Concluding a Steam Injection Remediation Project at a Dense Non-Aqueous Phase Liquid Source Zone at the Savannah River Site – 15303

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ABSTRACT

Multiple subsurface dense non-aqueous phase liquid (DNAPL) source zones served as the sources for a groundwater plume within the A/M Area of the Savannah River Site. Between 1952 and 1985 over 1,600 metric tons of trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane were released to the environment resulting in a 648 hectare plume with the M-Area Settling Basin receiving over half of the solvent discharges. In 1991, DNAPL was found in a water table well and steam injection technology was selected to remediate the source zone. Based on characterization data, the treatment area was 1.21 hectare with depths between 13.7 to 50.3 m. The remediation system included 96 vertical, horizontal, and angled steam injection and soil vapor extraction wells and a thermal monitoring system. Construction of the system began in 2004 and operation began in 2005. Steam was applied to the deep vadose zone first, then progressed to the aquifer, followed by the mid-vadose zone. Multiple steam strategies were utilized to enhance mass removal and were concluded in 2009. Soil vapor extraction continues, with residual temperatures in the deep permeability zones still exceeding 65°C. To date over 204 metric tons of volatile organic compounds (VOCs) have been removed. Post-remediation soil, vapor, temperature, and groundwater data were used to evaluate steam injection effectiveness and demonstrated significant reduction in soil concentration, including removal of DNAPL that was evident in several soil cores prior to treatment. Heating the subsurface increased VOC solubility in groundwater and increased mass removal rates outside the target zone.

INTRODUCTION

The M-Area Settling Basin (MASB) is managed under the Resource Conservation and Recovery Act (RCRA) Permit for U. S. Department of Energy’s Savannah River Site (Module IV-A for M-Area and Metallurgical Laboratory Hazardous Waste Management Facilities). The MASB received an estimated 900 metric tons (2 million lb) of waste volatile organic compounds (VOCs) from 1958 to 1985. The MASB was emptied and closed with a RCRA cover in 1991. In the early 1990s, DNAPLs containing primarily tetrachloroethylene (PCE) and trichloroethylene (TCE) were detected in the water table aquifer north of the basin. Under the RCRA Permit, the corrective action consisted of groundwater extraction and treatment and soil vapor extraction. In an effort to aggressively remediate the vadose zone and shallow groundwater contamination at the MASB, the Western Sector Dynamic Underground Stripping (DUS) project was initiated in August 2005. DUS is a process developed after the oil industry standard of injecting steam into the subsurface to enhance removal performance. A pilot scale project successfully demonstrated DUS at a nearby site. The pilot DUS targeted a 0.08 hectare (0.2 acre) area to approximately 48.8 m (160 ft) depth and removed 32 metric tons (70,000 lb) of DNAPL during one year of operation ending September 2001.

DESCRIPTION

Pre-remediation Characterization

Prior to the design and construction of the DUS system at the MASB, historic characterization data from the MASB area was compiled and evaluated. Based on the evaluation, possible source zone architecture depictions were constructed and the target zone (TZ) for the DUS remediation project was identified to include the mid to lower vadose zone, water table aquifer, and the underlying confining unit.

In A/M Area, the lithology consists of a series of unconsolidated, interbedded sands and clays. The vadose zone extends down to a depth of approximately 38.1 m (125 ft) and consists of 6.1 to 12.2 m (20 to 40 ft) thick sandy clay, approximately 15.2 m (50 ft) of sand, and transitions into 9.1 to 12.2 m (30 to 40 ft) of silty to clayey sand. The silty to clayey sands continue into the water table aquifer which is 1.5 to 3 m (5 to 10 ft) thick. The current water table is at an approximate depth of 42.7 m (140 ft). Underlying the water table is a 1.5 to 6.1 m (5 to 20 ft) thick confining zone that varies between a silty to sandy clay. The underlying aquifer is a 18.3 m (60 ft) thick very fine to fine sand bed with minor low permeability zones.

The TZ at DUS was a 1.21 hectare (3 acre) footprint with depths of 13.7 to 50.3 m (45 to 165 ft) and an estimated 340,000 cubic meters (12 million cubic ft) of soil to remediate. A calculation of mass in the DUS TZ estimated a maximum of 317.5 metric tons (700,000 lb) of total VOCs. There were 33 vapor extraction wells (VEW) fully screened across the TZ, including four with groundwater pumps, and a horizontal vapor extraction well that stretched over 91.4 m (300 ft) underneath the footprint of the closed settling basin. Sixty-three steam injection wells (SIW) were strategically placed throughout the TZ and thermal monitoring points (TMP) were installed to measure subsurface temperature. Fig. 1 shows the location of the TZ relative to the settling basin and the location of the SIWs and VEWs. The TZ was divided into four parcels to manage the input of steam and rate of extraction to comply with permit requirements.

While drilling the SIW and VEWs for the DUS project, soil cores were analyzed for VOC contamination at selected locations. These cores confirmed that the target area was a DNAPL-rich environment that showed discontinuous areas of highly concentrated DNAPL. The pre-remediation cores were used as comparative analysis for the soil borings that were completed during the post-remediation characterization.

