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Fractured Bedrock Pump-and-Treat Conversion to In Situ Bioremediation

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ABSTRACT: A groundwater pump-and-treat system was installed at an industrial facility in the late 1980s to address chlorinated volatile organic compound (VOC) contamination in a deep aquifer. Following the detection of perchlorate in the deep aquifer in September 2001, the pump-and-treat (P&T) system was deactivated. It was determined that, with relatively minor modifications, the existing P&T system could be converted to an *in situ* bioremediation system capable of the anaerobic reduction of both VOCs and perchlorate, while maintaining hydraulic control of the contaminant plumes. A phased pilot test is being conducted to evaluate the effectiveness of this bioremediation system. The first phase was conducted from October 2002 to May 2003, and the second phase began in May 2004 and is still in operation. Perchlorate concentrations have fluctuated in the deep groundwater at the extraction well, but the most recent sampling event in March 2006 indicated perchlorate levels have been reduced by approximately 88% with VOCs being reduced by approximately 62%. With continuous operation and maintenance of the bioremediation system, the reduction of VOCs and perchlorate will continue to concentrations that are protective of human health and the environment.

INTRODUCTION

A groundwater pump-and-treat system was installed at an industrial facility in the late 1980s to address chlorinated volatile organic compound (VOC) contamination in a fractured bedrock aquifer over 250 feet below ground surface (bgs) (76.2 m). The treatment process consisted of a coarse filtration system, an air-stripping tower, and a carbon adsorption system. With the air-stripper alone the removal efficiency for VOCs was approximately 99.99%. Following the detection of perchlorate in the deep aquifer in September 2001, the pump-and-treat system was deactivated. Perchlorate is a highly soluble inorganic ion that is not amenable to remediation via air stripping or carbon adsorption. After examination of the existing pump-and-treat system, it was determined that the existing system could be converted to a bioremediation system capable of promoting the *in situ* anaerobic reduction of both the VOCs and perchlorate, while maintaining hydraulic control of the contaminant plumes.

The bedrock identified beneath the site in the deep groundwater treatment area consists of two major types: a Jurassic igneous diabase and a Triassic metamorphosed siltstone/sandstone (metasediments). The diabase is located throughout most of the facility, with the metasediments located primarily in the north central portion of the facility. Based on site testing activities, including aquifer pump tests and downhole geophysical testing of selected wells, the diabase was found to have minimal to no primary or secondary fracturing and to lack any significant quantities of groundwater. Further evaluation of the collected data indicated the diabase to be relatively impermeable and to act as an aquitard. The physical evaluation of the metasediments indicated the formation to be more permeable and exhibit substantial fracturing in comparison to the diabase. Significant quantities of groundwater in the metasediment bedrock have been documented at the facility, and consist primarily of bedding-plane partings, master joints, and conjugate joints. Deep groundwater throughout the extent of the metasedimentary bedrock was found to be predominately fracture-controlled. The results of a deep aquifer test within the metasediments indicated aquifer responses consistent with confined or leaky (semi-confined) conditions that are fracture-controlled and have a radial flow component. From these deep aquifer test results, the metasediment aquifer is generally shown to be anisotropic and heterogeneous with two primary fracture zones connecting the wells located in the deep groundwater treatment area.

Chemical characterization of the deep groundwater aquifer has been accomplished via multiple investigations and periodic groundwater sampling events. Both historical and recent sampling data have shown perchlorate and VOC plumes centered in the north-central and central portions of the facility (i.e., the treatment zone). Facility-wide sampling in 2004 indicated perchlorate concentrations in the treatment zone ranging from 11.7 µg/L to 8,293 µg/L. The deep groundwater perchlorate plume extends approximately 2,250 feet (685.8 m) in a direction parallel to the natural hydraulic gradient and to a maximum width of approximately 1,750 feet (533.4 m) in the cross-gradient direction. Total VOC concentrations in the monitoring wells that represent the area within the VOC plume, ranged from 1.0 µg/L to 1,664 µg/L (2004). The smaller deep groundwater VOC plume lies within the horizontal extents of the perchlorate plume.

