



OVERVIEW

The site was a former manufacturing facility in Greenville, South Carolina. A trichloroethene (TCE) handling unit located adjacent to the facility, which was in operation for about ten years, was determined to be the primary contaminant source with an estimated total discharge of approximately 1,365 gallons of solvent. Site investigations revealed a groundwater plume (primarily of TCE) migrating off-site. The plume covers approximately 15 acres with concentrations historically greater than 250 mg/L in the source area, and up to 96 mg/L in the mid-plume area near an on-site access road. Site access is limited throughout much of the plume, with a steep slope near the source area, a public roadway adjacent to the property, and with a forest off-site.

The site geology consists of fill material (mostly silty sands) underlain by saprolite, a very dense partially weathered rock, and gneiss bedrock. The saprolite consists of thinly laminated, variably micaceous silty sand weathered from the underlying bedrock. The saprolite ranges in depth from approximately 2.5 to 26 ft below ground surface (ft bgs), the partially weathered rock ranges from approximately 10 to 35 ft bgs, and the bedrock ranges in depth from approximately 13 to 90 ft bgs depending on the area of the site. These depths become more shallow moving southwest from the source area. Similarly, groundwater flow moves in a southwestern direction and ranges from approximately 50 to 65 ft bgs in the source area and is as shallow as approximately 7 to 10 ft bgs in the most southwestern portion of the downgradient plume. Groundwater seepage velocity is relatively slow moving at approximately 60 ft per year.



Source Area and Access Road

Initial remediation efforts included the removal of the TCE storage tank, associated sumps, piping, and 140 tons of impacted material. Interim remedial technologies consisting of soil vapor extraction, *in situ* thermal desorption, and groundwater extraction were applied to address the remaining impacted groundwater and soils within the source area and affect hydraulic control of the contaminant plume in groundwater. Additional *in situ* remediation technologies were evaluated for the final remedy to treat the remaining elevated concentrations in the source and plume areas to the TCE maximum contaminant level (MCL) of 5 ug/L in the saprolite and bedrock zones. Results show that the primary treatment goal to significantly reduce VOCs in groundwater at the site was achieved and treatment is continuing as predicted by the model.

PILOT TREATMENT PROGRAM DESIGN

Geo-Cleanse International, Inc. (Geo-Cleanse) was contracted by Rogers & Callcott Environmental (Rogers & Callcott) to design and implement a pilot-scale treatment program for this challenging site. Based on the site conditions, a novel combination of technologies was proposed by coupling an aggressive source area approach using hydraulic slurry emplacement (HSE) of RemOx® S-B ISCO reagent (potassium permanganate (KMnO₄) sand blend) with a long-lasting, low maintenance approach using HSE of zero valent iron (ZVI) in the downgradient plume. Slurry emplacement is a process in which a fluid is introduced at a pressure sufficient to overcome the *in situ* confining stress and the material strength of the solid matrix, inducing or enhancing fluid flow into the formation. The resulting contrast in hydraulic conductivity between the emplaced ZVI and permanganate within the formation will result in deflection of groundwater flow into the more permeable treatment zone.

