Optimization of In-Situ Injection and Bioremediation Design at a Brownfield Site

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Abstract: The challenges associated with optimizing design, delivery and assessment of in-situ bioremediation are becoming more evident as the field matures. Radius of influence and uniform distribution of amendment materials are critical parameters for cost-effective and timely design, implementation and assessment of in-situ remedial actions. Enhanced in-situ bioremediation was implemented at a chlorinated ethene-impacted Brownfield site in Passaic County, New Jersey. We report our strategy, design and progress at this site, which should prove informative and useful to other sites that are either utilizing or proposing in-situ bioremediation approaches.
An innovative patented technology known as the Hornet Environmental Tool was evaluated to assess the tool's ability of enhancing radius of influence and amendment distribution. A pilot-scale study was designed to compare the distribution of an emulsified oil substrate (EOS®) via conventional hydraulic injection versus enhanced injection with the Hornet Environmental Tool. An electrical conductivity survey was implemented track EOS® distribution and the extent of influence. It was observed that zones where EOS® was effectively distributed resulted in increased electrical conductivity presumably due to the presence of sodium lactate, a component of EOS®, which was considered a tracer for the EC profiling. The Direct Image® EC System from Geoprobe® was employed to assess pre-injection and post-injection electrical conductivity at defined radial distances from the respective injection points. Analysis of the EC data proved to be a valuable tool for the assessment of the radius of influence, and the Hornet and conventional injection techniques.

Full-scale biostimulation with EOS® was completed based on the design parameters defined in the pilot tests. This optimized injection scheme and design resulted in more than 40% saving in remediation costs. Amendments were observed in treatment monitoring wells by visual observation, geochemical parameter measurements, and/or TOC analysis. Significant reductions in site contaminants were observed in post-injection sampling events. Favorable geochemical conditions, presence of amendment, and reduction of contaminants coupled with the detection of *Dehalococcoides* further support biological reductive dechlorination at this site. The EOS® treatment program resulted in greater than 98% mass removal in the shallow source zone. Additionally, treatment in the upper zone has resulted in evident treatment of portions of the less-permeable lower glacial till unit.

Introduction

TRC Environmental Corporation (TRC) was contracted to conduct a rapid, low-cost remediation program to address VOC impacted ground water at a Brownfield site in Passaic County, NJ. The site was formerly used as light industrial manufacturing facility located in a primarily residential area of Passaic County. The contaminants of concern at the site are volatile organic compounds (VOC), primarily tetrachloroethlyene (PCE) and trichloroethlyene (TCE). VOCs at the site also included BTEX compounds, chlorobenzene and PCE/TCE breakdown products cis-1,2 dichlorothelyne (cDCE) and vinyl chloride (VC). Due to high community interest, and the proposed redevelopment of the site into a residential use, the proposed schedule called for rapid treatment of the contamination, with minimal impacts to adjacent property owners. TRC designed and implemented an enhanced in-situ bioremediation (EISB) pilot test and a full-scale treatment program in less than 6 months.

TRC evaluated several remedial technologies for application at the site including chemical oxidation, reductive dechlorination, soil vapor extraction and air sparging. Based on the site conditions (low soil permeability, favorable geochemical conditions and the presence of PCE/TCE breakdown products) TRC conducted a pilot test to evaluate the efficacy of EISB, using emulsified vegetable oil as the substrate for Biostimulation. The presence of elevated concentrations of cDCE indicated that while biological degradation was taking place at the site, existing geochemical and biological conditions did not allow the complete dechlorination of PCE and TCE. The results of the pilot test were favorable, and a full-scale injection program was designed and implemented.

Microbial characterization was conducted to survey the microbial population within the subsurface and assess the need for biological augmentation. If the existing biological population was found to be insufficient, the addition of a commercially available culture containing the *dehalococcoides* bacteria would have been added to the subsurface to enhance the degradation. Bioaugmentation would have been implemented after biostimulation to optimize subsurface geochemical conditions for the *dehalococcoides* bacteria.

