) was applied by Borden (1990) to simulate the dissolution of organics from residual DNAPL following removal of mobile DNAPL fluids from TZ-unit strata. The mathematical model employed for this purpose consists of 1) an advection-dispersion equation to describe transport of organics in porous media and 2) an effective solubility relationship to describe equilibrium partitioning between the water and DNAPL phases. The results of this preliminary modeling study were used to design an in-situ field test for empirical measurement of DNAPL dissolution rates within the Transmissive zone underlying the Motco Site.

Effective Solubility Relationship Used in Model

The equilibrium partitioning of soluble organics between water and a separate oil phase (e.g., DNAPL) can be characterized by the following effective solubility relationship (see Borden, 1990; and Feenstra, MacKay, and Cherry, 1991):

$$C_{w_i} = X_{o_i} S_i \gamma_i$$

Where:

C_{w_i} is the concentration of indicator constituent i in the water phase (mg/L).

X_{o_i} is the mole fraction of indicator constituent i in the DNAPL phase (unitless).

S_i is the solubility of indicator constituent i in water (mg/L).

γ_i is a correction factor to adjust for constituent concentrations observed in the field (unitless).

The initial mole fraction of the soluble organic in the DNAPL phase is determined through laboratory analysis. The value of the correction factor is estimated by comparing actual dissolved constituent concentrations in groundwater from DNAPL affected areas to predicted concentrations based on the effective solubility relationship.

Modeling of DNAPL Dissolution

To estimate the volume of rinse water needed to meet the groundwater recovery standards for bis (2-chloroethyl) ether (i.e. BIS) and 1,2-dichloroethane (1,2-DCA), the following data were employed in the dissolution model:

- Amount of residual DNAPL in TZ-3 unit: 1% by volume
- DNAPL composition: 38% BIS and 2.5% 1,2-DCA by weight
- Correction factors: 0.31 and 0.38 for BIS and 1,2-DCA, respectively (based on dissolved concentrations in groundwater in contact with DNAPL).
- TZ-3 unit porosity: 0.2

The dissolution model was run to simulate the decline of indicator constituent concentrations over time during groundwater remediation. The primary indicator of remediation intensity required is the pore volume. This represents the number of times the groundwater in a given volume of aquifer, such as the zone between an injection well and pumping well, is replaced by clean water. The results of the modeling study are summarized below:

- Based on the above assumptions, approximately 50 pore volumes of injection water would be needed to meet the groundwater recovery standards for BIS and 1,2-DCA (2.4 mg/L and 39 mg/L respectively).
- Primary sources of uncertainty in predicting remediation times and volumes are the amount of DNAPL in the aquifer, the mass transfer rates from the DNAPL phase to the water phase, and the correction factors for BIS and 1,2-DCA.

The results of the modeling study were applied in design and operation of the field dissolution test. Design parameters, such as injection water flow rates, well spacing, and test duration, were modified to insure that approximately 50 pore volumes of injection water would be passed through the field test system during the test period.

FIELD ANALYSIS OF DNAPL DISSOLUTION

Objectives

To provide design basis information for the TZ-unit groundwater remediation system, a detailed field test was performed in October 1990 to approximate actual conditions during the operation of a recovery system. Based on the dissolution rates observed in the field, the minimum number of pore volumes of injection water required to adequately dissolve the indicator compounds from the trapped DNAPL residual was estimated. Dissolution test procedures and results are detailed below.

System Design and Installation

The field test system was designed to approximate, on a smaller scale, the actual hydraulic conditions which might be expected during a full-scale pumping and injection program. To maximize fresh water flushing of the DNAPL-bearing stratum within the limited time frame of the test, close spacing of the injection and recovery wells was necessary (see Figure 2 for test area location).

The test system consisted of a fresh water injection well (IW-1A) and a recovery well (P-CP-7D) located 11 feet away. Four piezometers, P-CP-A through P-CP-D, were installed at distances of 3 to 8 feet from the injection well to allow monitoring of the hydraulic gradient and changes in groundwater chemistry over the course of the test (see Figure 5). To facilitate optimal placement of the well screens, cone penetrometer tests were first conducted at the four locations shown on Figure 5, providing a detailed log

of sand, silt, and clay units based on correlation with logs of nearby soil borings (see Figure 4). Each piezometer was installed by using the cone truck in place of conventional drilling methods. The screened interval for each piezometer was set approximately 37.5 to 47.5 feet below site grade.

Field Test Procedures

In order to measure the response of the TZ-3 stratum to the injection and pumping program, a groundwater sampling and static water level monitoring program was conducted in accordance to the schedule shown on Figure 6. Groundwater samples collected from the four monitoring piezometers were analyzed for specific conductance and temperature in the field and for total organic carbon and indicator constituent concentration in the laboratory in accordance with EPA-approved methods. Static water level and DNAPL accumulation in each piezometer was measured prior to groundwater sample collection.