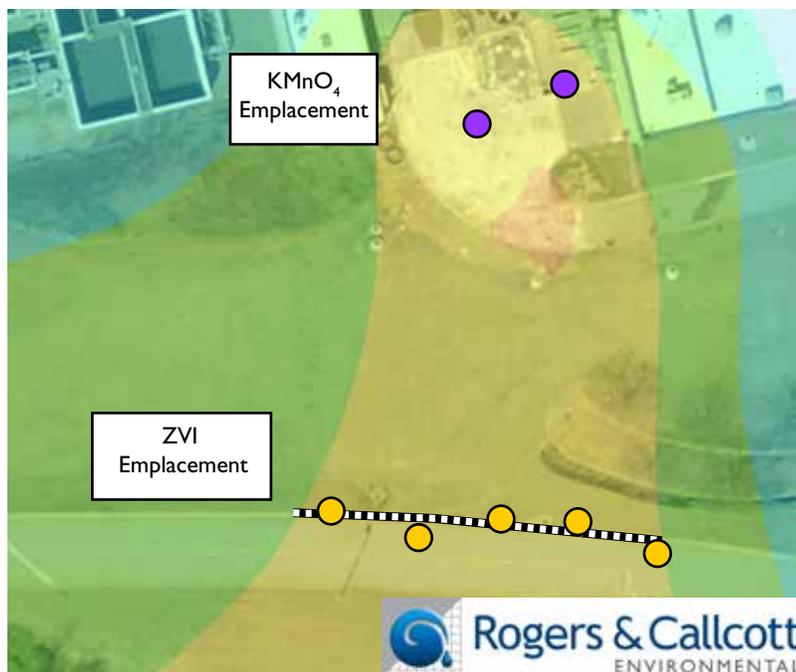
Reagents were emplaced as high-solid slurries to distribute large reagent volumes within specific and focused target zones in the low-permeability saprolite and fractured bedrock. Each treatment approach targeted the vertical interval from the water table in the saprolite to approximately 10 ft into bedrock, or 10 ft below the water table when the water table was encountered within the bedrock. The primary objectives of the pilot treatment program were to evaluate the potential overall effectiveness of each technology, and to assess engineering assumptions relevant for full-scale project design and implementation.



RemOx® S-B ISCO Reagent & ZVI Site Summary of Former Manufacturing Facility Trichloroethene (TCE) in Greenville, South Carolina

For the downgradient portion of the plume, ZVI was selected to create a barrier to reduce the dissolved phase contamination that was moving off-site. A total of five borings spaced approximately 30 ft apart were utilized for the ZVI slurry emplacement to create a 150 ft barrier oriented perpendicular to the direction of groundwater flow. A combination of emplacement through sonic drill rods (open borehole) and installation of 4 inch diameter, schedule 40 PVC casings was used to complete the borings. The PVC casing approach was more efficient and cost-effective compared to emplacement through the drill rods. The ZVI was emplaced at multiple discrete intervals within each boring location. A granular form of ZVI was utilized rather than microscale or nanoscale forms, due to the much longer lifetime (e.g., decades) in the subsurface. The emplaced slurry provided a high-permeability zone within a low-permeability formation, which deflected groundwater preferentially into the ZVI-filled structures.

In the source area, RemOx S-B was emplaced at two boring locations, which were constructed with 4 inch diameter, schedule 40 PVC casing that was grouted into place. The casings were installed using sonic drilling technology and were spaced approximately 25 ft apart. RemOx S-B was emplaced at four to six discrete depth intervals within each boring. Similar to the ZVI-filled structures, the groundwater within the source area will preferentially deflect into the permanganate-filled structures. Permanganate was selected for its various advantages including its ability to destroy unsaturated chlorinated solvents such as TCE without generating hazardous intermediates or breakdown products, its long life span (several months to over a year), and for its ability to chemically diffuse into fine-grained soil and bedrock, which will inhibit back-diffusion of TCE from the low-permeability matrices.



KMnO₄ and ZVI Pilot-Scale Treatment Areas

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PILOT-SCALE REMEDIATION OPERATION AND RESULTS

The ZVI slurry was prepared by blending the ZVI with guar gum in an aqueous matrix, which thickens the slurry to suspend the ZVI in the fluid. An enzyme is included in the slurry, which slowly breaks down the guar gum over a period of hours following emplacement in order to expose the ZVI to react with the groundwater. Approximately 73 tons of ZVI were emplaced into the five borings over a 12 day period. Following ZVI barrier construction, Geo-Cleanse emplaced the RemOx S-B over a 7 day period within the source area. During that time, approximately 29,000 lbs of RemOx S-B was emplaced at the two borings.