To compress the project schedule and reduce remediation costs, several substrate delivery optimization techniques including enhancing the radius of influence (ROI) and distribution of the substrate through the treatment zone and contracting the bulk mixture of the injection solution off-site were considered. An evaluation program was developed to determine an achievable radius of influence for use in the full-scale application, and to evaluate a new delivery enhancement tool, the Hornet Environmental Tool™, developed by Wavefront Energy and Environmental Services Inc. (Wavefront).

The successful expansion of the injection grid spacing resulted in a 75% decrease in the number of injection points required, saving more than 1 month in the field and more than 40% of the remedial costs, mainly in drilling and field over sight costs.

Site Geology and Hydrogeology. The ground water contamination at the site was located primarily in the overburden material, with trace to no ground water impacts in the shallow bedrock. The overburden soil comprises two distinct units. The shallow unit comprises 20 feet (6.1m) of a loose sandy silt with some surficial fill material, designated as the shallow zone (s1). The deeper unit is a lower permeability dense glacial till formation, designated as the till zone (s2), that consists of a mixture of silt, sand, clay and cobbles, ranging in size from 2 inches (5.1 cm) to boulders. The average thickness of the till zone was estimated to be approximately 20 (6.1m) feet. Ground water within the overburden flows radially in a northerly direction from a mound along the southwestern portion of the site. Ground surface elevations increase to the southwest, and decrease in a northerly direction.

The highest contaminant concentrations were located in the shallow zone ground water near the suspected source area (MW-8 cluster) as shown in Table 1.

Table 1. Initial VOCs Concentrations in Source Area Wells

Contaminant (μg/L)	MW-8s1	MW-8s2
PCE	278	149
TCE	579	238
c-1,2DCE	7,550	3,820
VC	305	121
BTEX	1,206	4,597
Total VOCs	14,585	14,422

Means and Methods

Phase I Pilot Test. A pilot test was conducted in August 2007 at the site, near the suspected source area to evaluate the effectiveness of EISB. The pilot test was conducted over a one week period and involved the injection of 3,780 lbs (1,718 kg) of EOS® 598 B42 in solution with 4,100 gallons (15,580 L) of water through 48 injection points. The treatment programs used the EOS® 598 B42 compound from EOS® Remediation Inc. EOS® is made of an emulsified soybean oil and water mixture, with the compound being approximately 60% oil by weight. Once introduced into the aquifer, EOS® acts as a slowly degrading carbon and energy source that can be broken down by indigenous microbes found in the subsurface. For anaerobic reductive dechlorination, the inter-species transfer of hydrogen to the dechlorinating population(s) of microorganisms accelerates the reductive dechlorination process. EOS® has been shown to be long lasting and effective for up to several years in the subsurface as a continually acting carbon and energy source. The additional components, such as amino acids, trace minerals and a vitamin B12 supplement included in this product mixture have been shown to be important amendments to the laboratory culturing of dechlorinating organisms.

The viscosity and density of the EOS® compound is similar to that of water, which results in a greater ease of injection and allows the compound to move more readily through the subsurface. The EOS® remediation compound is a food grade material that is generally recognized as safe to humans, which is a distinct health and safety advantage over other in-situ remediation amendments.

To distribute and spread EOS® within the aquifer, EOS® was mixed and diluted with water at a ratio that varied between approximately 10:1 (10 parts of water to 1 part EOS®) and 6:1. Batch mixtures were made on demand for each injection interval. Temporary injection points were advanced to a depth of approximately 19 feet (5.8 m) below grade using a Geoprobe® direct push drill rig. EOS® injection began from the bottom of the injection point and continued to approximately 10 feet (3 m) below grade. The injection program proceeded inward, conducting injections along the outermost sections of the grid (lower concentrations) to the inner sections (MW-8 cluster with higher concentrations) to confine and limit the potential spreading of contaminants due to potential ground water mounding.

The pilot test covered a treatment area of approximately 6,000 square feet (557 m^2). Injection points were laid out in grid-formation, with ten foot by ten foot (3m x 3m) spacing, and represented upgradient, downgradient and sidegradient locations of the area previously delineated to be the most impacted (monitoring well MW8 cluster). The 10 foot (3m) off center grid for the injection point layout represented a 5 foot (1.5m) radius of influence. The EOS volume used in the pilot test was determined using design software provided by EOS Remediation, Inc.

