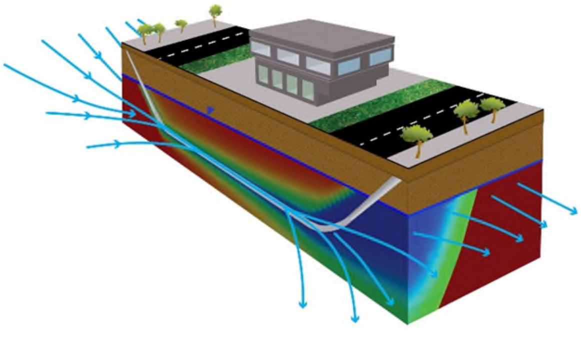
FINAL REPORT

DEMONSTRATION AND VALIDATION OF THE HORIZONTAL REACTIVE MEDIA TREATMENT WELL (HRX Well®) FOR MANAGING CONTAMINANT PLUMES IN COMPLEX GEOLOGIC ENVIRONMENTS



ESTCP Project ER-201631

Dr. Craig Divine, Arcadis
Dr. Michelle Crimi, Clarkson University
Dr. J.F. Devlin, University of Kansas

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Thank you for all your efforts and support!

ABSTRACT

Introduction and Objectives

The objective of this project is to field-validate the horizontal reactive media treatment well (HRX Well®), a new in situ remediation approach that uses directionally drilled horizontal wells filled with granular reactive treatment media. Groundwater is treated in situ as it flows through the HRX Well. The HRX Well concept is well-suited for sites where long-term mass discharge control is a primary performance objective and is particularly appropriate for recalcitrant and difficult-to-treat constituents, including chlorinated solvents, poly- and perfluoroalkyl substances (PFASs), 1,4-dioxane, and metals.

Technology Description

The HRX Well concept leverages natural "flow-focusing" behavior created by the well-to-aquifer permeability contrast to capture and passively treat proportionally large volumes of groundwater in situ. Treated groundwater exiting the HRX Well results in cleanup of the downgradient aquifer via elution. For this project, the HRX Well was operated in a fully passive configuration; however, for some higher-permeability aquifers, the HRX Well capture zone size and performance may be enhanced through pumping (i.e., active configuration).

Performance and Cost Assessment

The demonstration occurred at Site 003 at Vandenberg Air Force Base in Central California. The numerical model-predicted in-well flow and capture width of the HRX Well was consistent with estimates derived from Darcy's Law calculations, Point Velocity Probe (PVP) testing, and tracer testing. The actual average HRX Well capture zone width was likely between 45 and 69 feet. Trichloroethene (TCE) was treated in the HRX Well abiotically with zero valent iron (ZVI) and total TCE mass discharge reduction was >99.99 percent (%) relative to the upgradient well. Significant biologically mediated treatment also occurred, facilitated by the residual guar-based biopolymer drilling fluid. After 436 days, decreases from 50 to 74% in TCE were observed at four downgradient monitoring wells, and the timing of the first arrival of treated water was consistent with model predictions. The demonstration confirmed HRX Wells can be installed under active infrastructure, require limited ongoing operation and maintenance, and have low lifecycle energy and water requirements. For this site, estimated lifecycle HRX Well costs were lower than costs for permeable reactive barrier (PRB) and pump and treat alternatives.

Implementation Issues

The HRX Well uses a combination of standard commercial off the shelf materials and custom-built prototypes. The mud rotary directional drilling method used is applicable to both unconsolidated and bedrock aquifer settings. Site lithology and hydrogeology can pose performance risks for the HRX Well technology. In high hydraulic conductivity settings the HRX Well can be operated in a pumping "active configuration", however, high flow rates through the well and shorter residence times in the treatment media could become a limiting factor. The effects of incomplete recovery of the biopolymer drilling fluid should be considered in treatability testing.

Publications

Divine, C.E., Roth, T., Crimi, M., DiMarco, A.C., Spurlin, M., Gillow, J. and Leone, G. 2018. The Horizontal Reactive Media Treatment Well (HRX Well®) for Passive In-Situ Remediation. Groundwater Monitoring & Remediation, 38(1), 56-65. DOI: 10.1111/gwmr.12252

Divine, C.E., Wright, J., Wang, J., McDonough, J., Kladias, M., Crimi, M., Nzeribe, B.N., Devlin, J.F., Lubrecht, M., Ombalski, D., Hodge, W., Voscott, H., Gerber, K. 2018. The Horizontal Reactive Media Treatment Well (HRX Well®) for Passive In Situ Remediation: Design, Implementation, and Sustainability. Remediation J. 28 (4), 5-16.

EXECUTIVE SUMMARY

Introduction

This project was completed to field-validate the horizontal reactive media treatment well (HRX Well®), a new in situ remediation approach offering distinct advantages over traditional approaches for managing dissolved contaminants from source zones in complex geological settings. The approach uses directionally drilled horizontal wells filled with granular reactive media (such as zero valent iron ([ZVI]) installed in the direction of groundwater flow. Groundwater is treated in situ as it flows through the HRX Well, similar to a permeable reactive barrier (PRB). Contaminant mass discharge from source zones can be significantly reduced, which can be cost-effectively sustained over many years. By greatly reducing or eliminating source zone discharge, downgradient plumes can be effectively treated, possibly even achieving low water quality standards in a relatively short period of time. For many Department of Defense (DoD) sites, it is increasingly recognized that contaminant mass flux and discharge may represent the most appropriate measure of plume strength and potential migration risk; therefore, remedial objectives and technologies focusing primarily on long-term mass discharge reduction will be increasingly favored. The HRX Well concept is particularly well-suited for sites where long-term mass discharge control is a primary performance objective.

Objectives

The objective of this project is to field-validate the HRX Well, a new in situ remediation approach offering distinct advantages over traditional approaches for managing dissolved contaminants from source zones in complex geological settings. This demonstration project was completed to: (1) apply the HRX Well technology to control mass discharge at an appropriate DoD field site; (2) measure the actual hydraulic capture, treatment efficiency, and mass discharge reduction and compare to model-predicted performance; (3) assess overall technical and sustainability performance of the HRX Well; and (4) develop a user-friendly design tool and guidance regarding technology applicability and limitations, anticipated performance, design and installation considerations, and costing.

Technology Description

The HRX Well (**Figure ES-1**) is a large diameter horizontal well that functions as an in situ reactive barrier and is a novel approach to managing long-term mass discharge within a contaminant plume. Typically, the HRX Well is oriented in the general direction of groundwater flow and is filled with a granular (i.e., solid phase) reactive media such as ZVI, activated carbon, zeolites, ion exchange resins, slow-release oxidants, or other sparingly soluble material. Under passive operation, groundwater flow-focusing occurs, which is a result of the high in-well hydraulic conductivity of the engineered reactive media relative to the aquifer hydraulic conductivity. The HRX Well therefore captures a proportionally large zone of impacted groundwater into the well through the screen at the upgradient portion of the well. Because the well is filled with a treatment media, impacted groundwater is treated in situ as it flows through the HRX Well. The treated groundwater then exits the well through the screen along the downgradient section. This concept is illustrated in **Figure ES-1**: impacted groundwater (red shading) is drawn into the well due to flow-focusing, is treated in-well, and clean groundwater (blue shading) exits the well on the downgradient portion of the well. Therefore, the HRX Well controls contaminant mass discharge to downgradient aquifer zones, and these zones will clean up over time through flushing and contaminant elution. For some applications, the flow through the HRX Well and size of the capture zone can be increased through pumping, where the pump intake is placed in the upgradient screen and groundwater is pumped through a packer into the treatment media. In both the passive and active (pumping) configurations, no groundwater is brought to the surface for treatment.

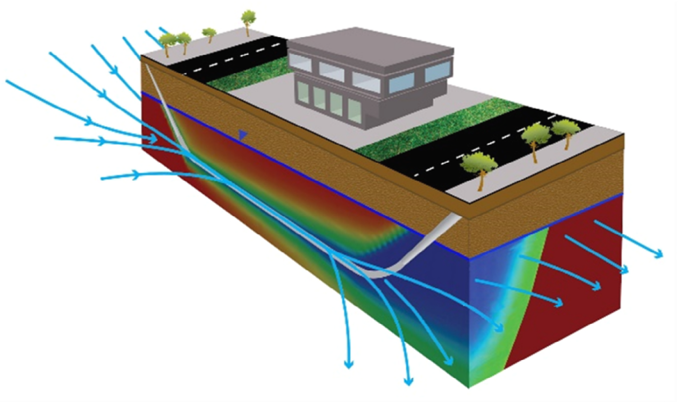


Figure ES-1. Illustration of the HRX Well Concept

Performance Assessment

The HRX Well field demonstration occurred at Installation Restoration Program Site 003 (SS003) at the Vandenberg Air Force Base (VAFB) in Central California (Site; see **Figure ES-2**). The key criteria for site selection included (1) a site where the objective is to significantly reduce mass discharge from a source or targeted plume zone to improve water quality in the downgradient plume, (2) a site where the geologic setting is appropriate and well understood, and (3) detailed lithologic, geochemical, and contaminant data are available. Some specific environmental and logistical conditions that made Site SS003 an ideal candidate include:

- The primary constituent of concern (trichloroethene [TCE]) can be treated with reactive media well-suited for an HRX Well (ZVI or other), is consistently present at high concentrations, generally ranging from 30,000 to 50,000 micrograms per liter (µg/L) at the upgradient location of the HRX Well.
- The target treatment zone (Principal Zone aquifer) is at a relatively shallow depth and thickness, allowing for ease in HRX Well installation and easy identification of and performance monitoring for the treatment target zone.