Phase 1 of the pilot study system began in October 2002 and was completed in May 2003 and was described in Morris et al (2004) and Early et al (2005). The Phase 1 configuration for the system consisted of the existing deep groundwater extraction well, air stripping tower (VOC treatment), coarse filtration system, a substrate amendment system, and an existing deep groundwater extraction well converted to an injection well. An inflatable packer system was later installed in this injection well to facilitate pressurized injections.

After a thorough review of the data and system operations it was determined that to optimize the *in situ* treatment of the contaminants, several upgrades were required. The upgrades were completed for Phase 1A of the pilot system to facilitate the distribution of substrate, reduce injection well fouling (mineral and biological) and interlock the treatment injection system with the extraction pump. Modification of the existing system for Phase 1A of the pilot test began in May 2004 and start-up was initiated in July 2004. The air-stripper was also replaced with the existing carbon adsorption system for VOC removal due to mineral fouling issues from aeration of groundwater via the air-stripping process.

Additional source areas for perchlorate and total VOCs were also identified during investigations in 2004 to the east of the original treatment area. To address this additional potential source area and to increase the treatment zone, three additional injection points were installed and activated in the fall of 2005.

MATERIALS AND METHODS

The current pilot-scale deep groundwater treatment system consists of an extraction well and four injection wells (see Figure 1). These wells were selected based on location (within the core area of impacted deep groundwater) and historically proven hydraulic connection (to maintain hydraulic control of the perchlorate and VOC plumes). A 7.5 horsepower submersible pump installed in the extraction well at 250 feet bgs (76.2 meters) is used to continuously pump groundwater to maintain hydraulic control of the contaminant plumes.