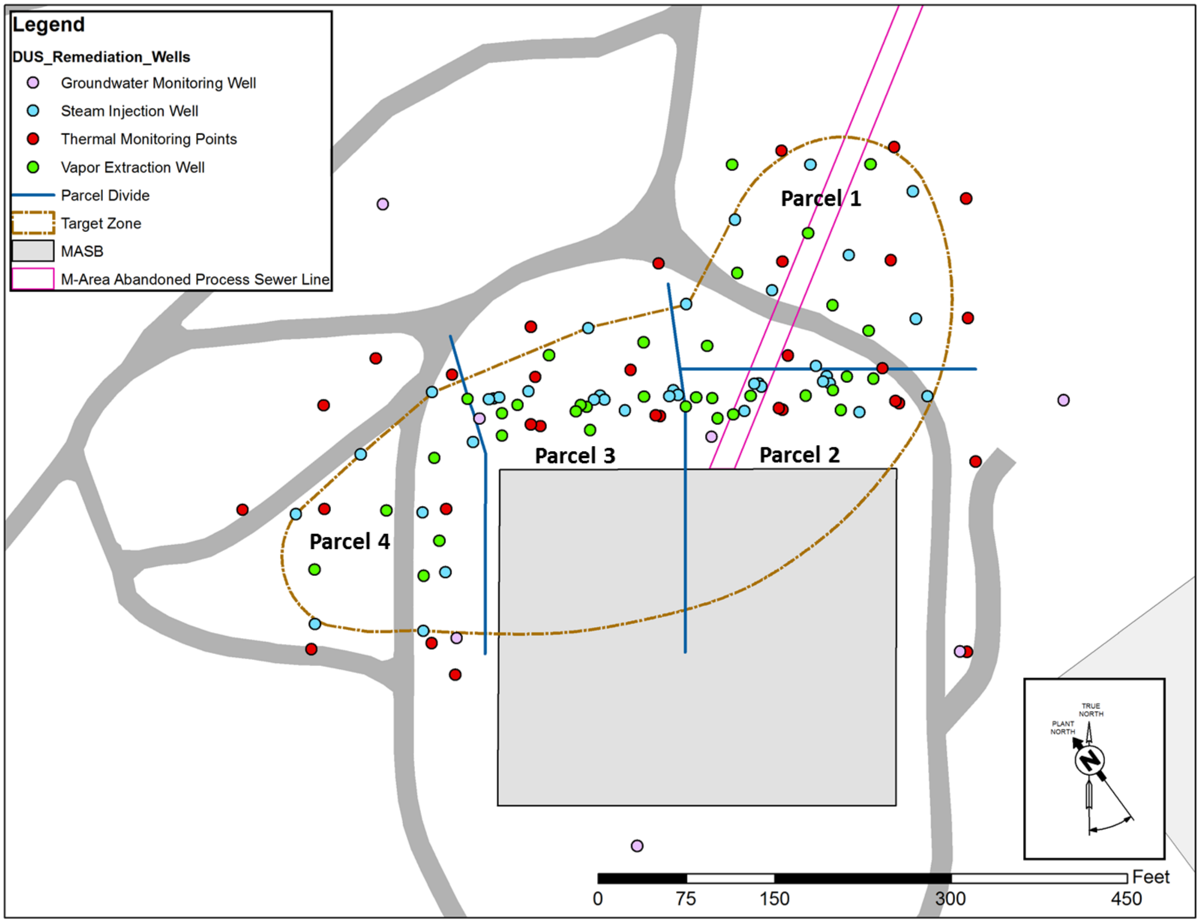

Fig. 1. The M-Area Settling Basin and location of the Dynamic Underground Stripping remediation system.

DUS Operational Data

During the first three years (2005 to 2008) of full-scale operation, the DUS system removed almost 181.4 metric tons (400,000 lb) of solvents from the target area. Heating criteria (110ºC [230°F] soil temperature) was met by the summer of 2006, but additional heating strategies were performed for the next three years to enhance extraction of contaminant mass. With diminishing returns after several different heating strategies, steam injection ceased in September 2009. At that time, total VOC removal in the area was estimated at over 195 metric tons (434,000 lb) of solvent.

As part of the completion of the DUS project, a post-remediation characterization effort was performed in the summer of 2013. The characterization was performed to evaluate the effectiveness of the DUS treatment system and determine the remaining source zone contamination architecture. Comparative information from pre- and post-remediation will be used to plan future remediation decisions.

Post-Remediation Characterization

The post-remediation characterization effort was designed to evaluate contamination remaining in the TZ with respect to soil, groundwater, and vapor data. The post-remediation activities in the TZ included the collection of depth-discrete soil samples throughout the TZ, vapor assessment of existing VEWs and some SIWs, and groundwater assessment from groundwater monitoring wells.

Depth discrete soil sampling was coordinated to mimic sampling performed during the pre-remediation characterization for comparison purposes. Soil borings were drilled in all parcels in vertical and angled orientations, but focused on areas that exhibited the highest concentrations measured from the pre-remediation characterization effort (Fig. 2). These locations were drilled when the localized subsurface temperature was measured at less than 70^{o}C (158°F).

Soil vapor was collected from the individual VEWs to assess the performance of the soil vapor extraction system. The overall VOC vapor concentrations have declined since steaming ceased in 2009. The VEWs with lower concentrations were either transitioned from an active to passive system or abandoned.

Groundwater was also assessed from extraction wells (EW) and monitoring wells (MW) in and out of the TZ. A number of MWs were abandoned during construction of DUS to prevent them from being damaged during steaming and were replaced during the post-remediation characterization effort (Fig. 2).