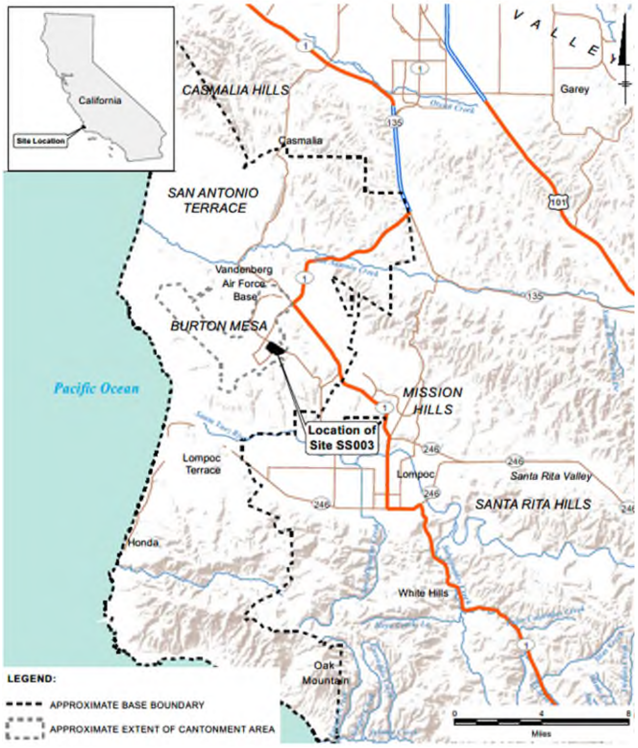


Figure ES-2. HRX Well Field Testing Site

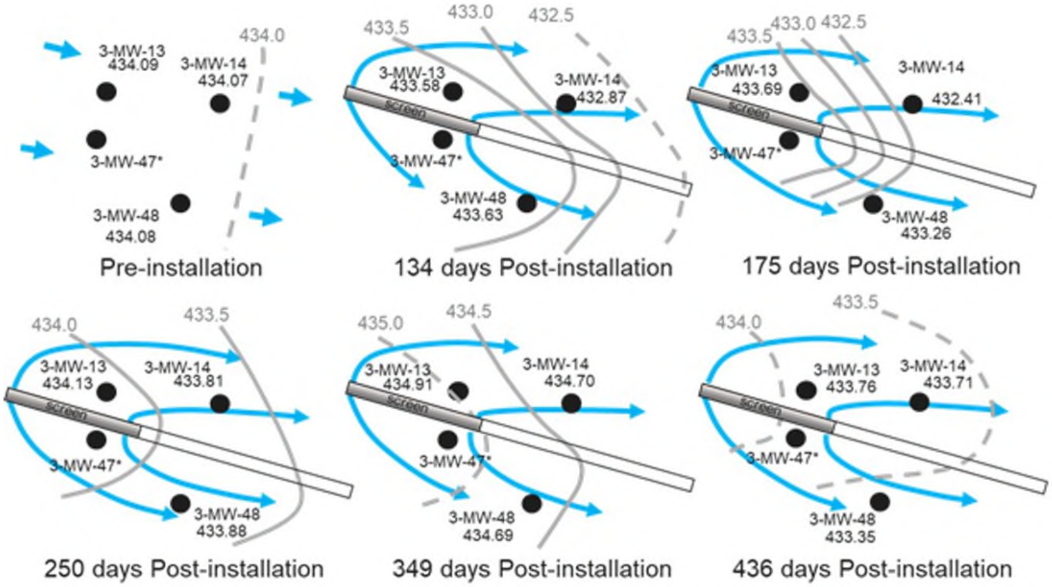
- The lithologic materials observed within the Principal Zone consist of silts and silty sands, with moderate to low hydraulic conductivity values, maximizing the hydraulic conductivity contrast (and therefore HRX Well hydraulic performance under a passive configuration) relative to the hydraulic conductivity of the in-well reactive media (ZVI).
- Potential logistical issues associated with drilling, installation, and performance evaluation are minimal.
- Site remedial objectives are consistent with use of this technology (i.e., targeted long-term reduction of mass discharge from the source area).

Based on the additional site characterization, treatability testing, and design modeling completed in 2016 to 2018, the project team proceeded with the field demonstration. The HRX Well installation was completed on August 1, 2018 and subsequent performance monitoring and analyses were used to evaluate key performance objectives summarized below.

Quantify HRX Well Capture Width and Hydraulic Performance

As shown in **Figure ES-3**, groundwater levels near the HRX Well clearly show mounding and the effects of treated water discharge, and interpreted flowlines were qualitatively similar to model predictions. The average flow through the HRX Well predicted by the calibrated steady state-model was compared to estimates derived from the average hydraulic gradient and Darcy's Law calculations, Point Velocity Probe (PVP) tests using the measured velocity, and the results of the HRX Well tracer test. Based on these analyses, there is high confidence that the actual average HRX Well flow during the performance period was likely between 1.5 and 2 cubic feet per day (ft^3/day), which is consistent with the success criteria of this performance objective.

The capture zone width of the HRX Well predicted by the calibrated steady-state numerical flow model (**Figure ES-4**) was compared to estimates derived from the average hydraulic gradient and Darcy's law calculations, PVP tests using the measured velocity, and the results of the HRX Well tracer test. There is high confidence that the actual average HRX Well capture zone width during the performance period was between 45 and 67 feet (ft), which is consistent with the success criteria for this performance objective.



Pre-installation

134 days Post-installation

175 days Post-installation

250 days Post-installation

349 days Post-installation

436 days Post-installation

Figure ES-3. Interpreted Groundwater Flow Field Depiction before and after HRX Well installation, showing hydraulic gradient and flushing zone consistent with model predictions

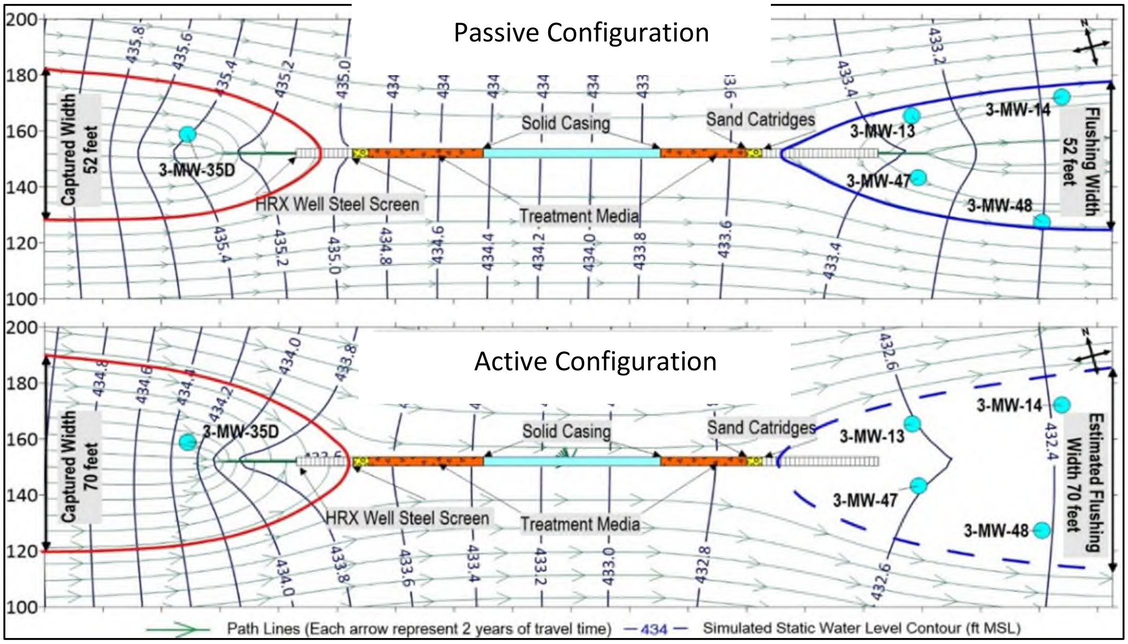


Figure ES-4. Updated Model Results Showing Predicted HRX Well Capture and Treatment Zones *Passive (top) and active (bottom) configurations*