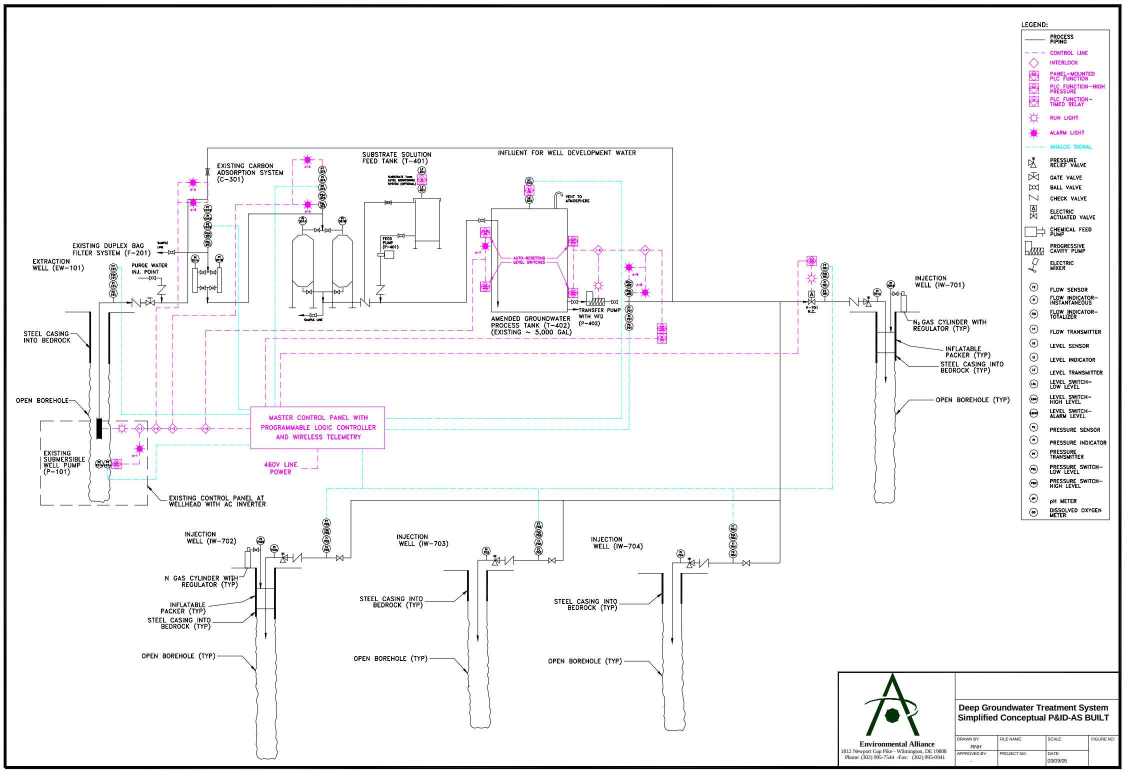

FIGURE 1. Simplified deep groundwater pilot test design.

Extracted groundwater is first filtered through a 50-micron bag-filter then enters the existing carbon adsorption system to remove VOCs. The treated, extracted water is then amended with substrate via a chemical feed metering pump and is staged in a 5,000-gallon (18,927 L) collection tank. The tank is equipped with a sonic level switch that controls the cyclic operation of a 15-horsepower positive displacement pump interlocking the injection and extraction systems to prevent overflow of the collection tank. Approximately 3,000 gallons (11,356 L) of treated and amended groundwater is then pumped from the tank into the four subsurface injection points in the core of the contaminant plumes.

An inflatable packer was installed in the original injection well (former Facility extraction well) and the new deep injection well, enabling the reinjection of groundwater at elevated pressures. A standard pressure relief valve rated for 125 pounds per square inch (psi) is installed at the injection wellhead to ensure that potentially harmful backpressures are not maintained during injection cycles.

The extraction rate was initially set at 20 gallons per minute (gpm) (75.7 L) during October 2002, and was increased to 30 gpm during January 2003 and finally increased to 35 gpm (132.5 L) in December 2005. To maintain the system water balance, the extraction and injection rates are adjusted such that the injection rate is always approximately twice the extraction rate (i.e., 60-80 gpm) (227-303 L), thus cycling the injection for an on and off cycle that allows the subsurface to dissipate the backpressure generated during each injection.

Hydraulic monitoring of the deep groundwater pilot system was initiated just prior to the beginning of the Phase 1 pilot test in October 2002 and is still ongoing. Monitoring of the pilot system during start-up periods (e.g., beginning of the pilot test, following system repairs and/or upgrades) occurred on a daily basis for a period of 3 to 4 weeks. Subsequent routine monitoring occurs on a monthly schedule. Routine hydraulic monitoring of the deep groundwater pilot system includes: 1) recording of flow rates (gpm) for the extraction and injection wells using existing flow meters; 2) recording of backpressure (psi) readings at the injection well during injection cycles using existing pressure gauges; and 3) water level gauging at deep wells in and around the groundwater treatment zone using an electronic water level meter. In addition to the active water level monitoring, a pressure transducer was installed in the extraction well to continuously monitor water levels at that location and assure that the groundwater level does not fall below the level of the pump.

RESULTS AND DISCUSSION

The deep groundwater Phase 1 of the pilot test was conducted from October 2002 to May 2003, with approximately six weeks of downtime for system repairs and upgrades. At the conclusion of Phase 1 in May 2003, approximately 3,132,000 gallons (11,855,656 L) of water had been extracted, treated for VOCs, and reinjected. As previously discussed, a thorough review of the data and system operations was completed and it was determined that to optimize the *in situ* treatment of the contaminants, several upgrades were required. The upgrades were completed for Phase 1A of the pilot system in July 2004 to facilitate the distribution of substrate, reduce injection well fouling (mineral and biological) and interlock the treatment injection system with the extraction pump.