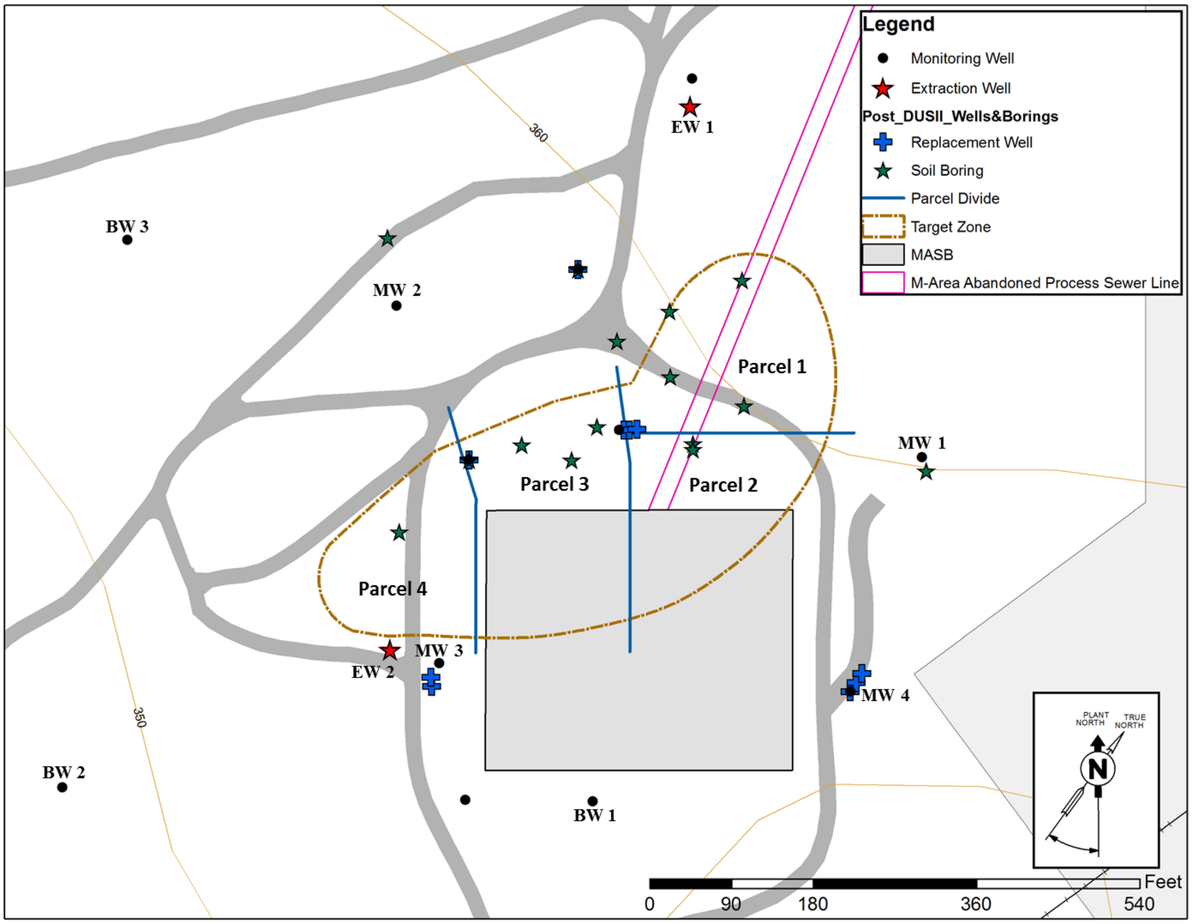

Fig. 2. Location of post-remediation soil borings, replacement monitoring wells, background wells, and extraction wells.

RESULTS

Thermal Monitoring Results

The TMPs were intermittently monitored since steam injection ceased in September 2009. Subsurface temperature data from May 2013 shows subsurface temperatures ranging from 33^{o} to 79^{o}C (91° to 174°F) with maximum temperatures located within the TZ.

At the end of the steaming campaigns, subsurface temperatures were over 105^{o}C (221°F) throughout the TZ. The rate of temperature decline observed from the vadose zone of the pilot DUS project was approximately 0.555^{o}C every month after steam injection ceased. Using this cool down rate, a starting temperature of 105°C (221°F), and a cool-down period of 50 months (through November 2013), it can be calculated that subsurface temperatures should be approximately 77°C (170°F). Current maximum observed subsurface temperatures of 79^{o}C (174°F) are slightly higher than the calculated temperature. At this rate, it is estimated that soil temperatures will return to background (~20°C [68°F]) in the year 2022.

Groundwater temperatures were monitored outside of the TZ at MWs and EWs. Groundwater temperatures increased from approximately 20°C to 32°C during steaming operations of DUS

(2005) and declined thereafter (2009) at MWs and EWs in the direct vicinity of the TZ. Although overall temperatures decreased to 25°C, they remain above ambient groundwater temperatures (20°C) measured at background wells (BW) located farther away from the MASB (Fig. 3). Groundwater temperatures have remained elevated (>30°C) at two wells (i.e., MW 3 and EW 2) located west and downgradient of the MASB, while two wells (i.e., MW 1 and EW 1) located to the north and east have had groundwater temperatures of 25°C since steaming ceased.