The pilot test treatment area extended from the water table (approximately 10 feet [3m] below grade) to the upper portion of the till zone, approximately 20 feet (6.1m) below grade. The EOS® dosage rate was maintained relatively uniform throughout the injection point, except for the deeper interval(s) near the bottom of the borings, where higher dosage rates were applied. The EOS® dosage rate ranged between approximately 0.5 gallons (1.9L) EOS®/vertical foot (3.5 lbs/foot; 5.2 kg/m) and 2.8 gallons/foot (21 lbs/foot; 31.3 kg/m), in the lowest intervals.

Phase II Full Scale Application. Based on analytical results obtained from post injection sampling, it was decided that a full-scale application of EISB was warranted. The full-scale treatment program began on October 23, 2007 and was completed in less than one month. The full-scale injection program addressed an irregular shaped area encompassing approximately one acre. The substrate demand for the treatment area was determined using the EOS design software. The treatment area/volume was again considered to extend from the top of the ground water to the top of bedrock. It was anticipated that the injection points would likely not reach the top of bedrock, as in the pilot test due to drilling equipment limitations. Post pilot test injection results from the source area till zone monitoring well (MW-8s2) indicated that injection in the shallow zone could effect a reduction in contaminant concentrations within the deeper till zone groundwater.

Several changes were made to the program to increase efficiencies and optimize the remedial action. Unlike the pilot program, the injection solution was not prepared in an on-demand fashion, but instead was mixed off site and brought to the site in 5,000 to 6,500 gallon (19,000 to 24,700 L) tanker trucks. The injection solution was stored on site in a 10,000 gallon (38,000 L) storage tank. This change in mixing and solution preparation reduced the infrastructure requirements and material handling and preparation efforts and down time needed at the site (mixing tanks and pumps, bulk water storage and bulk EOS storage).

Approximately 380 gallons (1,438L) (of EOS®-water solution was injected at each location for an average EOS® dosage rate of approximately 7 gallons (26.5L) of EOS® per vertical foot (53 lbs/foot; 79kg/m).

Hornet™ Tool. To increase the ROI in the Phase II injection program Wavefront Energy and Environmental Services, Inc. (Wavefront), of Edmonton, Canada, was contacted and arranged for the use of their Hornet Tool. The Hornet tool is an approximately 5-lb (2.3kg) steel cylinder, about 12 inches (30.5 cm) long and 3 inches (7.6cm) in diameter. The tool was directly attached to the injection rod using 2-inch (5.1cm) cam type fittings (Figure 1). The Hornet tool was developed by Wavefront to accomplish the Primawave™ process. The operational principle for the Hornet tool is to generate a differential pressure in the injection fluid, before and after the tool, which causes a momentary elastic dilation of the soil pores. The effect of the soil pore dilation is an increased evenness of distribution of the injection fluid, and an increase in the obtainable ROI.

Figure 1. Hornet™ Setup

Electrical Conductivity Survey. In order to assess the effectiveness of the Hornet tool, and to assess the effective ROI, an electrical conductivity survey was conducted around two injection points. ZEBRA Environnemental Corporation (Zebra) conducted the survey using a Geoprobe® direct push drill rig and the Geoprobe® Direct Image Electrical Conductivity (EC) system. The Direct Image system is an electrical conductivity survey tool, which measures conductivity, the inverse of resistivity, to log changes in soil type and unit thicknesses. The tool is commonly used to profile the subsurface lithography quickly and cost effectively, based on the inherently different ranges in electrical conductivity for different soil types. The program was developed and implemented in consultation with ZEBRA and EOS® Remediation where EOS® would be used as a tracer and its distribution would be tracked through an increase in electrical conductivity due to the presence of sodium lactate (4% by weight) in the EOS B598 B42. In order to comparatively assess the effectiveness of the Hornet tool versus conventional hydraulic injection techniques; one injection point used in the survey was conducted using the Hornet tool, whereas the other injection point used conventional pumping as the “Control” condition.

A series of electrical conductivity surveying points were installed at pre-set distances from the injection points in four directions. A pre-injection EC survey was also conducted to establish baseline conditions, and a post-injection EC survey was conducted following the same grid pattern to evaluate the two delivery techniques. Figure 2 below presents a layout of the EC survey points around each of the injection points.