A review of hydrographs for the pilot test area monitoring wells indicates that hydraulic heads are clearly influenced by system operation, with small but noticeable drawdowns in the wells closest to the extraction well. A review of mean hydraulic head among injection and extraction area wells and precipitation data suggests that the wells are subject to significant head fluctuations as a result of precipitation events, with hydraulic heads being subject to short-term fluctuations over periods of less than one day. Well hydrographs also indicate that the deep groundwater treatment system is competing with daily fluctuations due to barometric pressure changes and significant recharge events. Such fluctuations are to be expected in a semi-confined fractured bedrock system where very minor changes in storage can produce significant head fluctuations. However, the noted drawdown effects are a positive indication of the hydraulic connection in the groundwater treatment zone and the effectiveness of the treatment system at a relatively low extraction rate (i.e., 20 to 30 gpm) (75.7-113.6 L) despite recharge effects.

Figure 2 illustrates the potentiometric surface at the facility prior to pilot system startup during October 2002. The natural gradient is relatively shallow and the contours are parabolic in shape, indicating convergent flow to the south. Figure 3 illustrates the potentiometric surface after approximately 10 months of Phase 1A of the pilot system operation during May 2005. As is evident from this figure, the recirculation system significantly altered the potentiometric surface, creating an extensive cone of depression surrounding the extraction well and a cone of recharge surrounding the injection well. During the pilot test, the capture zone for the extraction well was sufficient to hydraulically control the VOC and perchlorate plumes. Additionally, the system is capturing the majority of the reinjected groundwater.

Groundwater samples were analyzed for perchlorate via EPA Method 314.0 and total VOCs via EPA method 8260 at the extraction well on a monthly basis and other wells in the pilot test area on a quarterly basis. The perchlorate concentration at the plume core extraction well was 3.56 mg/L in September 2001 and fluctuated considerably during Phase 1 of the pilot test. Since initiation of Phase 1A (July 2004) the perchlorate data at the extraction well has been decreasing from its highest perchlorate value of 10.7 mg/L (also collected July 2004). Data collected in February 2006 indicates a perchlorate concentration of 1.3 mg/L, indicating a reduction of 88%. Perchlorate concentrations in this well increase in apparent response to initiation of pumping, indicating that the extraction well is inducing perchlorate-impacted water from upgradient source areas into the treatment system, however the significant decreasing trend is a good indication that reduction of perchlorate is occurring.

Another indication of the reducing trend in the deep groundwater is the data from the monitoring well upgradient of the extraction well and downgradient of the injection well, that is the most influenced by the pilot test system. Again, perchlorate concentrations fluctuated during Phase 1, but have decreased during Phase 1A. Perchlorate at this location was 1.42 mg/L in August 2004, while the February 2006 data indicates 0.034 mg/L, showing a reduction of 98%. This monitoring well has also typically indicated the lowest dissolved oxygen levels in the pilot test area with 0.81 mg/L observed during the February 2006 sampling event.

The primary VOCs of concern for the deep groundwater at the Facility have historically been Tetrachloroethene, 1, 1, 1-Trichlorethane and 1, 1-Dichloroethene. Total VOCs (primarily those 3 constituents) fluctuated in the pilot test area during Phase 1, but like perchlorate, have shown reductions since initiation of Phase 1A of the pilot test. Total VOCs at the extraction well were 1.02 mg/L in July 2004 during start-up of Phase 1A. Data collected in February 2006 indicates total VOCs of 0.391 mg/L a reduction of 62%. VOCs in the central monitoring well have also significantly reduced during operation of Phase 1A. VOC data at this location in August 2004 indicated total VOCs of 0.472 mg/L. Total VOC data for the February 2006 sampling event indicates 0.303 mg/L, a reduction of 36%. It should be noted that no increase in daughter products have been observed during these events.