Since steam injection was stopped in 2009, the vapor extraction system has continuously operated. The extracted vapor temperatures have progressively dropped, which allowed the original vapor cooling system to be retired in 2012. The vapor temperatures recorded at the well heads in 2012 showed vapor temperatures that ranged between 32° and 74°C (90° and 165°F).

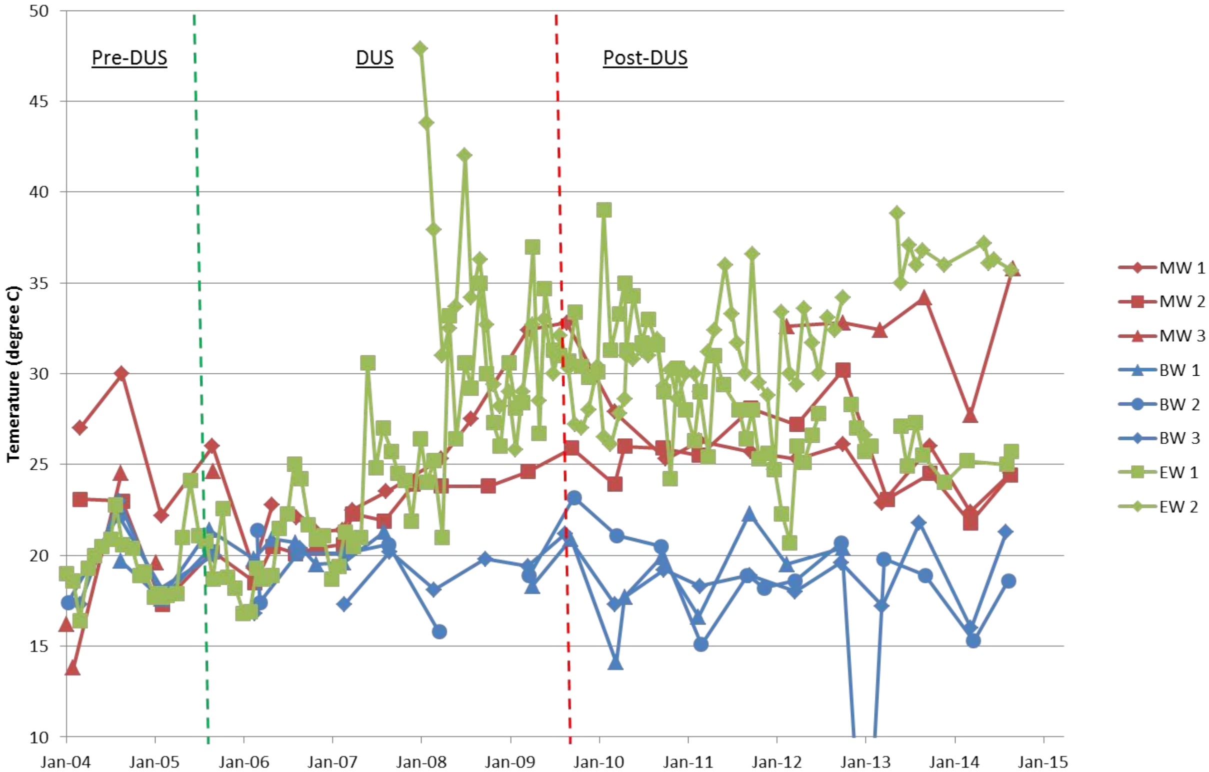

Fig. 3. Groundwater temperatures from MWs and EWs near the MASB.

Soil Boring Sample Results

Post-remediation soil samples within the TZ had significantly lower contaminant concentrations than pre-remediation samples. Sample locations outside the TZ showed concentrations that were comparable or slightly higher than pre-remediation samples. Fig. 4 shows a representative soil profile from each parcel comparing pre- and post-remediation soil concentrations for PCE. In Parcel 1, PCE concentrations were reduced by up to 4 orders of magnitude in the TZ while PCE concentrations were 3 times greater above the TZ, upper 18.3 m (60 ft). Parcel 2 had some of the highest soil concentrations (600,000 µg/kg) during pre-remediation sampling, while the post-remediation PCE concentrations were less than 1 µg/kg (greater than 99%). The soil concentration in Parcel 3 and 4 were low to non-detect through the vadose zone but showed elevated PCE concentrations into the water table of 400,000 and 12,000 µg/L, respectively.

Post-remediation samples declined to less than 100 µg/L in Parcel 3 and 4. However, similar to other post-remediation soil samples, PCE concentrations in Parcel 3 and 4 were 95 to 99% less than the respective pre-remediation samples.