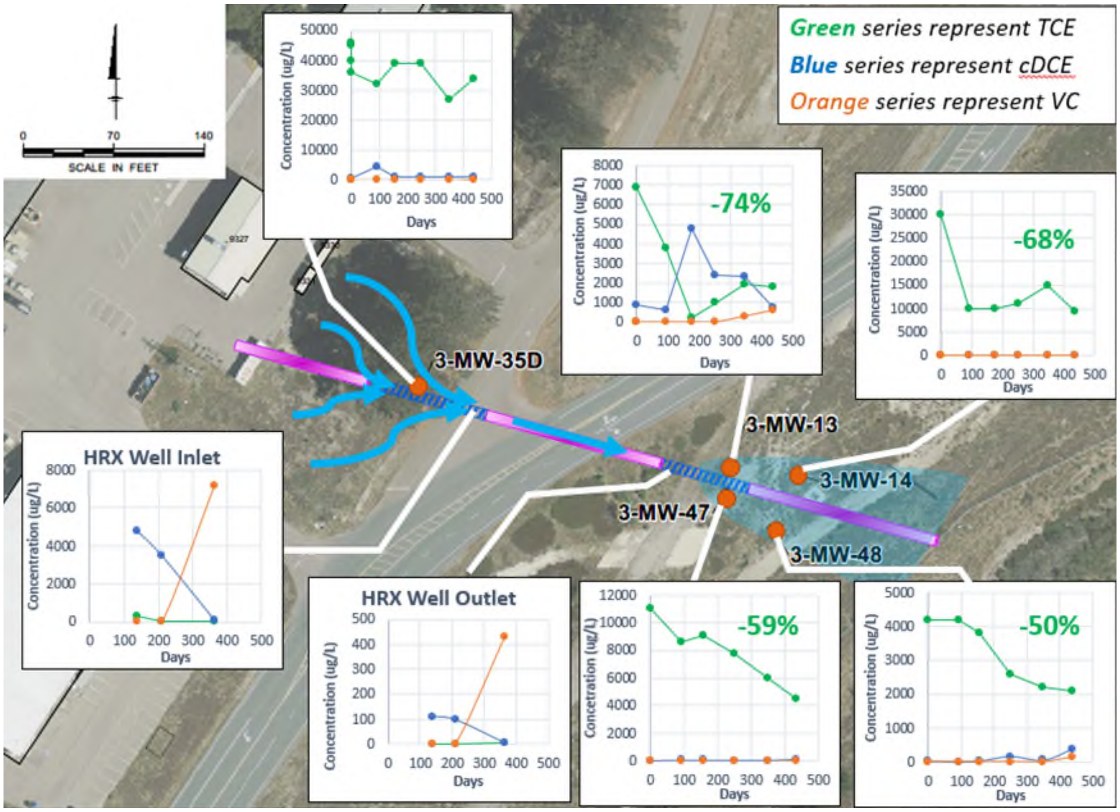


Figure ES-5. TCE and cis-1,2-DCE Concentration Trends at HRX Well Performance Monitoring Wells *Data are plotted as elapsed time since HRX Well installation (the most recent data prior to installation was used for Day = 0). The distance between 3-MW-14 and 3-MW48 is 45 ft.*

The HRX Well treatment zone that was achieved during the performance period was also assessed. **Figure ES-5** shows the TCE, cis-1,2-dichloroethene (cis-1,2-DCE), and vinyl chloride concentration trends at HRX Well performance monitoring wells (most other volatile organic compounds were detected only at low concentrations). TCE concentrations decreased at all four monitoring wells, from 50 to 74 percent (%). The Mann-Kendall and Sen's Slope trend tests were applied to evaluate performance monitoring data. Trend analysis results at downgradient monitoring wells 3-MW-13, 3-MW-47, and 3-MW-48 provide a strong line of evidence for HRX Well influence. The statistically significant increase in reductive dichlorination daughter products cis-1,2-DCE and vinyl chloride results suggest that there is some degree of biologically-mediated degradation in this area associated with the residual biopolymer drilling fluid, but that the overall effect of the drilling fluid induced degradation for downgradient wells was not significant over the HRX Well implementation period (treatment at these wells is primarily a result of clean water flushing). It is expected that drilling fluid will continue to be consumed over time and biologically-mediated reductive dichlorination rates will further decline. Multiple calculations supported by different data types and various tests and calculations confirm significant flow focusing and a resulting capture zone size that is generally consistent with model predictions and meets the success criteria of this performance objective.

Determine Reactive Media Treatment Efficiency

TCE concentrations at the HRX Well Outlet ranged from non-detect (<2 µg/L) to 7.6 µg/L, lower than the performance goal of 50 µg/L throughout the performance period. The average TCE concentration reduction between upgradient well 3-MW-35D and the HRX Well Outlet was about 32,700 µg/L (>99.99%) and the initial TCE concentration reduction compared to the HRX Well Inlet was 310 µg/L (99.9%). There was a significant decrease in TCE concentration between upgradient well 3-MW-35D and the HRX Well Inlet, as result of enhanced biotransformation promoted by unrecovered residual biopolymer drilling fluid. Therefore, HRX Well outlet concentrations are compared to both upgradient well 3-MW-35D and the HRX Well inlet, which allows for the relative contribution of biotic and abiotic processes to be estimated.

Assuming an average flow velocity in the treatment media of 7.2 ft per day, the calculated treatment media residence time is about 8 to 9 days, within the initial design goal of 6 to 20 days. The estimated TCE transformation rate (0.9 day^{-1}) is about 50% lower than the value assumed in the design based on previous treatability testing (1.8 day^{-1}), but greater than the estimated minimum rate (0.7 day^{-1}) needed to treat TCE from 35,000 µg/L to 50 µg/L. There was no evidence of significant decrease in permeability due to media plugging or fouling during the performance period. Overall, performance data and analyses indicate the success criteria was met for reactive media treatment efficiency.

Quantify Contaminant Mass Discharge Reduction

The contaminant mass discharge reduction was estimated to be between 1.1 and 2.2 grams per day with a best estimate of 1.4 grams per day (g/day). This represents >99.99% reduction in contaminant mass discharge across a transect defined by the capture width, and meets the performance objective success metric of mass discharge reduction of more than 90%.

Determine PVP Performance

The PVPs successfully and reliably measured flow velocities within the HRX Well and the average standard deviation of PVP measurements was 16%, which met the performance objective of less than 25%.

Identify Challenges and Limitations of HRX Well Installation

There are potential implementation challenges associated with the directional drilling methods used to install HRX Wells. These potential issues are not specific to HRX Wells and would be the same for a given site if directional drilling were used to install other types of horizontal remediation wells (e.g., horizontal groundwater extraction wells). Examples include the potential for inadvertent drilling fluid returns to the ground surface along preferential pathways and electromagnetic interference with borehole navigation. The HRX Well technology uses a combination of standard commercial off the shelf materials and custom-built prototypes. Standard materials include biopolymer drilling fluid, horizontal well screen and casing, and cement-bentonite grout for the annular grout seals. Custom build prototypes for this demonstration included the media and monitoring cartridges (using standard high-density polyethylene [HDPE] pipe and fittings) and the PVPs suited for horizontal orientation. Based on this demonstration, challenges and limitations associated with HRX Well installation are well understood and can be readily mitigated or avoided with simple design changes; this understanding is considered sufficient to meet the success criteria for this performance objective.

Compare Sustainability of HRX Well Treatment Approach with Others

The sustainability impacts for three alternatives (HRX Well, groundwater extraction and treatment system [GETS], permeable reactive barrier [PRB]) were measured by estimating a system design to address the same contaminant plume. The impacts were compared across four lifecycle phases where Phase 1 was materials transport and travel, Phase 2 was materials manufacture, Phase 3 system installation, and Phase 4 operation and maintenance. In each phase, the estimated energy used, the resulting carbon dioxide emissions equivalents, nitrogen oxides, sulfur oxide, and particulate matter 10 micrometers or less in diameter emissions were all determined. The sustainability analysis results indicated that the HRX Well sustainability performance objectives were met including that HRX Well compares favorably with the alternatives. The overall sustainability impacts were reflective of the materials or equipment used, particularly during system operation. The transportation impacts were greatest for the PRB because of the total mass of ZVI to be transported. The results were similar for materials manufacture where both PRB media placements involved a greater mass of ZVI than the HRX Well. The installation impacts for all systems were small compared to the impacts from materials manufacture or system operation. Phase 3 impacts were greatest for the GETS system due to nearly continuous equipment operation and regular media replacements. The PRB alternative does not require equipment use during operation; however, the initial and year 15 media replacement had substantial impacts in terms of energy use and emissions. The HRX Well performed favorably in comparison to GETS and the PRB because the HRX Well would not require equipment operation and the mass of media used throughout the lifecycle is a fraction of that required for the other alternatives.

Characterize Life Cycle Costs

A feasibility evaluation was completed to compare the HRX Well technology to other appropriately scaled remedial technologies capable of achieving similar objectives. The HRX Well is a passive technology, appropriately suited for long-term plume treatment. Therefore, aggressive source removal/destruction technologies are not comparable, and the comparison focused on a

GETS and a funnel and gate PRB. The remedial alternatives were evaluated by comparing six criteria, including life cycle cost. Lifecycle cost estimates included capital and operations costs. The results of this cost analysis confirm the HRX Well costs compare favorably to appropriate comparable technologies and are considered sufficient to meet the success criteria for this performance objective.

Finalize and Validate the HRX Well Design Tool

In order to facilitate future efficient HRX Well designs, capture lessons learned, and promote technology transfer, an Excel-based HRX Well design, cost, and sustainability tool was developed. Many HRX Well configurations are possible, but the applicability of any design is subject to site-specific factors. The tool allows the user to optimize the design based on user-provided values. Supplemental literature values can also be used as inputs to support high-level estimations. To validate the reliability and usefulness of this tool, HRX Well designs were successfully evaluated for the VAFB site as well as two additional DoD sites.

Cost Assessment

A feasibility evaluation was completed to compare the HRX Well technology to other appropriately scaled remedial technologies capable of achieving similar objectives. This feasibility cost evaluation is based on addressing the TCE groundwater plume (target plume width of 150 ft and depth of 25 ft) extending downgradient from the “hot spot”, where the HRX Well was installed. The existing HRX Well has a capture width of 50 ft; therefore, two additional HRX Wells would be required to treat the full width of 150 ft. A typical remediation timeframe of 30 years was used for this cost comparison.