Remedy evaluation, permitting, management, oversight and field monitoring were conducted by Rogers & Callcott and included groundwater sampling events prior to, during, and after the emplacement of each reagent. During emplacement, tiltmeters were utilized to evaluate fracture geometry and determine reagent distribution. Three soil borings were advanced and soil cores visually examined for the presence of ZVI particles and were analyzed with a magnetic susceptibility meter to quantify the presence of ZVI. Furthermore, core sections were used to evaluate the physical distribution of the ZVI, and ZVI particles collected from the borings were analyzed by X-ray diffraction.



Post-treatment sampling events indicated TCE destruction in the targeted source and downgradient areas. Permanganate was observed in 11 of the 15 monitoring locations within the source area, with significant TCE reductions ranging from 84 to 100% compared to baseline concentration. One target monitoring well within the source was reduced from 82,000 µg/L to non-detect.

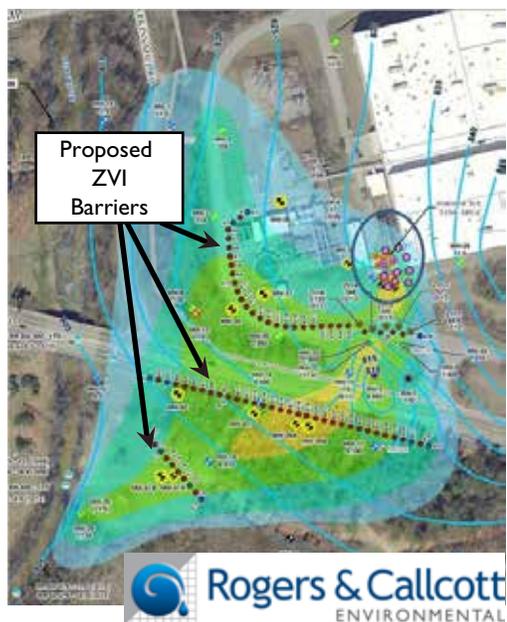
TCE concentrations in monitoring wells downgradient of the ZVI barrier were reduced from 46 to 100%. Some locations did exhibit increases in cis-1,2-dichloroethene (cis-DCE). This was most likely due to a small percentage of the TCE going through hydrogenolysis instead of the β -elimination pathway. Typically, about 90% of the TCE degraded by the ZVI is degraded through the β -elimination pathway, while approximately 10% is degraded via the hydrogenolysis pathway. Following the pilot-scale treatment program, design assumptions were reevaluated for development of the full-scale design.



Active ZVI Emplacement

FULL-SCALE TREATMENT PROGRAM DESIGN

Based on the pilot field observations and post-treatment monitoring, two design alterations were made for full-scale implementation. The design changes included increased ZVI volumes in each boring location and decreased spacing between each ZVI boring location. These changes were primarily based on elevated levels of cis-DCE observed during pilot-scale groundwater performance monitoring. These alterations were made to increase the residence time of groundwater in the ZVI structure, which would effectively treat the cis-DCE degradation product and reduce total volatile organic compounds (VOCs).



The proposed full-scale ZVI treatment program design included the installation of three barriers (Barriers A, B and C), which included 73 borings spaced approximately 20 ft apart. Similar to the pilot, the barriers were oriented perpendicular to the direction of groundwater flow. Barrier A, the most upgradient and only on-site barrier, extended over 600 ft with a total of 30 borings. Barrier B extended over 660 ft with a total of 33 borings, and Barrier C was positioned in the southern most portion of the plume and had 12 borings spanning over 200 ft. The full-scale final design was further evaluated and confirmed during field implementation, which included additional delineation and investigation.

The proposed full-scale source area design included RemOx S-B emplaced at nine borings over a 6,500 ft² area. The borings were spaced in a grid-like pattern approximately 25 to 30 ft apart and, similar to the pilot, the borings were installed 10 ft into bedrock. The two pilot borings were also utilized during the full-scale program to emplace additional RemOx S-B.