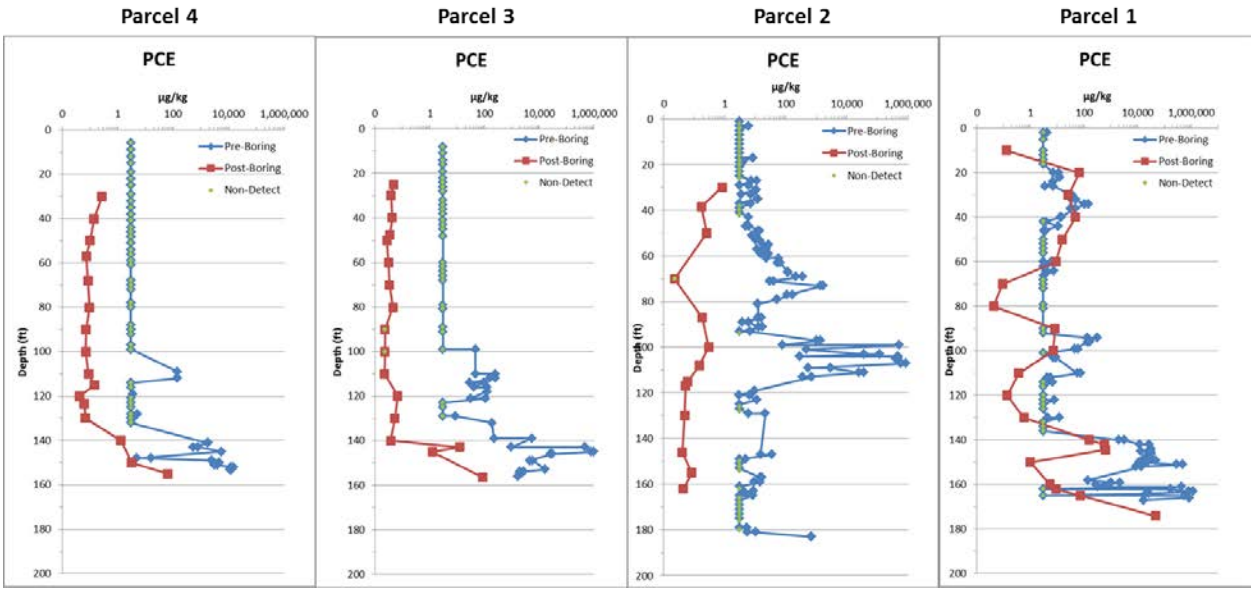

Fig. 4. Representative soil profiles for each parcel comparing pre-remediation PCE concentrations to post-remediation concentrations.

Soil borings located outside of the TZ were performed to confirm contaminant mass was actually removed from the TZ rather than just being redistributed in the subsurface. The maximum post-remediation PCE concentration at MW 1 was 289,000 µg/L, which is higher than the pre-remediation maximum concentration of 25,000µg/L. The pre- and post-remediation concentrations at MW 2 were very similar (Fig. 5). The soil data from MW 1 and MW 2 also indicate that PCE concentrations are also prevalent in the aquifer underlying the water table aquifer (>160 ft depth).

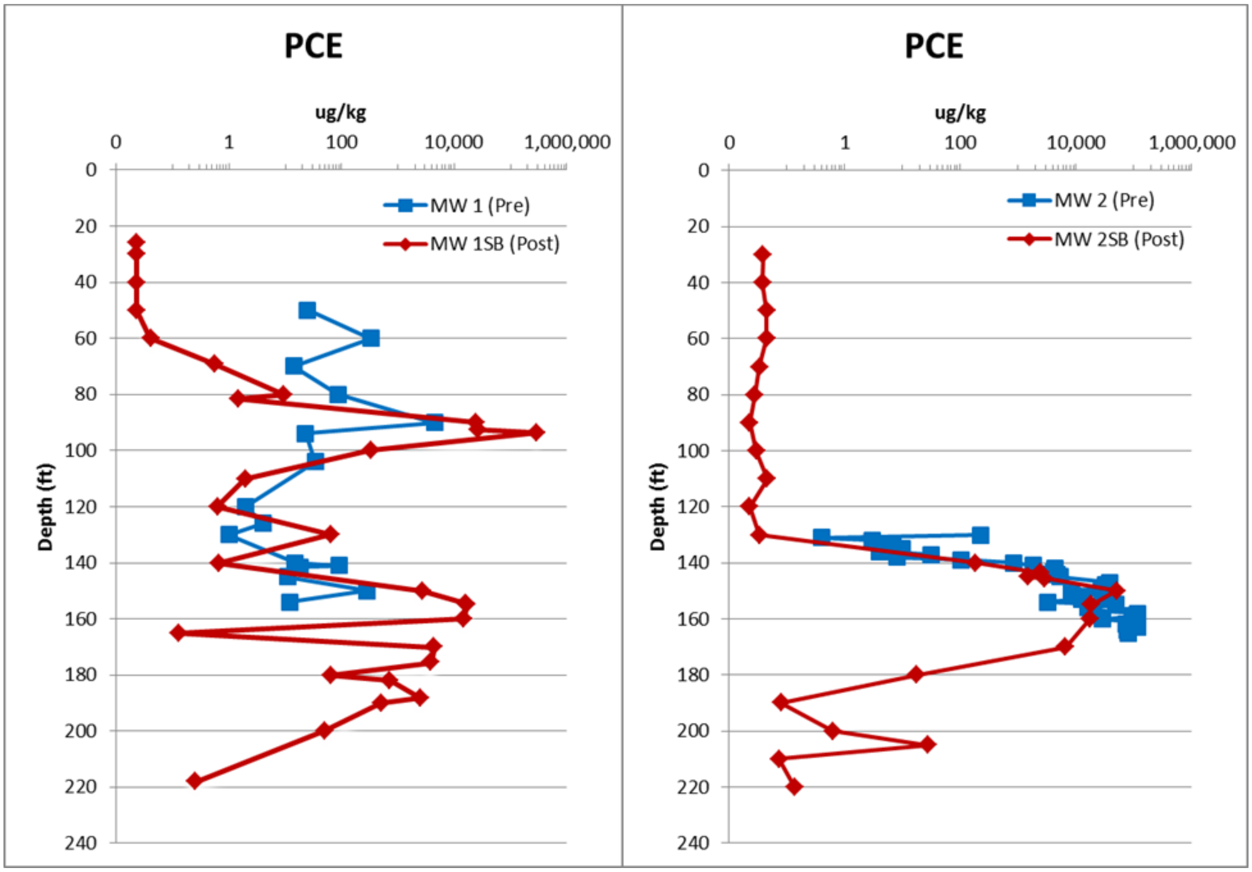

Fig. 5. Soil profile comparing pre-remediation and post-remediation PCE concentrations at MW 1 and MW 2.