Therefore, the evaluated remedial technologies are:

Alternative 1 –HRX Wells (Assumes 3 HRX Wells, each with 50-ft capture width).

Alternative 2 – GETS (Assumes 10 vertical extraction wells).

Alternative 3 –Funnel and Gate PRB (Assumes PRB 150 ft long and 3 ft wide).

Overall, this analysis found the costs of the HRX Well technology compare favorably to other applicable technologies, as shown in the summary table below (**Table ES-1**). The HRX Well was a more cost effective option than either GETS or PRB. The efficient use of media in the HRX Well combined with passive operation resulted in lower lifecycle costs compared to the other alternatives. The cost estimates include capital costs (costs associated with installation), operation, monitoring and maintenance costs (costs associated with ongoing operations necessary to operate the remedial alternative), and present worth cost (forecasted life-cycle costs accounting for both inflation and interest).

Table ES-1. Summary of Costs for Each Remedial Alternative

Cost Element	HRX Well (3 HRX Wells)	GETS (10 vertical extraction wells)	PRB (150 foot long PRB)
Capital Costs			
Engineering & Design	$250,000	$200,000	$250,000
Treatability Study	$15,000	$0	$15,000
Baseline Characterization	$50,000	$50,000	$50,000
Installation & materials	$1,175,000	$485,000	$1,050,000
Waste Disposal	$150,000	$30,000	$115,000
Total Capital Costs	$1.6 M	$0.8 M	$1.5 M
Operation, Maintenance, & Monitoring Costs			
Operation and Maintenance (30 years)	$82,500	$3,000,000	$1,050,000
Long-term Monitoring (30 years)	$900,000	$900,000	$900,000
30-year Lifecycle Total	**$2.6 M**	**$4.7 M**	**$3.4 M**

Notes: Forecasted lifecycle costs account assume 4% interest and 3% inflation. Capital expenses were not depreciated, either at the onset or when incurred over the lifecycle.

Implementation Issues

There are potential generic implementation challenges associated with the directional drilling methods used to install HRX Wells. Examples include the potential for inadvertent drilling fluid returns to the ground surface along preferential pathways and electromagnetic interference with borehole navigation. Environmental regulations and necessary permits required for a HRX Well are expected to be consistent with those required for vertical well remediation projects, and will vary by jurisdiction. Utility clearance will be required prior to drilling and many states require a licensed well driller for installation of remediation wells. Drilling waste will require characterization and disposal in accordance with local rules and regulations.

The HRX Well technology uses a combination of standard commercial off the shelf materials and custom-built prototypes. Standard materials include biopolymer drilling fluid, horizontal well screen and casing, and cement-bentonite grout for the annular grout seals. As noted in this demonstration, recovery of the biopolymer drilling fluid may be incomplete, and subsequent fermentation of this carbon source will affect local redox conditions and electron acceptor concentrations. For this demonstration, this effect resulted in a beneficial complimentary biotic treatment processes; however, these geochemical conditions might not be desirable for some treatment strategies (e.g., slow-release chemical oxidation treatment media). The potential effects of residual drilling fluid should be considered in treatability studies and designs for future installations. Custom build prototypes for this project included the media and monitoring cartridges (using standard HDPE pipe and fittings) and the PVPs suited for horizontal orientation.

1 INTRODUCTION

This Final Report (report) describes the field installation and performance monitoring associated with Environmental Security Technology Certification Program (ESTCP) Project ER-201631, which field-tested the Horizontal Reactive Media Treatment Well (HRX Well®) concept at a Department of Defense (DoD) site. This report documents the data, cost comparison, key implementation factors necessary for successful deployment of this technology, key lessons learned from the demonstration, a design tool and guidance, and future research or recommended design changes.

1.1 Background

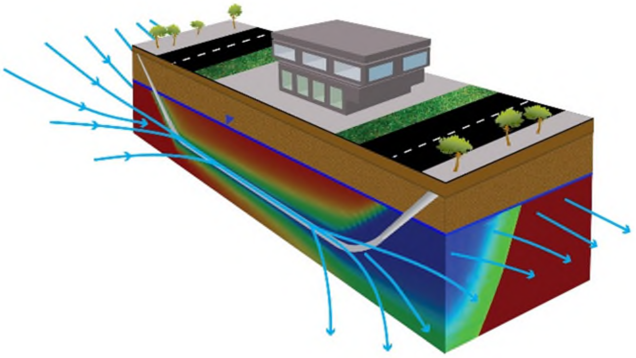


Figure 1. Illustration of the HRX Well Concept

The patented HRX Well concept (**Figure 1**; Divine et al. 2013) addresses many of the challenges inherent to remediation, including: (1) costs and time requirements associated with hydraulic containment (e.g., conventional pump and treat); (2) effective delivery of injected reagent-based strategies; and (3) limitations associated with up-front costs and long-term hydraulics in flow-through permeable reactive barrier (PRB) treatment schemes. The approach uses directionally drilled horizontal wells filled with granular reactive media, such as zero valent iron (ZVI), installed in the approximate direction of groundwater flow. Contaminant mass discharge can be significantly reduced, which can be cost-effectively sustained over many years. By greatly reducing/eliminating source zone discharge via implementation of the HRX Well, downgradient plumes can be more effectively treated, possibly even achieving low water quality standards in a relatively short period of time. Site selection, treatability testing, and other project activities were initiated in 2017 and the results of this work support the final design and field installation of the HRX Well, which was completed in August 2018. Performance monitoring and assessment was conducted for one year following installation.

1.2 Objective of the Demonstration

The purpose and scope of ER-201631 was to field-validate the HRX Well, a new in situ remediation approach offering distinct advantages over traditional approaches for managing long-term dissolved phase contaminants downgradient of source zones in complex geological settings. The overall goal of this effort was to complete a field demonstration of this promising technology to validate the technology concept, quantify technical performance and limitations, develop a practitioner-oriented design tool, and provide a basis for wider application at DoD and other sites. Specifically, this demonstration was designed to measure the HRX Well hydraulic capture and treatment width, residence times within the HRX Well, reactive media treatment effectiveness and longevity, and contaminant mass discharge reduction at a representative DoD contaminated field site.

1.3 Regulatory Drivers

It is increasingly recognized that contaminant mass discharge represents the most appropriate measure of plume strength and potential migration risk, and therefore regulatory support for remedial objectives and technologies focusing primarily on long-term mass discharge reduction will be increasingly favored, especially for recalcitrant contaminants. This is particularly true for sites characterized by low permeability and/or and complex hydrogeologic conditions, where complete aquifer restoration may not be cost-effective or possible. The HRX Well concept is ideally suited for applications where long-term mass discharge control to protect potential receptors is the primary regulatory concern and therefore a critical performance objective. Additionally, because the HRX Well is an in situ technology that can be installed beneath surface infrastructure and requires minimal aboveground footprint, it can be implemented in active areas and creates minimal impact to site operations. Because there are different granular media types already available, the HRX Well can potentially be applicable for many different contaminant classes, including chlorinated solvents, 1,4-dioxane, poly- and perfluoroalkyl substances (PFASs), perchlorate, and metals. Some contaminant mixtures could be treated using multiple media types within the HRX Well in a treatment train approach.

2 TECHNOLOGY

This section provides an overview of the HRX Well concept, which uses directionally drilled horizontal wells filled with granular reactive media, installed in the direction of groundwater flow. The concept leverages natural “flow-focusing” behavior created by the strong well-to-aquifer permeability contrast to capture and passively treat proportionally large volumes of groundwater in situ. Contaminant discharge from sources and high-concentration plume zones can be significantly reduced and cost-effectively sustained over many years. By greatly reducing or eliminating source zone contaminant discharge, downgradient zones can more be effectively treated, possibly even achieving low water quality standards over time. More detailed technology descriptions were provided in previous ESTCP submittals (Divine et al. 2015, 2016, and 2017a) and in the literature (Divine et al. 2013; Divine 2018a, b, c; Horst et al. 2019).

2.1 Technology Description

The HRX Well (**Figure 1**) is a large diameter horizontal well that functions as an in situ reactive barrier and is a novel approach to managing long-term mass discharge within a contaminant plume. Typically, the HRX Well is oriented in the general direction of groundwater flow and is filled with a granular (i.e., solid phase) reactive media such as ZVI, activated carbon, zeolites, ion exchange resins, slow-release oxidants, or other sparingly soluble material. Under passive operation, groundwater flow-focusing occurs, which is a result of the high in-well hydraulic conductivity of the engineered reactive media relative to the aquifer hydraulic conductivity. The HRX Well therefore captures a proportionally large capture zone of impacted groundwater into the well through the screen at the upgradient portion of the well. Because the well is filled with a treatment media, impacted groundwater is treated in situ as it flows through the HRX Well. The treated groundwater then exits the well through the screen along the downgradient section. This concept is illustrated in **Figure 1**: impacted groundwater (red shading) is drawn into the well due to flow-focusing, is treated in-well, and clean groundwater (blue shading) exits the well on the downgradient portion of the well. Therefore, the HRX Well controls contaminant mass discharge to downgradient aquifer zones, and these zones will clean up over time through flushing and contaminant elution. As indicated in **Figure 2**, water exiting the HRX Well screen is clean nearly immediately, while locations further downgradient in the aquifer (i.e., downgradient monitoring wells) begin to clean up (through elution) after a period of time when the 'news of cleanup' arrives. For some applications, the flow through the HRX Well and size of the capture zone can be increased through pumping, where the pump intake is placed in the upgradient screen and groundwater is pumped through a packer into the treatment media. In this configuration, no groundwater is brought to the surface for treatment.