In order to establish baseline conditions prior to test start-up, initial sampling was conducted on October 1, 1990 and the 30-day pumping and injection test commenced on October 2, 1990. During the first two days of the test, the pumping and injection rates were stabilized at approximately 0.3 gpm each. Throughout the test, pumping and injection rates were maintained in approximate equilibrium to facilitate control of the hydraulic gradient.

On November 1, at the conclusion of the dissolution test, a 2-hour constant-rate aquifer pumping test was conducted to determine the hydraulic conductivity and transmissivity of the TZ-3 zone. The average calculated hydraulic conductivity in the TZ-3 unit in the area of the dissolution test was 2×10^{-3} cm/sec (i.e., 6.3×10^{-5} ft/sec), and the average transmissivity was 50 gpd/ft.

Field Test Results

Field Test Operation Summary

During the 30-day test period, a total of 14,500 gallons of fresh water were injected at injection well IW-1A at an average rate of 0.34 gpm, and 11,700 gallons of groundwater/DNAPL mixture were pumped from pumping well P-CP-7D at an average rate of 0.27 gpm.

Field Results

To monitor the performance of the dissolution test, the following field measurements were taken during each sampling event: specific conductance, DNAPL accumulation and production, and static water level. Over the course of the 30-day test, the specific conductance of groundwater samples taken from the four piezometers decreased from initial values ranging from 1674 to 4500 umhos/cm to values ranging from 711 to 1026 umhos/cm. The specific conductance stabilized at values representative of the injection water within two weeks of system operation, and little variation was seen at the four piezometers during the second half of the test. The specific conductance of the groundwater recovered from sample port P-CP-7D exhibited a range of 1754 to 3380 umhos/cm, reflecting recovery of groundwater outside the injection zone with high dissolved solids concentrations.

Periodic measurements were performed to determine the amount of DNAPL in the TZ-3 unit and to monitor the amount of DNAPL produced from the recovery well. To indicate the presence of DNAPL in the formation, DNAPL accumulation in each monitoring piezometer was measured using a weighted nylon string during each sampling event. DNAPL accumulations of 7 to 121 inches were measured at the start of the test; no DNAPL was detected in the monitoring piezometers by the end of the test. This suggests that little or no additional DNAPL fluid migrated into the test area during the 30-day test. DNAPL content in the groundwater recovered from pumping well P-CP-7D decreased from an initial

volumetric percentage of 12% during the early stages of the test to an average volumetric content of 1% after 30 days of pumping.

Static water level measurements were taken at regular intervals during the test to monitor hydraulic flow gradient across the test area. Due to the cycling of the groundwater recovery pump, the gradient varied moderately during the test. The hydraulic gradient between piezometer P-CP-B and pumping well P-CP-7D ranged from 0.13 to 0.22 ft/ft.

Field Test Hydraulic Performance

The number of pore volumes passed through the test area and the transmissivity of the TZ-3 unit was developed from available field data: observed hydraulic gradients, specific conductivity, transmissivity, and hydraulic conductivity. After employing two different calculation approaches, the following pore volume estimates for each piezometer were obtained:

Test Day	Estimated Total Pore Volumes			
	Piezometer P-CP-A	Piezometer P-CP-B	Piezometer P-CP-C	Piezometer P-CP-D
0	0	0	0	0
6	6	10	4	3
10	10	15	7	5
15	15	22	10	8
20	19	29	12	9
24	23	34	15	11
30	29	43	19	14

Results of Laboratory Analyses

To monitor the effect of dissolution on organic concentrations in the groundwater, samples were analyzed for TOC as well as the specific indicator constituents identified for the Motco Site. These results indicate that the dissolution test successfully tracked the removal rate of these constituents in the DNAPL-affected area during application of a pilot-scale groundwater remediation process.

TOC concentrations dropped significantly in the four monitoring piezometers, from a range of 610 to 1650 mg/L at the beginning of the test to a range of 18.5 to 128 mg/L after 30 days of injection. The groundwater sampled at piezometer P-CP-B exhibited the largest percentage reduction in TOC, dropping from 1,650 mg/L to 18 mg/L, representing a 98% reduction after 43 pore volumes of fresh water injection. Piezometer P-CP-C, located farther away from the injection well, was exposed to 19 pore volumes of fresh water injection and experienced an 84% reduction in TOC, falling from 820 mg/L to 128 mg/L over the test period.