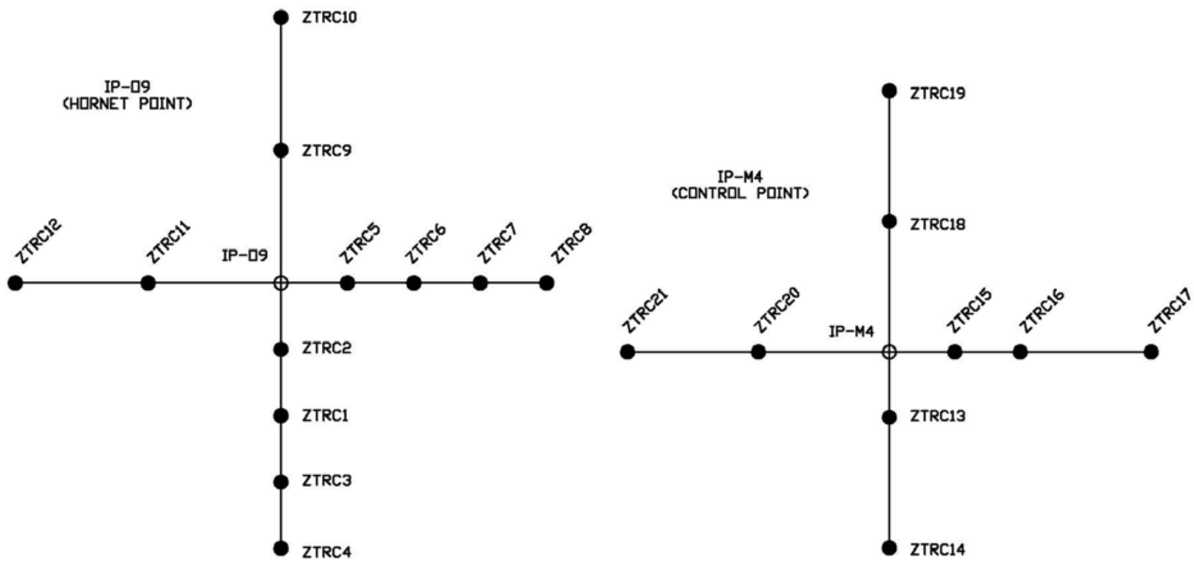


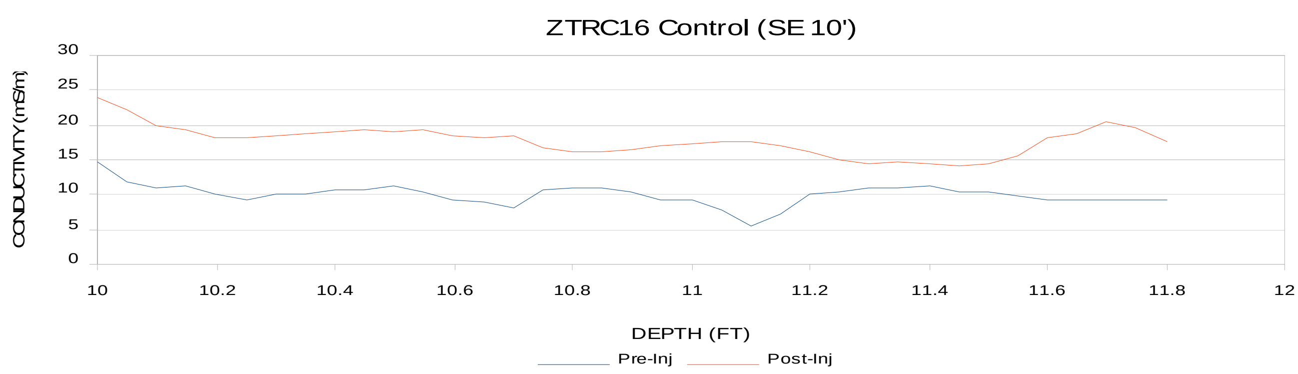
Figure 2. EC Survey Layout around the Hydraulic (Control) and Hornet Injection Points

A preliminary analysis of the EC survey results indicated that a 10-foot (3m) radius of influence was achievable, and the reminder of the injection program was continued using this ROI and corresponding grid spacing. The overall program consisted of 114 injection locations, and a volume of 43,000 gallons (163,400L)of solution was introduced into the subsurface using a 20 (6m) foot off center grid. The Hornet tool was used for the remaining 112 injection points.