FULL-SCALE REMEDIATION OPERATIONS

Full-scale implementation began in July 2013 and was completed in August 2014. The source area was targeted first, followed by installation of the three ZVI barriers. Approximately 77,000 lbs of RemOx S-B was initially emplaced throughout the source area. Then, in June 2014, an additional 62,000 lbs of RemOx S-B was emplaced to address incomplete RemOx S-B coverage that became evident in post-treatment sampling events.

Prior to ZVI emplacement, additional groundwater samples were obtained to further delineate the plume extent and ensure that the barrier designs provided sufficient coverage. The additional delineation reduced the size of the proposed downgradient barriers, which provided cost savings. Of the originally proposed 73 boring locations, only 57 boring locations were utilized. Approximately 655 tons of ZVI were emplaced into the 57 borings utilizing a total of 345 vertical intervals.

FULL-SCALE TREATMENT RESULTS

The primary treatment goal was to significantly reduce VOCs in groundwater at the site and eventually reach the TCE MCL of 5 µg/L within a reasonable timeframe. Following full-scale RemOx S-B emplacement, TCE concentrations were significantly reduced in nearly all the monitoring wells within the treatment area (Figures 1 & 2). Many of the wells were reduced to non-detect from baseline concentrations ranging from 4,400 µg/L to 82,000 µg/L. Further TCE reductions are expected at the wells that have not reached non-detect (e.g., RW-4).

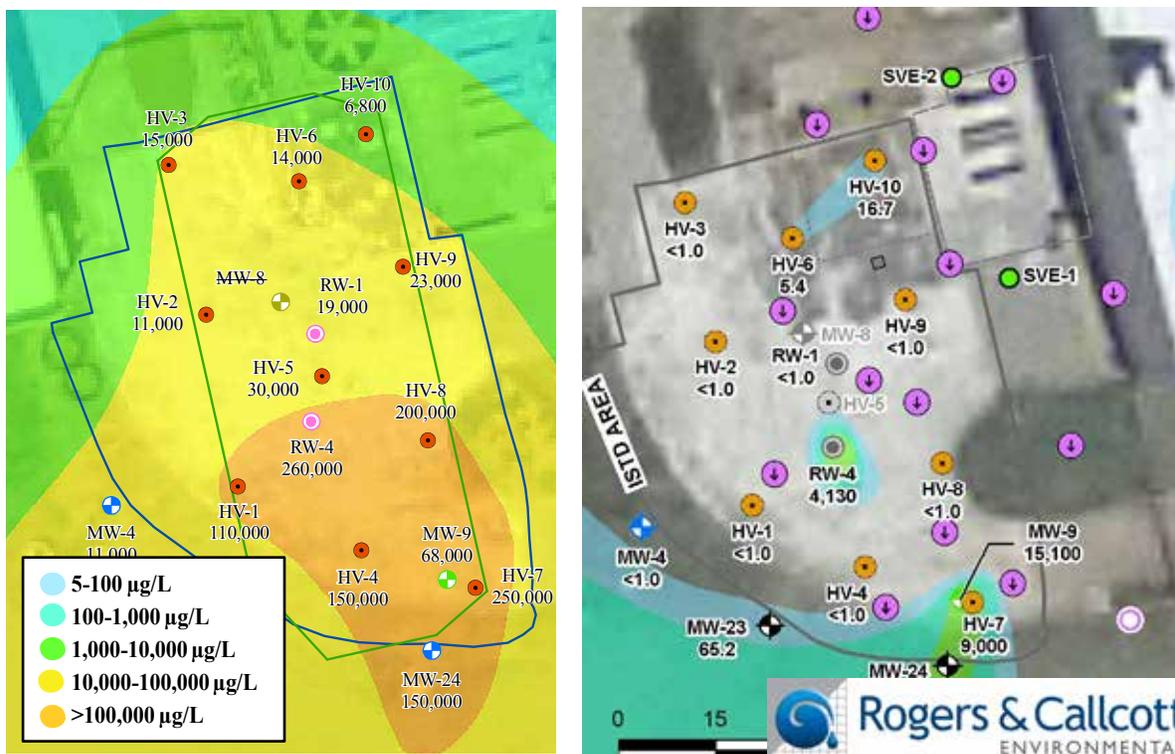


Figure 1 (left): Source Area TCE Concentrations March 2009, Figure 2 (right): Source Area TCE Concentrations July 2014