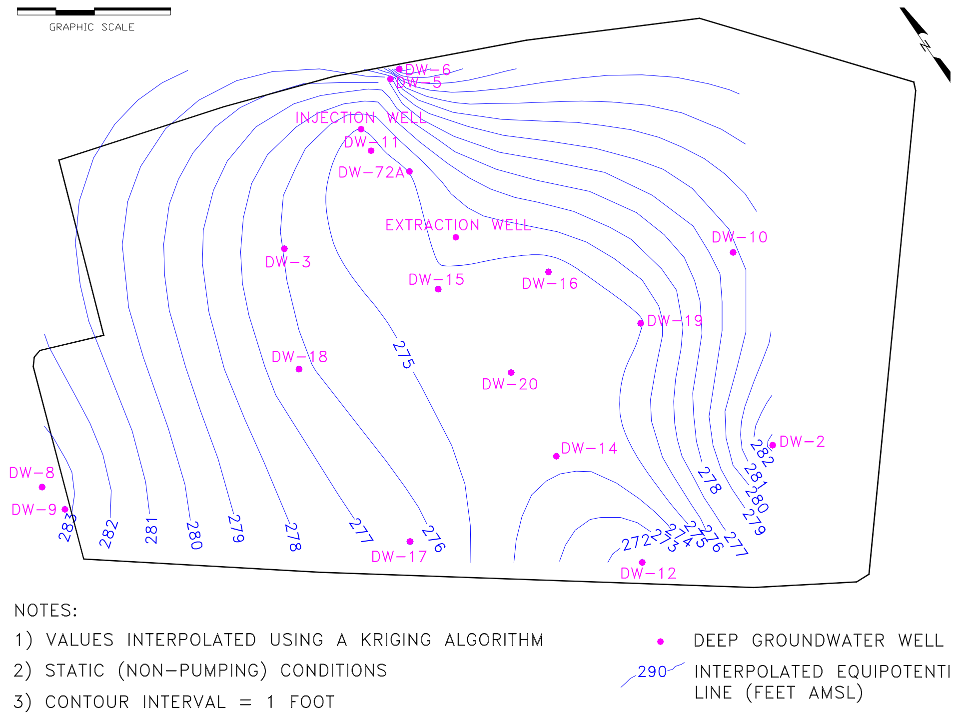

FIGURE 2. Potentiometric surface map prior to pilot system operation.

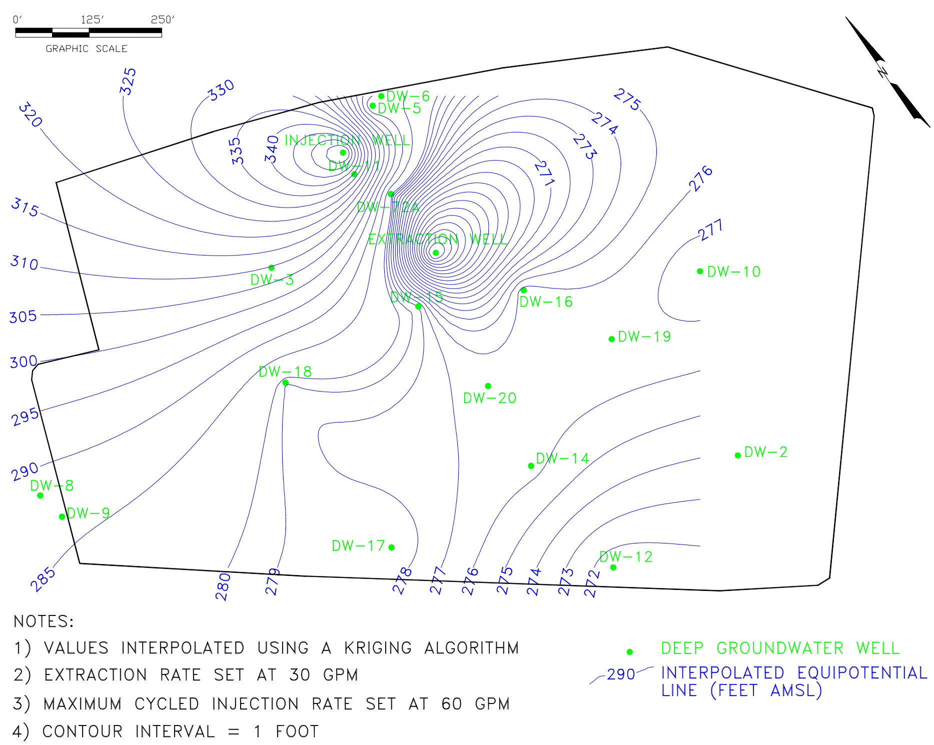

FIGURE 3. Potentiometric surface map during pilot system operation.