Microbial Characterization. Ground water samples were collected from monitoring well MW-8s1 and temporary well point installed near a Phase II injection point. Monitoring well MW-8s1 is located in the Phase I injection area, where EOS had already been applied. The samples were analyzed in a specialized laboratory for the presence of DNA from specific bacteria (*Dehalococcoides*), known to degrade the target CVOC.

RESULTS AND DISCUSSION

EC Survey. The electrical conductivity survey was conducted using the Geoprobe® Direct Image® system proved to be useful and illustrative evaluation tool to assess effective injection radius of influence. The results of the survey were downloaded and graphed to present the pre and post injection electrical conductivity readings from the survey points. The graphs in Figure 3 depict the electrical conductivity response due to the presence of sodium lactate in the EOS® 598B42 compound.



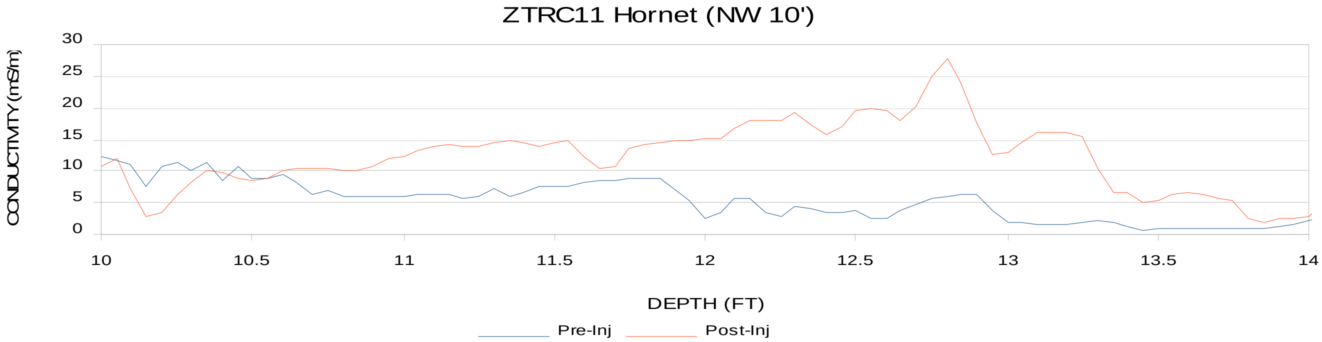


Figure 3. Representative EC Profiles for Hydraulic Injection (Control) and Hornet

A sustained increase in the electrical conductivity, measured in miliSiemens per meter (mS/m) was considered indicative of the presence of EOS® at the survey point which was useful in justifying a ROI. The survey indicated that an average increase of 7.18 mS/m through the injection zone.

The EC survey was used to evaluate the effectiveness of the Hornet at increasing the ROI and enhancing a uniform EOS® distribution. Overlays of Hornet and Control (no Hornet) survey points from equal distances were created to compare the increase in EC. The Hornet area survey showed an average increase of 8.76 mS/m, as opposed to 5.6 mS/m in the Control survey area. A maximum increase of 106.12 mS/m was observed at the ZTRC-12 survey point, located 20 feet (6.1m) northwest of the IP-O9 injection point, near the top of the injection interval. The average increase in EC at survey point ZTRC12, located approximately 20 feet (6.1m) northwest of injection point IP-O9, was 26.13 mS/m, compared to the highest average increase of 8.29 mS/m at control point ZTRC19. Generally, the increase in EC at Hornet locations was more pronounced at the more distant survey points.

Figure 4 below presents an example comparison of the EC survey results for the Hornet and Control areas taken 10 feet (3m) northwest of the injection points. This graph illustrates the trend that while injection without the Hornet was capable of achieving a 10-foot (3m) ROI, the general increase in EC was greater at the Hornet survey locations, confirming the enhanced distribution of the substrate.