Soil Vapor Results

In 2012, the VEWs were sampled to determine individual output because the overall mass removal rates had fallen nearly 25% over three years (2010 thru 2012). Based on that assessment, it was determined that individual wells could be grouped into three categories: active, passive, or abandon. The active group category removed greater than 0.45 kg (1 lb) of solvent per day, while the passive group removed between 0.45 kg (1 lb) and 0.045 kg/day (0.1 lb/day). The abandon group category removed less than 0.045 kg/day (0.1 lb/day). The active group will remain connected to the active soil vapor extraction unit, the passive group will be connected to low energy solar powered well head soil vapor extraction units, and the abandon group will be abandoned in place. The majority of the active group is in Parcel 1, the passive group in Parcel 2, and the abandon group is in Parcel 3 and 4 (Fig. 6).

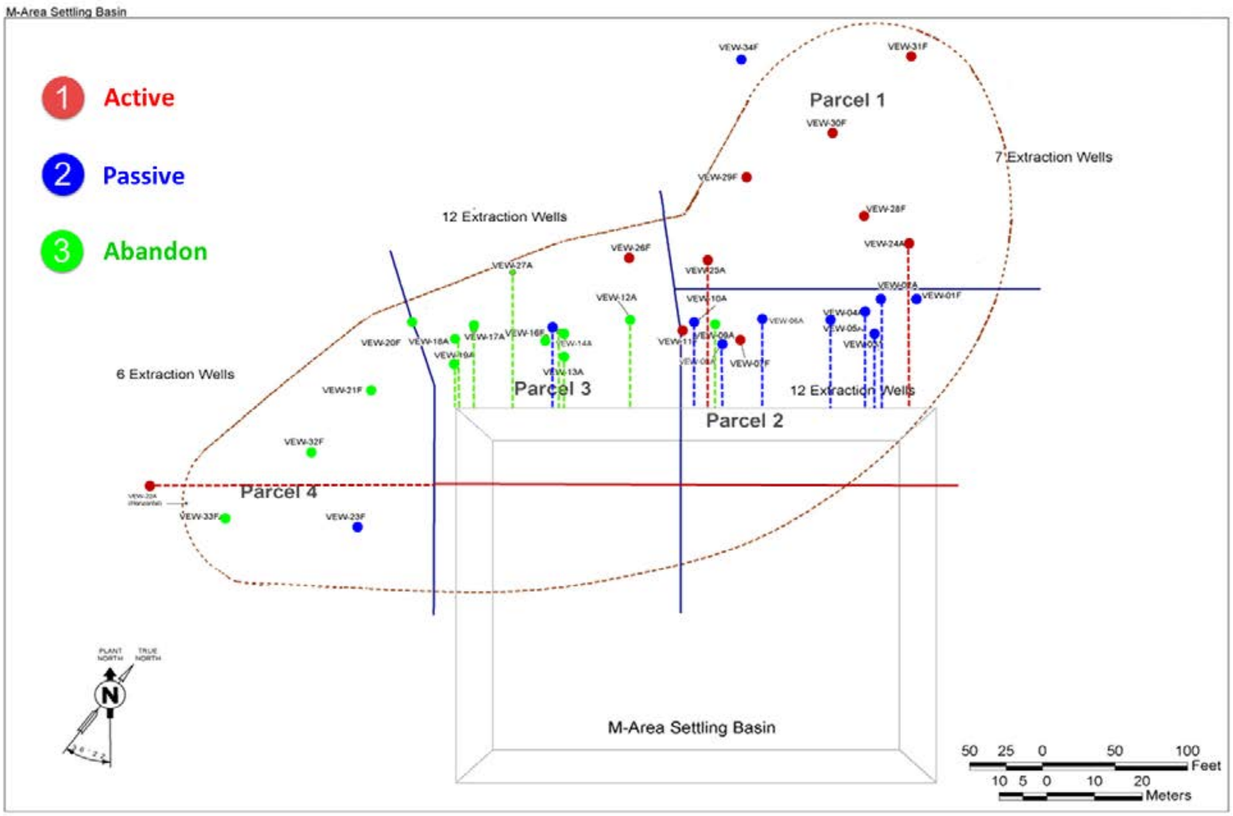

Fig. 6. The VEWs separated into three groups based on vapor data collect post-remediation.

The VEWs in the passive group were converted to low-energy systems in 2014 and will be used as a polishing system to remove contaminant vapors that are outside the zone of influence of the active system. This combination will aid in the removal of contaminants in the TZ and keep the subsurface in an equilibrium state that does not allow contaminant to diffuse or transport to the groundwater.