CONCLUSIONS

Although perchlorate concentrations in the deep groundwater samples collected at the extraction well fluctuated during Phase 1 of the pilot test, the most recent sampling event conducted during February 2006 indicated that after eighteen months of operation of Phase 1A, the perchlorate concentration at the extraction well was reduced by 88%. VOCs have also been reduced by 62% at the extraction well. Overall, the pilot testing conducted to date has shown the deep groundwater in situ bioremediation system is capable of initiating development of an anaerobic environment and is effective in reducing perchlorate and VOCS in the metasediment bedrock aquifer system for the extent the pilot study has been applied to the facility, particularly since initiation of Phase 1A in July 2004. At this stage of the pilot study the following observations can be made:

- Despite natural hydraulic head fluctuations, pumping of the extraction well at 25 to 35 gpm provided an adequate flow field to capture the entire area of the perchlorate and VOC plumes.
- Several deep groundwater wells showed an abrupt increase in perchlorate and VOCs concentrations immediately following system startup. These fluctuations, which were also observed during operation of the original P&T system, can be explained by the extraction well drawing higher concentrations via pumping through a continuing source area north and east of the pilot test area. Additionally, this effect may be attributed to desorption of contaminants from small pore spaces and small fractures above the pumping water level.
- Many deep wells continue to show significant decreases in perchlorate, particularly due east of the pilot test area a monitoring well has shown a significant reduction in total VOCs during the Phase 1A operation. In general, the pilot testing to date has seen significant reductions along the edges and moderate reductions in the downgradient interior and upgradient source areas of the perchlorate plume. This is a positive indication that the system is effective in addressing perchlorate and VOCs in deep groundwater at the facility.

In order to optimize the deep groundwater recirculation system and address additional source areas identified during the ongoing investigation, further development of the bioremediation technology is needed. This includes a shallow infiltration gallery treatment in a known perchlorate source area as well as identifying the VOC source area. Also, the introduction of a combination of soluble substrates that have been previously used (e.g., methanol, CMA, citric acid) will be evaluated in 2006. If successful, these enhancements to improve substrate distribution and reduce substrate travel times will reduce the overall cleanup time for the deep groundwater at the Facility.

Application. Overall, the results of this pilot test suggest that the retrofitting of existing remediation systems, including pump-and-treat, for use as bioremediation systems may be a cost-effective method to address newly discovered contaminants and/or accelerate the remediation of impacted sites. Phased technology approaches to site remediation have gained acceptance and can often lead to reduced projects costs and timelines to meet project goals.

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REFERENCES

McDonald, M.G., and A.W. Harbaugh. 1988, "A modular three-dimensional finite-difference groundwater flow model." In: *U.S. Geological Survey Techniques of Water Resources Investigations.* Chapter 6-A1.

Pollack, D.W. 1989. "Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference groundwater flow model." *U.S. Geological Survey Open File Report.* 89-391.

Environmental Alliance, Inc. 2003. *Deep Groundwater Interim Pilot Study Report and Work Plan.*

Environmental Alliance, Inc. 2005. *Deep Groundwater Pilot Study Update Report.*

Environmental Alliance, Inc. 2006. *Deep Groundwater Pilot Study Update Report.*

Kevin Morris et al. Environmental Alliance, Inc. "Fractured Bedrock Pump-and-Treat Conversion to In Situ Bioremediation." At: Battelle 4th International Conference on the Remediation of Chlorinated Solvents and other Recalcitrant Compounds. 2004.