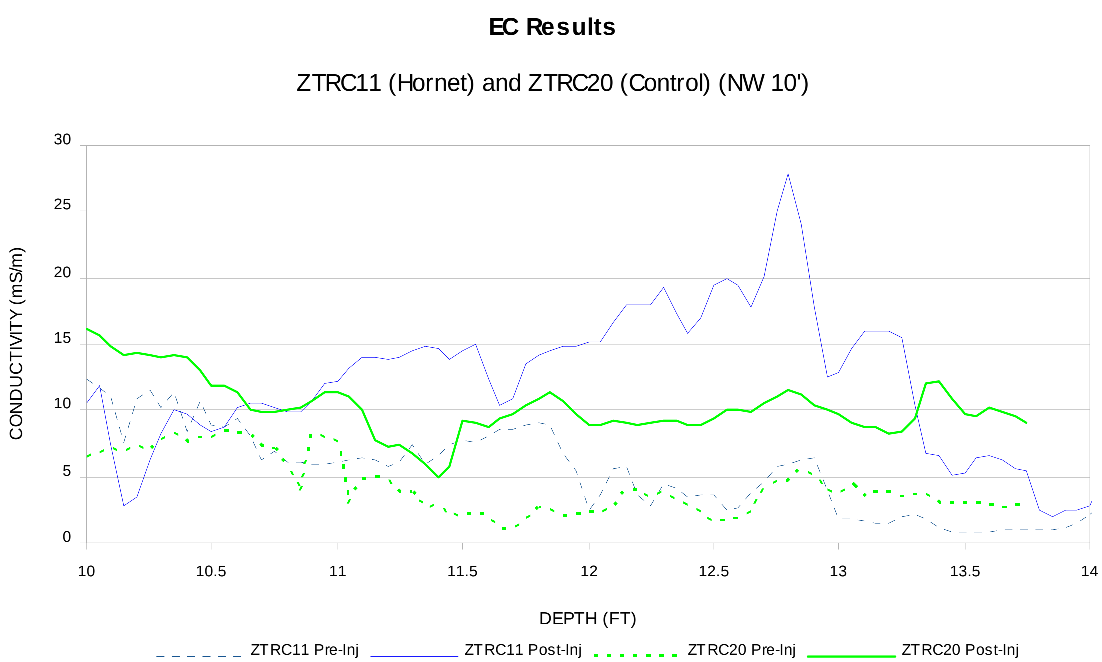


Figure 4. Comparison of EC Data for the Hornet and Control Techniques

It is recommended that future applications of the EC survey technique consider the use of a more discernable tracer that may be added to the injection solution. While the difference was observed relying only on the sodium lactate present within EOS®, the addition of sodium bicarbonate or another safe and commonly available substance may enhance the change in EC profile. A larger difference in pre and post injection EC readings would lead to more certainty in determining the ROI, as natural variability in EC values through a survey location would be expected to span a smaller range.

Additionally, the use of the EC survey technique described in this paper would likely be more beneficial in a pilot scale application. The incorporation of the EC survey allows for optimizing the injection grid and the full-scale design. In addition to optimizing the ROI and grid-spacing, the EC survey could be used to identify anisotropies and heterogeneities in the subsurface, and allow for the development of an injection scheme with directionally and spatially varying spacing and intervals.

ROI Impact discussion. The increase in ROI from 5 feet (1.5m) to 10 feet (3m) was justified, based on the EC survey, and field observations. If the same ROI and grid pattern from the pilot test were used to conduct the full-scale program, approximately 483 injection points would have been necessary. The relationship between an increase in ROI and the number of injection points required to cover the treatment area varies directly with the ratio between the two ROIs raised to the second power. If the ROI is doubled, the number of injection points required to cover the treatment area is divided by 4. Additionally, if the ROI is cut in half, the number of injection points required will be multiplied by four. The inclusion of additional injection points into a treatment program will likely increase the time needed to complete the program, increasing the remedial cost. Although the relationship between an achievable ROI and project costs is generally applicable, it is not always efficient, as the injection volume per injection point also increases with an increase in ROI. An analysis of the ROI impact on the project costs and schedule indicates that the increase to a 10-foot (3m) ROI resulted in a Phase II cost saving of more than 40%, and a one-month reduction in implementation schedule.