Groundwater Results

The MWs and EWs surrounding the MASB are sampled at least semi-annually per the RCRA permit. During post-remediation, monitoring wells were installed to replace wells abandoned during the construction of the DUS remediation system.

The extraction wells (i.e., EW 1 and EW 2) had notable increases in total VOC concentrations during operation of DUS (Fig. 7). The most significant increase (greater than 100 mg/L) in concentration was observed at EW 1, which has since decreased (40 mg/L) but is still exhibiting higher concentrations than pre-DUS. The increase observed at EW-2 (4 to 25 mg/L) was gradual and lasted almost three years after steaming ceased. VOC concentrations at EW 2 have been declining but are still greater than pre-DUS concentrations.

In general, VOC concentrations in water table MWs near the MASB have declined with time. This trend was also observed at the replacement wells installed during post-characterization. Groundwater samples from the TZ have not yet been collected due to elevated groundwater temperatures (65°C [149°F]). The aquifer beneath the water table which is outside of the TZ (deeper than 50.3 m [165 ft] depth), has high VOC concentrations.

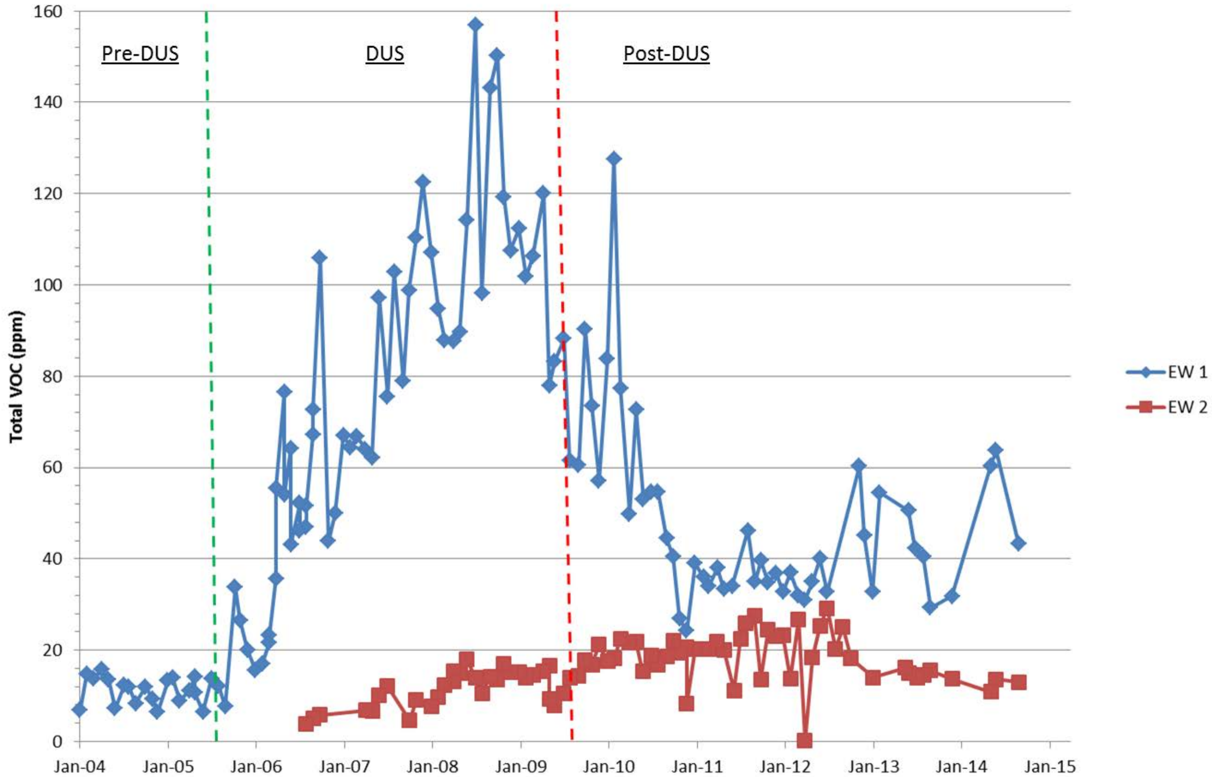

Fig. 7. Time series trend of total VOC concentration at EW 1 and EW 2 before during and after operation of DUS.

DISCUSSION

All the data collected during the post-characterization at the MASB suggest that the DUS remediation system was effective in heating the subsurface and removing contaminant mass in the TZ. From 2005 to 2013, the DUS system was able to remove an estimated 207.5 metric tons (457,425 lb) of VOCs from the subsurface. In the TZ, direct comparison between the pre- and post-DUS PCE soil concentrations revealed greater than 99% reduction in soil concentration.