Significant reductions in total VOCs have also been observed throughout the downgradient plume areas (Figures 3 & 4). Groundwater plume treatment using ZVI barriers is a long process compared to *in situ* chemical oxidation. This is because VOCs are sorbed to the soil in addition to dissolved in groundwater. The groundwater is treated as it passes through the ZVI barriers, but desorption of VOCs from the soil is a long process. The lifetime of the ZVI was a key parameter, as it will persist long enough to address long-term desorption. Based upon the results to-date, it is clear that treatment is occurring across the site and should continue under the current model.

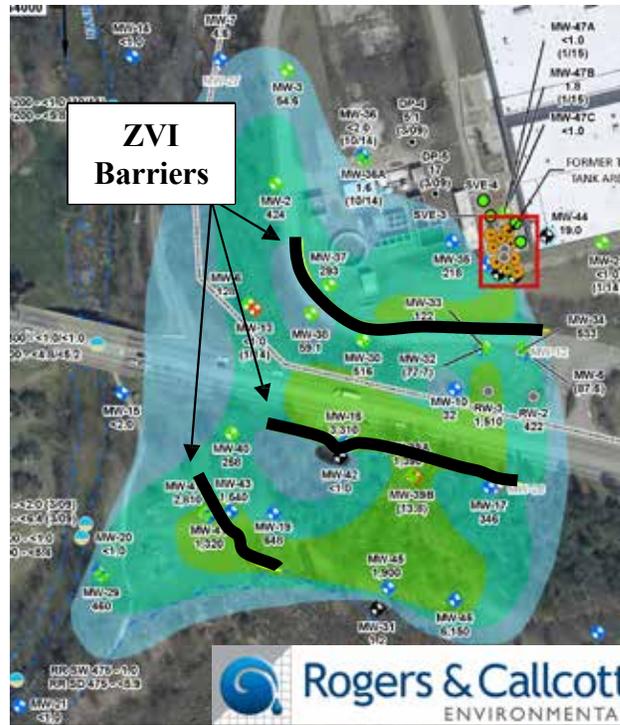
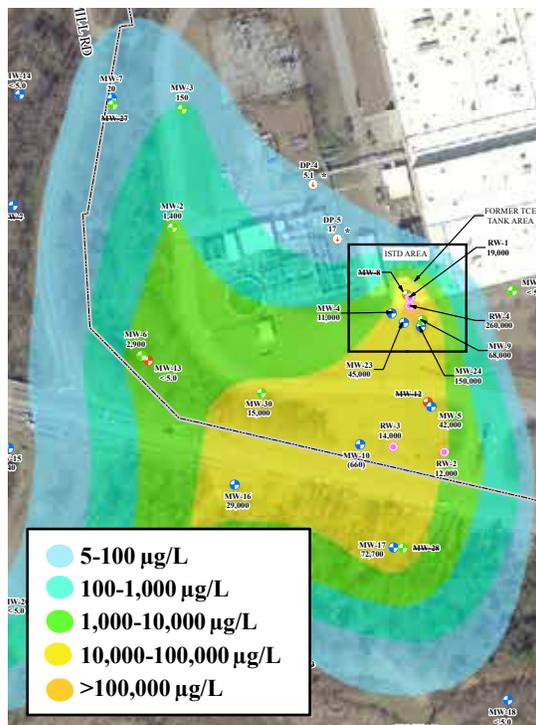


Figure 3 (left): Plume TCE Concentrations March 2009
Figure 4 (right): Plume TCE Concentrations July 2014

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