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Optimization Strategies for In Situ Bioremediation of a TCE Plume at a Complex Site under a Regulatory Paradigm Shift

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Background/Objectives. An extensive trichloroethene (TCE) groundwater plume was identified at a former industrial facility in central New Jersey. The impacted unconfined aquifer consists of up to 60 feet of sand with silt and clay interbeds. Groundwater flow patterns at the site are complex due to diverging horizontal flows with both upward and downward flow potentials due to hydraulic and lithological divides. TCE concentrations vary from 5 to over 20 mg/L in groundwater and from 100 to 500 mg/kg in soil at former source areas. Little to no TCE degradation was evident due to the aerobic and strongly acidic environment, especially near clay interbeds and wetlands. Pursuant to a multi-phase pilot test, enhanced in situ bioremediation (EISB) was selected as the interim remedial measure (IRM). The objectives of the IRM were to reduce contaminant mass and flux across the large plume to stabilize the plume and to establish conditions amenable for monitored natural attenuation. Following IRM implementation and in response to changes in regulatory framework and requirements, a detailed characterization with high resolution profiling was conducted and a 3-D visual model was developed. These efforts helped identify preferential pathways and residual source areas, adjust remedial strategies and design parameters and techniques. This study critically evaluates successes and gaps of the historical conceptual site model (CSM) and IRM program and underscores the significance of iterative characterization and visualization tools in assessing preferential pathways and refining the remedial design.

Approach/Activities. An EISB IRM, which included injecting nearly 500,000 gallons of solution comprised of emulsified vegetable oil (EVO), pH buffer, and *Dehalococcoides* (DHC) culture at variable loadings into 326 temporary points, was implemented over a 15-month period. The IRM targeted multiple source areas across 2.3 acres and aquifer zones between 4 to 45 feet below ground surface (ft. bgs) with TCE concentrations above 500 µg/L. The IRM groundwater monitoring program included a suite of remediation analytes and qPCR targets. Source areas were reassessed post-IRM using Hydropunch™, membrane interface probes, and hydraulic profiling tool (HPT) in addition to borings and wells. A 3-D visualization model incorporated lithology from over 100 soil borings, analytical results from over 200 soil samples and over 150 temporary and permanent wells, groundwater elevations from over 70 wells, and injection loadings at 326 temporary injection points to update the CSM and support evolving remediation strategies.

Results/Lessons Learned. TCE degradation was significant across all treated areas though stalling at *cis*-1,2-dichloroethene was observed locally due to insufficient loading or pH buffering, limiting hydraulic conditions, and/or potential clogging due to biofouling or precipitation. EVO loading at 0.2%–0.5% of soil mass was effective. $NaHCO_3$ loading at approximately 2 lbs. per ton of soil showed significant impacts on the groundwater pH but was insufficient and short-lived for zones with unusually high buffer demands. Spatial evaluations and 3-D visual representations were used to evaluate the effectiveness of injection loadings in relation to contaminant degradation, lithology, and unique hydrogeological layers. Temporary injections proved more successful in shallow zones to depths of 15 to 20 ft. bgs than in deeper zones down to 45 ft. bgs. Multiple factors resulted in optimizing the implementation strategy from temporary to permanent injection wells including the need for iterative and seasonal injections of the EISB amendments, changes in the regulatory framework and requirements, and the discovery of significant preferential pathways. Characterizing subsurface conditions and delivery of amendment and design optimizations (buffering capacities, confirmatory hydraulic and tracer tests for recirculation evaluations, and source and preferential pathway definition) proved to be vital for IRM expansion, establishment of well-defined performance metrics, and design of monitoring strategies.