Microbial Characterization. Analysis conducted on the samples was used to identify and quantify the presence of *Dehalococcoides* (Dhc) bacteria in the sampled ground water. The Dhc bacteria are known to be capable of facilitating biological reduction of PCE and its breakdown daughter products. Both samples tested positive for the presence of Dhc. The sample collected from MW-8s1, which represented post-EOS® injection conditions in the shallow ground water, returned a Dhc enumeration value of 1×10^7 cells/Liter. A value of 10^7 or higher indicates that the sample contains high concentrations of Dhc, which are associated with high rates of dechlorination. The result from the TP-J4 sample returned a Dhc enumeration number of 5×10^5 cell/Liter. This result indicates that there is a moderate presence of Dhc bacteria within the microbial population, which may be associated with observable dechlorination. The results for TP-J4 represent pre- EOS® injection conditions in the shallow ground water in the treatment area. The application of EOS® is intended to promote amenable subsurface conditions for the development of a robust Dhc microbial population. A comparison between pre- and post-EOS® injection conditions confirms a two-order of magnitude increase in the Dhc population due to Biostimulation with EOS®.

Analytical Results. Post treatment analytical results showed significant decreases in contaminant concentrations across the site. The most encouraging results were observed in the shallow zone, where EOS® was directly injected. Significant contaminant destruction rates were also observed in the till zone monitoring wells, however, the treatment was not able to reduce all contaminant concentrations below applicable ground water quality standards. Figure 5 below presents the post treatment sample results from the most recent sampling event (December 8, 2008).

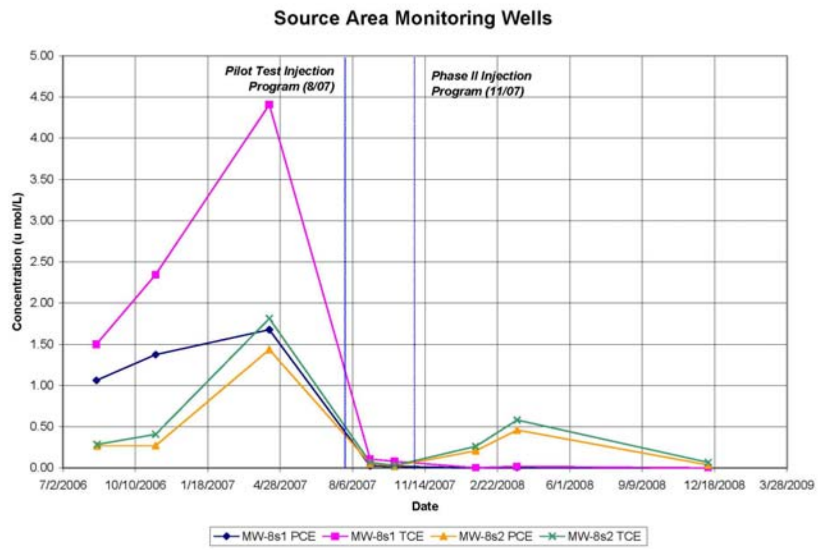


Figure 5. Molar Concentration Graph

Table 2. Post Treatment VOC Concentrations in Source Area Wells

Contaminant (μg/L)	MW-8s1	% Reduction	MW-8s2	% Reduction
PCE	ND	100%	*6*	96.04%
TCE	ND	100%	*9*	96.39%
c-1,2DCE	2	99.97%	2,070	45.81%
VC	ND	100%	62	49.17%
BTEX	35	97.06%	1,743	62.08%
Total VOCs	198	98.64%	6,051	58.04%

Table 2 presents tabulated ground water quality data, and observed contaminant reduction rates. The post treatment results show nearly 100% destruction of all contaminants in the shallow zone within the source zone. Contaminant reductions observed in the till zone are encouraging, indicating that some of the EOS® solution infiltrated into the till. Till contamination has been addressed through an additional injection program, which utilized different drilling and delivery enhancement techniques to allow for the direct application of the EOS® solution into the tight till.