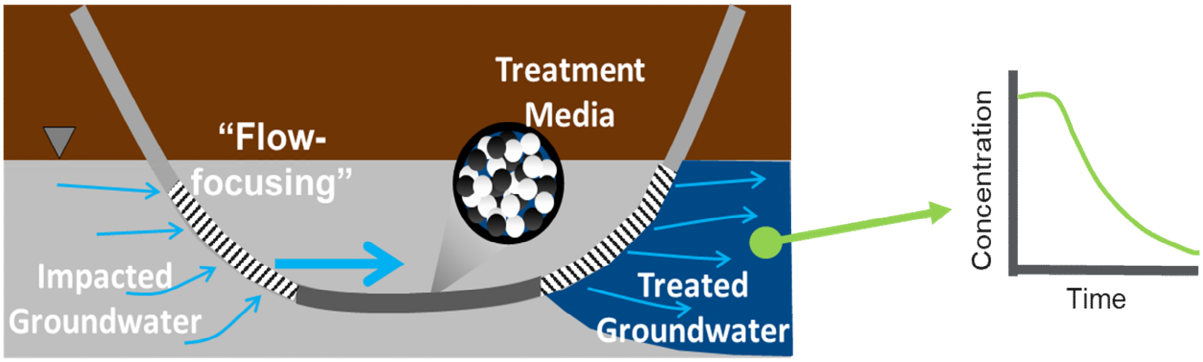


Figure 2. Conceptual Depiction of the HRX Well Treatment Process

A distinct element to the concept is that the remedial agent is not liquid that must be injected, but is rather granular material that is emplaced within the well. This eliminates injection-related challenges, allowing many new types of treatment media to be considered, which potentially increases the list of contaminants that can be successfully treated. **Table 1** summarizes reactive media currently available and associated target contaminants that could potentially be used in an HRX Well system. Furthermore, because solids promote reactions at the reactive media surface-water interface, they can be attractive as reactive substrates due to their compatibility with a wide range of groundwater chemistry conditions, their relative rapid reactivity, and because they generally do not rely on microbial processes to be effective (e.g., Hey et al. 2015). Solids, emplaced to promote groundwater contact are isolated from the aquifer and generally do not undergo competing interactions with soil matrix. Because of its demonstrated ability to treat a broad range of contaminants, iron is one of the most promising reactive media types for this application. Other potential reactive media include granular activated carbon, magnetite, zeolite, biodegradable particulate organic matter (e.g., mulch), apatite, limestone, magnesium, and iron sulfide. Magnesium hydroxide may be used to generate alkalinity to treat acidic groundwater; conversely, reactive sulfide minerals (such as iron sulfide) may be used to generate acidity to treat alkaline groundwater. As noted previously, multiple media types could be used in a single HRX Well in a treatment train approach. When necessary, exhausted reactive media can be subsequently removed and replaced or regenerated *in situ*.

Table 1. Potential Reactive Treatment Media Types and Target Groundwater Contaminants for an HRX Well

Treatment Media	Target Groundwater Contaminant
Zero valent iron (ZVI), sulfidated ZVI, Bimetallics (ZVI + palladium (Pd), platinum (Pt), or nickel (Ni))	Chlorinated solvents (CVOCs), nitrate, perchlorate, energetics (e.g., trinitrotoluene; TNT), chromium, arsenic, other metals
Granulated Activated Carbon, Organosilicates (e.g., Osorb®)	CVOCs, PFASs, Hydrocarbons, Halomethanes
Biodegradable particulate organic carbon (e.g., mulch)	CVOCs, nitrate, perchlorate
Phosphates (e.g., apatite)	Lead, uranium, other metals and radionuclides
Sustained Release Oxidants (e.g., RemOxSR+ ISCO)	CVOCs, 1,4-dioxane, polyaromatic hydrocarbons (PAHs), phenolic compounds, and energetics
Limestone, lime, magnesium oxide	Low pH, Acid Rock Drainage
Barium sulfate (barite)	Radium
Ion exchange resins	PFASs, Brines
Iron sulfide	High pH
Zeolites	Ammonium, radionuclides (including cesium and strontium)

As presented in Divine et al. (2018a), passive flow rate through an HRX Well (Q_{HRX}) can be described by Darcy's Law:

$$Q_{HRX} = K_{HRX} \cdot \pi r_{HRX}{}^2 \cdot i_{HRX} \tag{1}$$

where K_{HRX} is the hydraulic conductivity of the well, r_{HRX} is the radius of the well, and i_{HRX} is the hydraulic gradient along the well. Therefore, the vertically averaged capture and treatment zone width ($\overline{w}$) for an individual well can then be simplistically approximated by:

$$\overline{w} = \frac{K_{HRX} \cdot \pi r_{HRX}{}^2 \cdot i_{HRX}}{K_A \cdot b_A \cdot i_A} \quad \text{or equivalently,} \quad \overline{w} = \frac{Q_{HRX}}{K_A \cdot b_A \cdot i_A} \tag{2}$$

Where K_A is the average hydraulic conductivity of the aquifer and b_A is the targeted aquifer zone thickness. For long wells with long well screens, i_{HRX} can be assumed to be approximately equal to the ambient aquifer hydraulic gradient, i_A. The approximate average flow velocity $\overline{v_{HRX}}$ and minimum average residence time $\overline{t_R}$ of groundwater within the treatment media can be estimated by:

$$\overline{v_{HRX}} = \frac{Q_{HRX}}{\emptyset_{HRX} \cdot \pi \cdot r_{HRX}^2} \tag{3}$$

$$\bar{t}_R = {}^{L_{HRX}}\!\Big/\!_{\overline{v_{HRX}}} \tag{4}$$

where $\emptyset_{HRX}$ is the flowing porosity of the reactive media within the horizontal well and L_{HRX} is the length of the treatment media segment within the well. Note that these equations assume homogenous and isotropic conditions and that the well is long and oriented in the direction of groundwater flow. As such, they provide only approximate estimates; actual treatment widths, treatment zone geometry, velocity, and particle travel distances profiles vary with depth and are influenced by the specific well design and aquifer conditions. More detailed site-specific numerical modeling is necessary to more accurately understand the effects of complex aquifer geometry, anisotropy, and permeability distribution on treatment zone geometry. Further, the equations presented above describe an HRX Well system that is fully passive; however, Divine et al. (2013) propose an alternative configuration where a pump installed in the upgradient screen zone that pushes water through reactive media on the other side of a packer within the HRX Well. This will greatly enhance hydraulic capture and treatment width without bringing any groundwater to the surface, and may be particularly appropriate for higher-permeability sites. For this demonstration, the installed HRX Well was operated under a passive configuration; however, as described in subsequent sections, the active pumping configuration was briefly tested and validated.

The HRX Well approach requires no above-ground treatment or footprint and limited ongoing maintenance. Additionally, it should be noted that there is already a wide range of demonstrated solid phase reactive materials that could be potentially deployed within an HRX Well, and therefore a broad potential to address other challenging contaminants (in addition to chlorinated solvents) often encountered at DoD facilities (e.g., 1,4-dioxane, select metals, polycyclic aromatic hydrocarbons, explosives and energetics, and PFASs). Furthermore, some media types may be amenable to relatively easy removal and regeneration or replacement when exhausted.

For this field demonstration, chlorinated solvents (primarily trichloroethene [TCE]) were destructively treated using in situ chemical reduction via a ZVI/sand mixture packed into the HRX Well. The application of ZVI to mediate the abiotic reductive dechlorination of chlorinated solvents is well-established (e.g., Arnold and Roberts 2000; Scherer et al. 2007; Henderson and Desmond 2007; Fu, et al. 2014). Various ZVI deployment methods that have been investigated include PRBs (Johnson et al. 2008), in situ treatment wells (e.g., Johnson et al. 2008), and injection schemes for delivering nano-iron particles to aquifers (e.g., Keane 2009; Crane and Scott 2012; and Liu et al. 2015). These studies generally conclude that ZVI technologies are effective at facilitating abiotic reductive dechlorination in groundwater; however, challenges associated with in situ delivery of ZVI adversely influence treatment kinetic rates and efficiencies. Deployment of ZVI within an HRX Well offers the potential to overcome distribution limitations as impacted groundwater is passively directed through staged ZVI media. This approach may also improve the efficiency of the ZVI mediated treatment because exposure of the ZVI media to oxygenated groundwater near the capillary fringe can be minimized or eliminated. Further, the HRX Well provides advantages over conventional PRBs due to more efficient use of the treatment media, installation methods that are less constrained by surface access and target zone depth (drilling versus trenching), and because groundwater flow is focused parallel to the ambient groundwater flow direction. Although not anticipated at the demonstration site based on treatability testing, any reduction in hydraulic permeability of the ZVI media over the long-term will gradually reduce the focusing efficiency of the HRX Well. However, because of the very small cross-sectional area of the HRX Well relative to the cross-sectional area of the aquifer, potential "plugging" of the HRX Well will not result in detrimental hydraulics (e.g., mounding or damming) or contaminant plume spreading.