Despite the large number of pore volumes passed through the test section, the recovery standards for BIS and 1,2-DCA were not achieved during the 30-day test (see Figures 7 and 8). The TZ groundwater recovery standards specified for the Motco Site are 2.4 and 39 mg/L, respectively, for BIS and 1,2-DCA. Concentrations of BIS in the groundwater decreased from initial levels ranging from 470 to 3,800 mg/L to final concentrations ranging from 19 to 330 mg/L, representing an average decrease of 86% for the four piezometers. Similarly, concentrations of 1,2-DCA measured in groundwater samples decreased from initial levels in the range of 910 to 2,200 mg/L to final levels ranging from 75 to 370 mg/L, an average decrease of 88%. These data indicate that more intensive remediation efforts will be required to achieve the specified groundwater recovery standards for these two compounds than for the other indicator constituents present in TZ groundwater.

Summary and Conclusions

- 1) **System Operation:** The DNAPL dissolution system was successfully installed and operated during the 30-day test period. During the 30-day test, approximately 14,500 gallons of clean water was injected into the test area through well IW-1A. Between 14 and 43 pore volumes of clean injection water were passed through the four dissolution study monitoring points.
- 2) **DNAPL Dissolution:** The concentrations of each of the indicator constituents in the groundwater exhibited a logarithmic decline during the 30-day field test. Assuming that the constituent concentrations continue to decline at the same rate, as shown in Figures 7 and 8, between 50 to 100 pore volumes of injection water would be needed to meet the groundwater recovery standard for bis (2-chloroethyl) ether (i.e., ≤ 2.4 mg/L). Similarly, approximately 30 to 60 pore volumes of injection water would be needed to meet the groundwater recovery standard for 1,2 dichloroethane (i.e., ≤ 39 mg/L). The other indicator constituents are either below or very close to the groundwater recovery standards at this time, and, therefore, are not likely to be a critical factor in the design of the ultimate remediation system. The dissolution data developed for this study do not reflect the influence of possible "bounce-back" of indicator constituent concentrations after groundwater recovery system shutoff.
- 3) **Accuracy of Dissolution Model:** The volume of injection water needed to meet the TZ groundwater recovery standards, as determined by the in-situ field test, was somewhat higher than the 50 pore volume flush predicted by the dissolution model. Uncertainty in estimating the amount of residual DNAPL in the aquifer, the mole fraction of indicator constituents in the DNAPL, and aquifer heterogeneities may account for this discrepancy. Better definition of these parameters would lead to a more accurate estimation the volume of injection water needed to meet the groundwater recovery standards.

DESIGN CONSIDERATIONS FOR GROUNDWATER REMEDIATION AT DNAPL SITES

Conceptual Remedial Design for Motco Site

As shown by the DNAPL recovery pilot test, mobile DNAPL fluid can be removed from the transmissive strata by means of groundwater pumping. Under long-term operating conditions, DNAPL production at each recovery well location can be expected to attenuate as the mobile fraction of the DNAPL is drained from the silt stratum. After the artificial gradient is removed, the residual DNAPL would be immobilized under background gradient conditions. As illustrated on Figure 9, the conceptual DNAPL management program would consist of three distinct phases: 1) removal of continuous phase DNAPL fluid, 2) reduction of DNAPL residual saturation, and 3) removal or containment of DNAPL dissolution products. Phase 3 of the remediation program, indicated by negligible recovery of DNAPL, will involve the continued operation of selected wells for the purpose of recovering DNAPL dissolution products. To meet the groundwater clean-up standards specified for the Motco Site, an estimated 50 to 100 pore volumes of flushing with freshwater may be required using a combination of wells and/or trenches.

Please note that the Motco groundwater clean-up standards were based on highly saline conditions in the Transmissive Zone, and drinking water standards in the low ppb range were not directly applicable to the TZ groundwater. By extrapolating the results of the dissolution test, however, it appears that several hundred pore volumes (at a minimum) would be required to reach low ppb levels in the DNAPL affected zones, if these low concentrations could be reached at all.

General Remediation Strategy for DNAPL Sites

Due to the effects of DNAPL dissolution, restoration of groundwater to drinking water standards (organic constituents in the ppb range) may prove infeasible at most DNAPL-affected sites. In such cases, alternate approaches to managing DNAPL problems may be needed. A general DNAPL management strategy, shown in Figure 10, divides a DNAPL site into three zones:

- 1). Dissolved phase zone
- 2). Confirmed free-phase DNAPL zone
- 3). Potential DNAPL zone (either free-phase or residual DNAPL)

As shown in Figure 10, this classification system is based on the confirmed or suspected presence of DNAPL in the aquifer. Areas where site data indicate a low probability of DNAPL in the aquifer would be designated as "dissolved phase zones" where conventional clean-up standards and remediation technologies would be applied. At many sites, the applicable clean-up standards could be at or near current drinking water standards, and pump-and-treat systems could be used to reach the required concentration levels. Please note that this system is probably not applicable to fractured rock settings, where the difficulty in delineating and remediating DNAPL plumes is much greater than porous media aquifers.