The data also suggest that contaminant concentrations have increased outside of the TZ. This was evident near Parcel 1 in the shallow vadose zone (Fig. 4) as well as at MW 1 (Fig. 5). The steam used to heat the TZ allowed it to reach its target temperatures and radiate outward into the area surrounding the TZ. Elevated groundwater temperatures were observed at distances of up to 122 m (400 ft) from the TZ in the water table and underlying aquifer. Data from the TMPs indicate the majority of the latent heat remaining in the subsurface is being stored in the confining unit separating the water table and underlying aquifer. The latent heat is increasing aqueous VOC concentrations due to increased solubility in groundwater and increased mass transfer from the clays of the confining unit into more permeable sediment. The increased solubility and mass transfer is evident by an increase in groundwater temperature at EW 1 corresponding with an increase in VOC concentrations (Fig. 8). The EW 1 is screened from the water table, through the confining unit, and into the underlying aquifer. The EW 1 and EW 2, which are on the north and western side of the MASB respectively, removed additional mass from the aquifer because of the latent heat associated with DUS. The east side of the MASB, however, is outside the zone of capture of the two EWs. VOC concentrations at MW 4, one of the replacement wells on the east side of the MASB, are currently greater than 100 mg/L. The groundwater temperature at MW 4 is elevated above background. The high dissolved concentrations of VOCs and elevated temperatures provide an opportunity for additional corrective action outside of the TZ to continue removing mass from the subsurface.

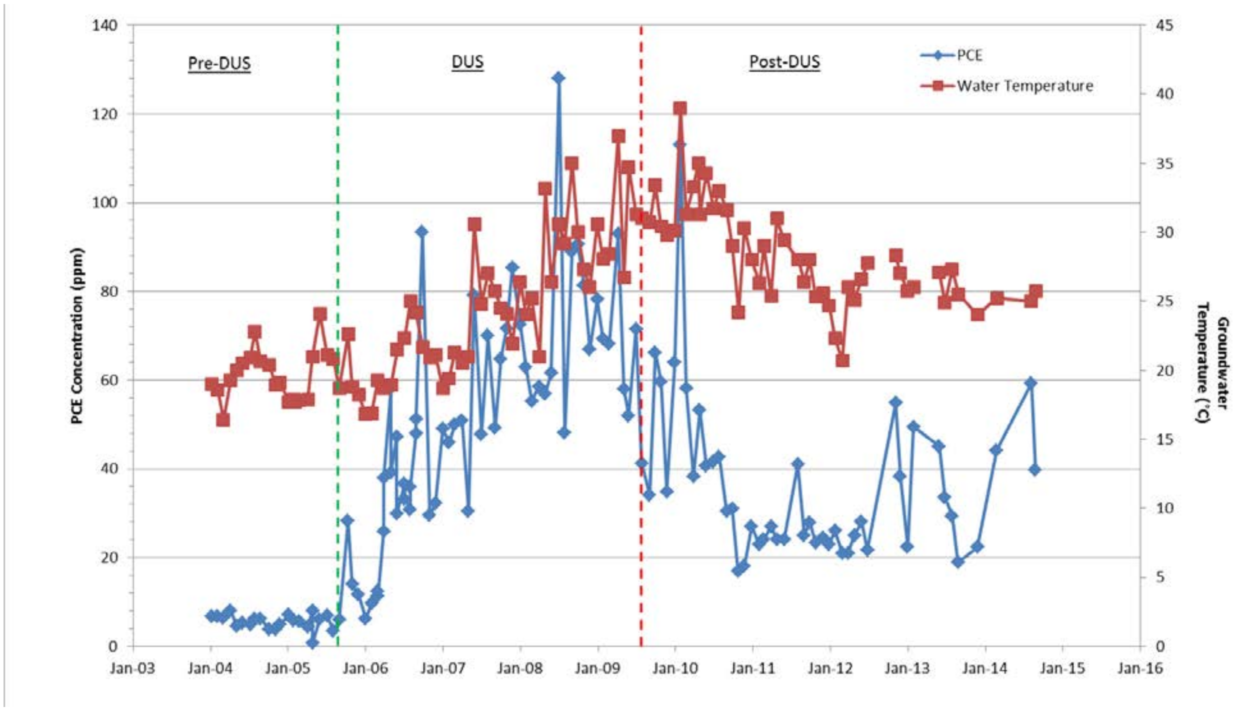

Fig. 8. Groundwater PCE concentration and water temperature at EW 1.

CONCLUSIONS

It is evident from the data collected during the post-remediation evaluation of the DUS system that the deployment of DUS was able to heat the subsurface and significantly reduce VOC concentrations in the TZ. Although DUS was discontinue in 2009, the elevated subsurface temperatures allow for continued mass removal through vapor and groundwater extraction; therefore, preventing further impact to downgradient sources. The following are major points determined from this analysis:

1) The remedial effort was very successful in mass removal (>99% based on direct comparison of pre- and post-heating analytical results) of volatile contaminants, dominantly PCE and TCE, particularly in the vadose zone throughout the TZ.
2) Conditions are appropriate for a phased transition of SVE wells from active to low-energy units. Eleven (11) SVE wells were converted to low-energy SVE units in September 2013.

3) Subsurface temperatures are declining as expected and temperatures are estimated to be near background (~20^{o}C [68°F]) by 2022.
4) Since latent heat in the area is still contributing to a higher solubility of the VOCs, groundwater concentrations of VOCs have increased in recovery wells EW 1 and EW 2 and surrounding monitoring wells. Elevated levels of PCE and TCE are also observed in deeper aquifer sediments from borings in the area surrounding the MASB.

Post-remediation characterization results demonstrate that steam heating is an effective technology in removing VOC contamination from a heterogeneous mix of unconsolidated sediments, including low permeability silts and clays. The overall costs were high (~$30M) but were mitigated by the availability of a steam source produced by a local on-site power plant. Although significant contamination remains in the associated deeper aquifer zones, the source zone is now in a polishing stage of SVE, and may be considered complete within a reasonable time frame (<10 years).