2.2 Technology Development

The HRX Well technology is patented (Divine et al. 2013) and was developed and tested through numerical modeling (e.g., Divine et al. 2011; DiMarco 2016) and physical modeling (i.e., laboratory tank testing) completed as part of Strategic Environmental Research and Development Program (SERDP) project SERDP ER-2423 In Situ Treatment Train for Remediation of Perfluoroalkyl Contaminated Groundwater: In Situ Chemical Oxidation of Sorbed Contaminants (ISCO-SC).[1]

The ESTCP project work that is the focus of this report demonstrated the feasibility of horizontal well capture (Divine et al. 2018a, b), treatability testing, and field pilot scale tests that are described in detail in the Treatability Testing Report (Divine et al. 2017a) and the Go/No-Go Decision Recommendation, and the field Demonstration Plan (Divine et al. 2017b), and provided data and tools to upscale design and predict field-scale performance, with details provided in the project's final report (this document).

2.3 Advantages and Limitations of the Technology

It is now widely understood that groundwater in many source and high concentration areas cannot economically be restored to drinking water quality standards or risk-based limits in short time frames. This is particularly true of source zones and settings with complex geologic conditions. For many DoD sites, it is increasingly recognized that contaminant mass flux and discharge may represent the most appropriate measure of plume strength and potential migration risk. Therefore, remedial objectives and technologies focusing primarily on long-term mass discharge reduction will be increasingly favored and practical. Groundwater extraction with ex situ treatment processes (i.e., "pump and treat") remains one of the most commonly employed approaches for controlling contaminant flux and mass discharge. However, it often requires significant initial capital and recurring costs, and commonly cannot achieve cleanup to desired levels for many decades.

Injected reagent-based strategies (such as enhanced reductive dechlorination or in situ chemical oxidation [ISCO]) provide some advantages over conventional pump and treat, but there are also specific limitations and risks associated with these technologies. Although several important factors influence the implementability and success of an injected reagent-based approach, one of the most important and desired site features is a relatively high hydraulic conductivity to support as close to homogenous and uniform distribution as possible. In most cases, sites with moderate or low natural average hydraulic conductivity values (typically less than approximately 5 feet per day [ft/day]) are not considered ideal candidate sites for injected reagent-based in situ remedial strategies. This is primarily because at these sites, injection times necessary to deliver adequate reagent volume under non-fracturing pressures are prohibitively long. Furthermore, even for sites compatible with injected reagent-based remedies, there can still be notable long-term operation

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[1] Accessible at https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-2423/ER-2423.

maintenance and monitoring and remediation costs associated with managing slow advection from inaccessible storage zones within the aquifer. It is important to note that in contrast to injected reagent-based in situ strategies, the treatment performance of the HRX Well approach potentially increases with decreasing aquifer hydraulic conductivity (due to the increased permeability contrast and flow-focusing).

The HRX Well concept addresses many of the challenges inherent to remediation, including: (1) costs and time requirements associated with hydraulic containment (e.g., conventional pump and treat); (2) effective delivery of injected reagent-based strategies; and (3) limitations associated with up-front costs and long-term hydraulics of the similar flow-through PRB treatment scheme. The HRX Well concept is best applied at sites where long-term mass discharge control is a primary performance objective, site access is restricted, and in situ treatment is preferred over above ground management and ex situ treatment of impacted groundwater (**Figure 3**).

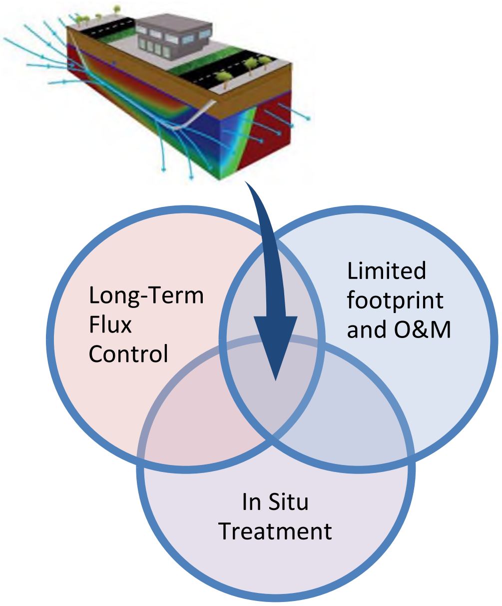

Figure 3. HRX Well Applicability
The HRX Well is well-suited for sites where long-term mass discharge control is a primary performance objective, site access is restricted, and in situ treatment is preferred over above ground management and ex situ treatment of impacted groundwater.

In many regards, the HRX Well concept is similar to funnel and gate PRB applications. Both technologies can provide flow-focusing as well as long-term reductions in mass discharge that are often necessary to address slow advection from lower permeability zones. However, the HRX Well offers several advantages over PRBs. The HRX Well requires minimal above-ground space for installation, and the drilling location can be off-set from the target treatment zone. The HRX Well can be targeted at deeper source zones and zones not accessible from the surface (i.e., under buildings or within areas with active surface operations). In addition, the directional drilling technology used to install horizontal wells is not limited to unconsolidated settings and can be used to target some types of bedrock aquifers. Because groundwater is focused in the well, reactive media contact and consumption is more efficient than most PRB applications. A unique feature of the HRX Well concept is that the hydraulic residence time can be readily controlled to optimize contaminant treatment by modifying well length and reactive media permeability. Finally, as the reactive media ages, there is minimal risk that reductions in permeability could cause groundwater “damming” and subsequent plume spreading. In contrast to a PRB, if reactive media permeability decreases in an HRX Well, the HRX treatment width will decrease and the groundwater flow-field will gradually revert to original conditions.

As with any remedial technology, there are limitations that need to be considered when evaluating suitability of HRX Wells for a given site. A permeability contrast between the aquifer and the engineered treatment media must be maintained for flow focusing to occur. In higher hydraulic conductivity settings (e.g., greater than 5 ft/day), the achievable treatment media permeability contrast may limit the size of the capture and treatment zones, and therefore, the HRX Well may need to be operated in the active (pumping) configuration. However, in cases where the active pumping rates are high, the diameter and length of the treatment media could also become limiting factors, as these dimensions would need to increase to provide appropriate residence time. A potential consideration related to lithology would be thin, discontinuous water bearing zones that would require closely spaced vertical pilot borings for characterization prior to HRX Well installation, because lithologic information is not obtained during directional drilling. Another limitation is the magnitude of concentrations that can be targeted. As this is a passive technology that provides long-term reduction in mass discharge, HRX Wells are not intended for sites where complete near-term aquifer restoration is the primary objective. A final consideration could be the longevity of the treatment media, which will depend on several factors. Depending on contaminant loading and media characteristics, the treatment media replacement frequency may be an important life cycle cost consideration.

3 PERFORMANCE OBJECTIVES

The overall objectives of this HRX Well field demonstration were to field-validate the technology concept, quantify technical performance and limitations, and provide a basis for wider application at relevant DoD and other sites. Specific objectives of this demonstration project include:

1. Utilize a numerical modeling tool and insights from physical laboratory and pilot-scale field testing to design, demonstrate, and field-validate the HRX Well technology to control and reduce mass discharge from a contaminant source zone.
2. Apply the HRX Well technology to control mass discharge at an appropriate DoD field site.
3. Quantify the actual hydraulic capture, in-well media treatment efficiency, and mass discharge reduction and compare to model-predicted performance.
4. Assess overall sustainability performance of the HRX Well technology relative to other typical approaches.
5. Develop a user-friendly design tool and guidance regarding technology applicability and limitations, anticipated performance, design and installation considerations, and costing.

Overall, all quantitative and qualitative performance objectives were achieved. The specific performance objectives and criteria that were used to evaluate success were defined in the Demonstration Plan and are presented below in **Table 2.** Detailed evaluations of each performance objective are presented in Section 6.

Table 2. Performance Objectives

Performance Objective	Metric	Success Criteria	Success Criteria Achieved?
Quantitative Objectives			
Quantify HRX Well capture width and hydraulic performance	• Hydraulic capture at the upgradient section of the HRX Well • Focused groundwater flow within the HRX Well	• Observe changes in head levels within 25% of model-based design predictions and maintain this through project lifecycle • Observe focused flow and velocity within 25% of model-based design predictions and maintain this through project lifecycle	**Yes** Average flow and capture width within 25% of model
Determine reactive media treatment efficiency	• Observe treatment of contaminants from influent levels (approximately 10,000 micrograms per liter [µg/L]) to <50 µg/L at the end of the HRX Well. • Maintain high reactive media permeability relative to aquifer permeability over time	• Concentration and mass flux reduction within 25% of 14 milligrams per day over the 1-year monitoring period.	**Yes** Total average reduction >30 mg/L
Quantify contaminant mass discharge reduction	• Post-treatment contaminant concentrations and mass discharge reductions	• Measurements within design model prediction ranges and maintained through project lifecycle • The HRX Well is expected to achieve a contaminant mass flux reduction of more than 90%	**Yes** Mass discharge reduced by >99.99%
Determine PVP performance	• PVP velocity in HRX Well is consistent with treatability testing results	• Measurement precision is +/-25%	**Yes** Precision +/- 16%
Quantitative Objectives			
Identify challenges and limitations of HRX Well installation	• Feedback from drillers, installation and monitoring personnel, and project technical staff	• Challenges and limitations are understood and can be readily mitigated or avoided with design changes	**Yes** No critical issues identified
Compare sustainability of	• Materials, natural resource use, and overall	• The HRX Well approach compares favorably to	**Yes**