In areas where the presence of DNAPL is confirmed, due to the presence of free-phase DNAPL in monitoring wells, a DNAPL containment strategy could be applied in place of conventional groundwater remediation standards. Containment of DNAPL would be achieved by imposing a relatively high hydraulic gradient across the site to remove free-phase material and to ensure that residual DNAPL will remain immobilized under natural flow conditions. Long-term hydraulic containment of groundwater within the residual DNAPL zone would then be required to control DNAPL dissolution products. Operation of such a system could require a longer-term financial commitment than is currently afforded these sites.

As the presence of DNAPL is difficult to confirm in many areas at a site, a third zone has been defined for areas where residual and/or free-phase DNAPL may be present. For example, the presence of relatively high concentrations of dissolved organics or proximity to DNAPL entry points would be sufficient to designate an area as a potential DNAPL zone. The remediation approach for these areas would be identical to confirmed DNAPL zones: long-term containment of DNAPL and all dissolved constituents.

The remediation goals outlined above can be achieved with existing, proven technologies (e.g. groundwater recovery wells), and would provide a significant level of protection to both human and environmental receptors. Implementation of this remediation approach would require modification of current regulatory policies regarding clean-up standards and financial assurance for long-term corrective action programs. At some point during long-term containment of dissolution products, new remediation technologies may be developed so that drinking water standards can be achieved at DNAPL sites.

Biographical Sketches

Charles J. Newell is an Environmental Engineer and Vice-President of Groundwater Services, Inc. He received his Ph.D. in Environmental Engineering from Rice University in 1989, and has directed projects involving environmental software development, management of DNAPL problems, and groundwater remediation using in-situ bioremediation. Groundwater Services, Inc., 5252 Westchester, Suite 270, Houston, Texas 77005. (713) 663-6600.

John A. Connor is a Geotechnical Engineer and President of Groundwater Services, Inc., of Houston, Texas, and has managed numerous groundwater remediation projects. He received an M.S. in Civil Engineering with a specialty in Geotechnical Engineering from Stanford University in 1979. Groundwater Services, Inc., 5252 Westchester, Suite 270, Houston, Texas 77005. (713) 663-6600.

Dale K. Wilson is a Principal Engineering Specialist for Monsanto Company, St. Louis, Missouri. He has managed several site investigations and remedial projects, including the pilot DNAPL recovery system design at the Motco Superfund Site. He received a B.S. and MS. in Geological Engineering from the University of Missouri at Rolla. Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, Missouri, 63167. (314) 694-6921.

Thomas E. McHugh is an Environmental Scientist with Groundwater Services, Inc. He received a B.A. degree from Rice University and has specialized in the aquifer characterization studies and the design of groundwater remediation systems. Groundwater Services, Inc., 5252 Westchester, Suite 270, Houston, Texas 77005. (713) 663-6600.

REFERENCES

- Borden, R.C. , 1990, "Evaluation of Water Flushing for Groundwater Remediation of the TZ-3 Zone - Motco Site ", unpublished report to Groundwater Services, Inc., Houston, Texas.
- Borden, R. C., and C. Kao, 1989, "Water Flushing of Trapped Residual Hydrocarbon: Mathematical Model Development and Laboratory Validation", Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Nat'l. Water Well Assoc., Houston, Texas, pp. 473-486.
- Connor, J.A., C.J. Newell, D.K. Wilson, 1989, "Assessment, Field Testing, and Conceptual Design for Managing Dense Non-Aqueous Phase Liquids (DNAPL) at a Superfund Site", Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration, National Water Well Association, Houston, Texas, pp. 519-533.
- Feenstra, S., D. M. MacKay, and J.A. Cherry, A Method for Assessing Residual NAPL Based on Organic Chemical Concentrations in Soil Samples, Groundwater Monitoring Review, Vol. 11, No. 2, 1991.
- Groundwater Services, Inc., 1990, "Final Report DNAPL Dissolution Study", Groundwater Services, Inc. Houston, Texas.
- Hunt, J.R., N. Sitar, and K.S. Udell, 1988, "Nonaqueous Phase Liquid Transport and Cleanup", Water Resources Research, Vol. 24, No. 8, pp. 1247-1258.
- Miller, C.T., M.M. Poirier - McNeill, and A.S. Mayer, 1990, "Dissolution of Trapped Nonaqueous Phase Liquids: Mass Transfer Characteristics", Water Resources Research, Vol. 26, No. 11, pp. 2783-2796.
- Wilson, J.L. and S.H. Conrad, 1984, "Is Physical Displacement of Residual Hydrocarbons A Realistic Possibility in Aquifer Restoration?", Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Nat'l. Water Well Assoc., Houston, Texas, pp. 274-297.