Performance Objective	Metric	Success Criteria	Success Criteria Achieved?
HRX Well treatment approach with others	carbon footprint for HRX Well approach is less than other approaches	other approaches including pump and treat (P&T) and Permeable Reactive Barriers (PRBs)	HRX Well sustainability metrics were favorable than alternative
Characterize life cycle costs	• Costs associated with HRX Well are comparable to other technically-feasible approaches	• The HRX Well approach compares favorably to technically viable approaches, including P&T and PRBs	**Yes** HRX Well Lifecycle costs were lower than alternatives
Finalize and validate the HRX Well design tool	• All metrics identified above will be used as metrics to evaluate this performance objective	• Evaluation of another DoD site for HRX Well application	**Yes** Developed designs and costs for two other DoD sites

4 SITE DESCRIPTION

Based on the evaluation presented in the Site Selection Memorandum (Divine et al. 2016), the HRX Well field testing occurred at Installation Restoration Program Site 003 (SS003) at the Vandenberg Air Force Base (VAFB) in Central California (Site; see **Figure 4**). The key criteria for site selection included a site where: (1) the objective is to significantly reduce mass discharge from a source or targeted plume zone to improve water quality in the downgradient plume, (2) the geologic setting is appropriate and well understood, and (3) where detailed lithologic geochemical and contaminant data are available. Specific environmental and logistical conditions at Site SS003 made this site an ideal candidate:

- Site lithology and contaminant distributions are well-understood and delineated.
- The primary constituent of concern (TCE) can be treated with reactive media well-suited for an HRX Well (ZVI or other), is consistently present at high concentrations, generally ranging from 30,000 to 50,000 micrograms per liter (µg/L) at the upgradient location of the HRX Well.
- The target treatment zone (Principal Zone aquifer) is at a relatively shallow depth and thickness, allowing for ease in HRX Well installation and easy identification of and performance monitoring for the treatment target zone.
- The lithologic materials observed within the Principal Zone consist of silts and silty sands, with low hydraulic conductivity values, maximizing the hydraulic conductivity contrast (and therefore HRX Well hydraulic performance under a passive configuration) relative to what can be achieved with the in-well reactive media (ZVI).
- Groundwater chemistry and redox conditions supportive of minimizing reactive media passivity (e.g., low/modest alkalinity, total dissolved solids).
- Potential logistical issues associated with drilling, installation, and performance evaluation were minimal at Site SS003.

- The nearby location of project field staff (San Luis Obispo, California) was convenient, and the VAFB Remediation Program Manager and California Regional Water Quality Control Board regulator were highly supportive of the demonstration.
- Site SS003 remedial objectives are consistent with use of this technology (i.e., targeted long-term reduction of mass discharge from the source area).

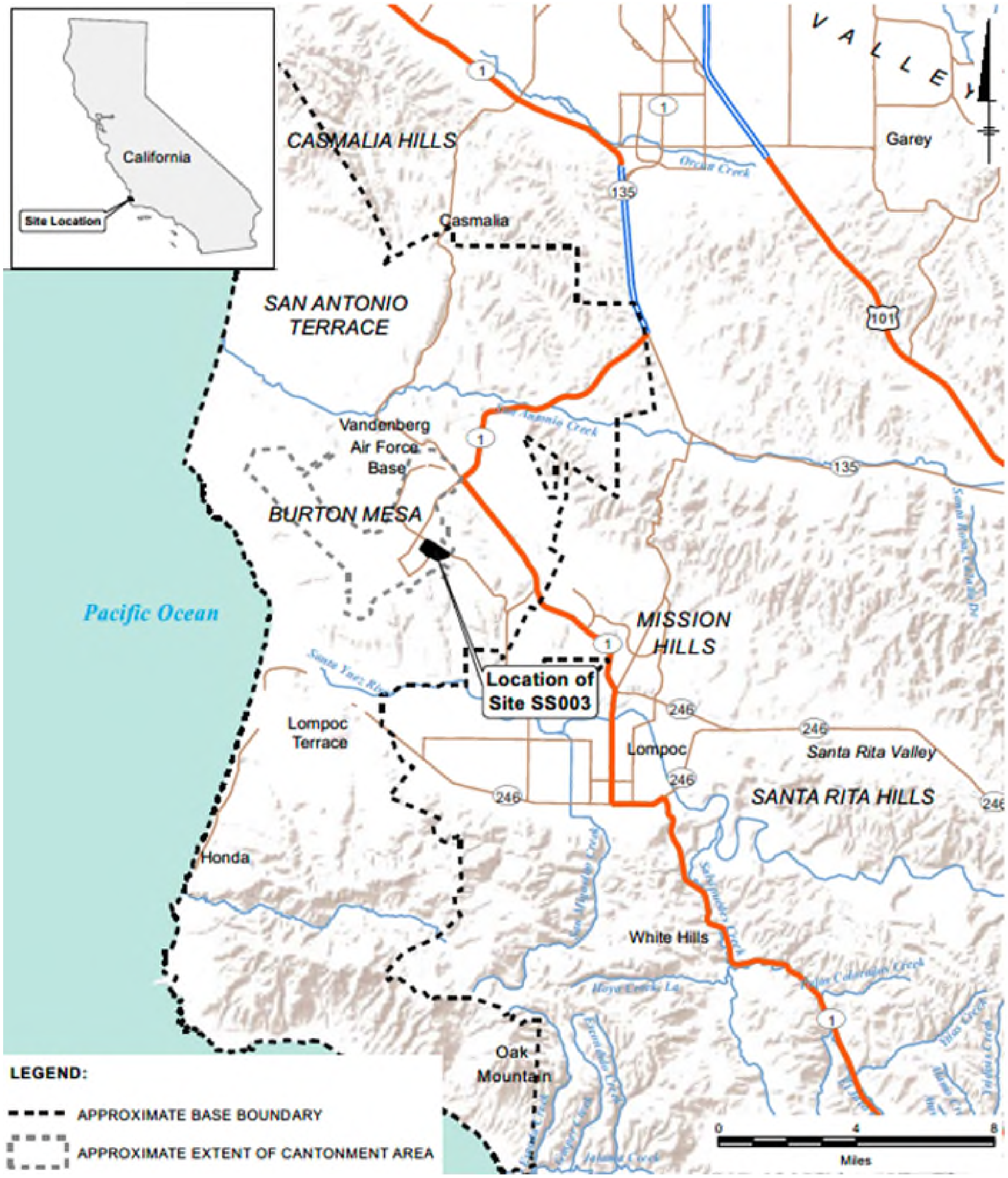

Figure 4. HRX Well Field Testing Site

4.1 Site Location and History

Site SS003 has been divided into the following three adjoining geographical areas (**Figure 5**) to clearly communicate historical and current site conditions and uses:

- The 9300 Block is relatively flat with distinctive features that include seven onsite buildings and a wastewater line that bisects the 9300 Block. The majority of this area is upgradient of the HRX Well.
- The Mesa Area is flat with little vegetation and included a former old railroad pumping station, former underground storage tanks, and former aboveground storage tanks. The edge of the Mesa Area along Oak Canyon was also historically utilized as a landfill.
- The Oak Canyon Area comprises a portion of Oak Canyon and is bounded by the VAFB sanitary landfill to the east. The Oak Canyon Area consists of moderate relief with heavy vegetation and a seasonal creek. This area is downgradient of the HRX Well.

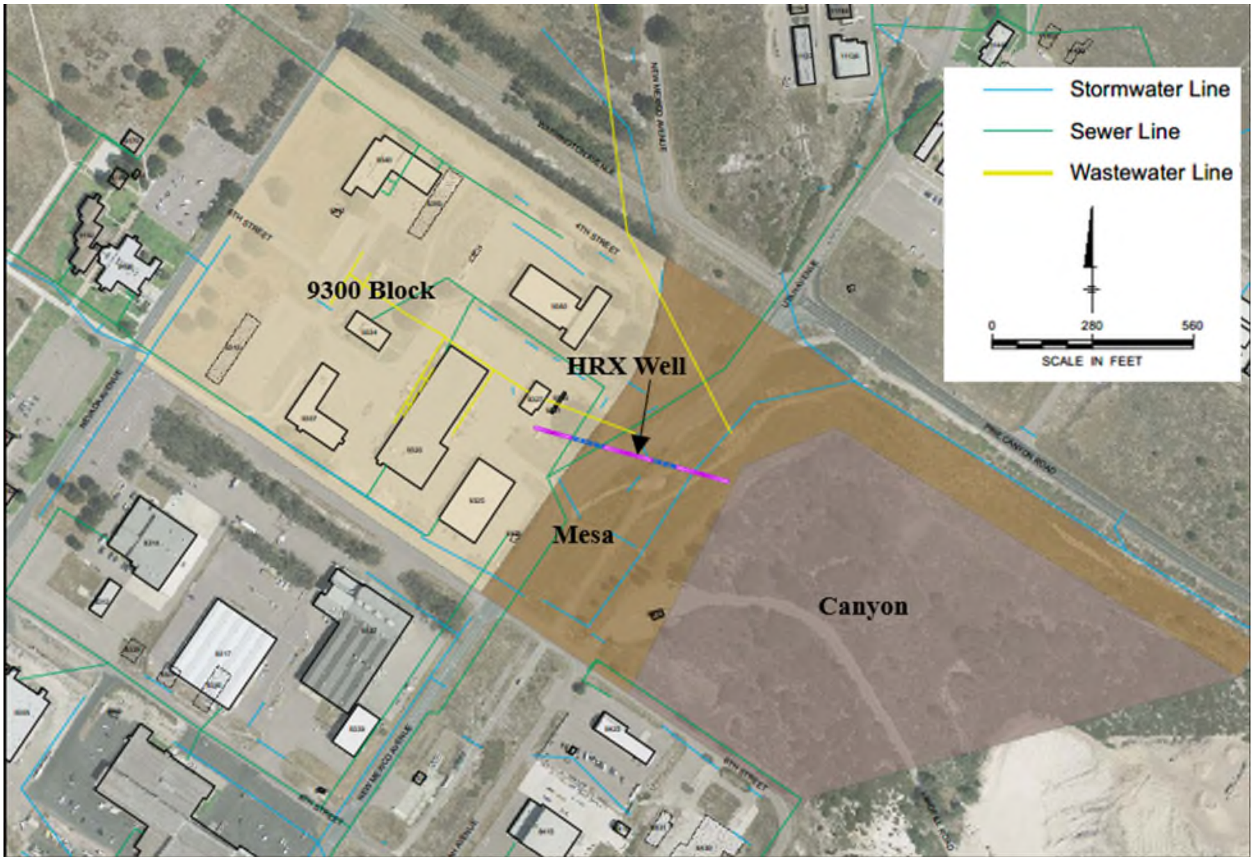

Figure 5. Site Plan

Former industrial activities conducted on the 9300 Block include electroplating, printed circuit board manufacturing, washing of heavy equipment, missile assembly activities, and photographic processing (Tetra Tech, Inc. [Tetra Tech] 2007). TCE and its degradation products represent the main volatile organic compounds (VOCs) present in soil, groundwater, and soil vapor at SS003.

The 9300 Block is bisected by a concrete wastewater line that formerly conveyed wastewater from industrial facilities and two former vehicle wash racks (Tetra Tech 2007). Previous investigations indicate the primary source of the TCE at SS003 was via leaks of industrial waste from the wastewater line. Since 2000, VOCs have been detected in groundwater samples collected at SS003, including elevated levels of the primary constituent of concern, TCE, near the wastewater line. TCE concentrations greater than 50,000 µg/L are present near the up-gradient end of the HRX Well (**Figure 6**). The location of the HRX Well was selected based on the limited infrastructure in this area, the absence of hydraulic effects due to site remedial activities, and the TCE distribution (discussed in more detail below).

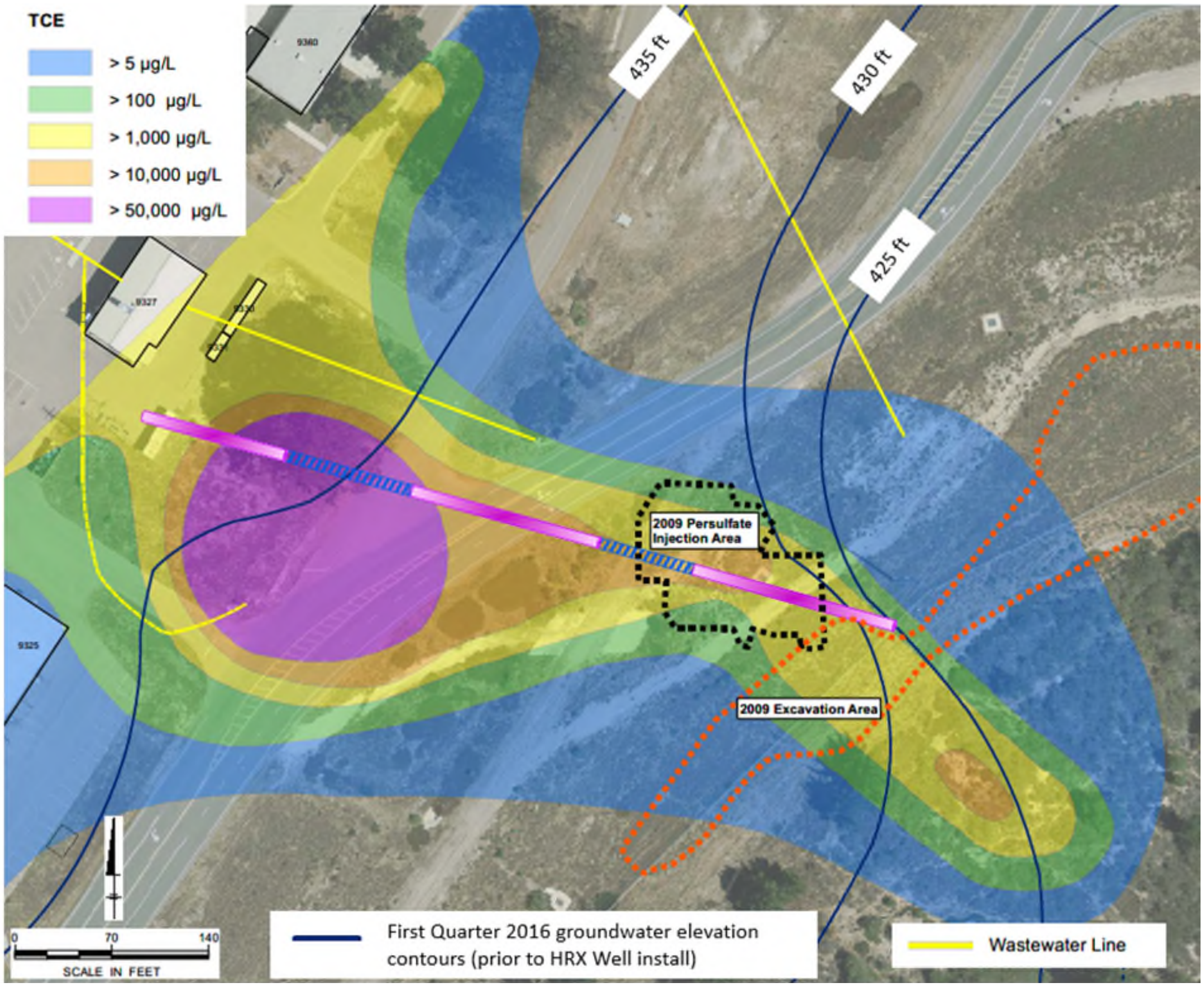

Figure 6. 2016 Groundwater Elevations and TCE Concentrations in Groundwater (Prior to installation of HRX Well)

The HRX well was installed in August 2018. Previous remediation areas are shown on the figure, along with 2016 groundwater elevations and TCE groundwater concentrations. Prior to HRX Well installation the hydraulic gradient was 0.007 feet per foot.

The likely presence of residual source mass, the high groundwater concentrations, and the presence of buildings and active surface infrastructure has resulted in a recommended remedial alternative combining remedial actions with long-term site management goals. Specifically, the goal is targeted reduction of contaminant mass discharging from the source area to achieve short-term remedial action objectives and support the eventual attainment of long-term cleanup goals (i.e., maximum contaminant levels) further downgradient. These site objectives are clearly in alignment with use of HRX Well technology.

Previous remediation efforts conducted near the HRX Well are shown on **Figure 6** and include:

- A sodium persulfate ISCO treatability study was performed in 2009 near the future outlet of the HRX Well (Tetra Tech 2009, 2010).
- In 2009, approximately 30,300 tons of soil impacted with petroleum hydrocarbons was removed from the Mesa Area, down-gradient of the future HRX Well (Shaw Environmental Inc. 2012).

4.2 Site Geology/Hydrogeology

4.2.1 Site Geology and Hydrostratigraphy

SS003 is on the eastern edge of the Burton Mesa, which is a broad, flat platform (approximately 50 square miles) that rises approximately 400 feet (ft) above the Santa Ynez River floodplain. Most of SS003 is relatively flat, and the southeastern portion gradually dips toward the southeast to Oak Canyon, which ultimately leads to the VAFB Landfill. The Burton Mesa, a paleomarine terrace, is characterized by a relatively thin mantle of unconsolidated Holocene alluvial sediments overlying Miocene Monterey Formation shale bedrock. The top of the Monterey Formation shale has been observed between 35 to 50 ft below ground surface (bgs) onsite, and appears to dip towards Oak Canyon.

The unconsolidated alluvial materials include fine-grained sands interspersed with discontinuous deposits of clay, silts, clayey sands, and silty sands designated as the Orcutt Formation sand of the Late Pleistocene age (Dibblee 1989). A geologic cross-section oriented parallel to the HRX Well location is included as **Figure 7**. As shown in the cross-section, the unconsolidated sediments at this location range in thickness from approximately 40 to 50 ft or greater, and comprise predominantly discontinuous deposits of clay, silt, sand, clayey sand, and silty sand. Cross-section A-A’ also includes identification of the two water-bearing zones relevant to this project that have been identified within the subsurface of SS003:

- Shallow Perched Zone: The Shallow Perched Zone is laterally discontinuous with a 5-foot average thickness of saturated, poorly graded fill sands perched on a clayey/variably cemented sand aquitard (often referred to onsite as the “hardpan”). The top of the Shallow Perched Zone generally occurs at 2 to 5 ft bgs (Arcadis 2016).
- Principal Zone: The Principal Zone consists of a very fine-grained sand and silt overlying deeper greenish/olive gray clay. The top of the Principal Zone generally occurs at 6 to 33 ft bgs in the 9300 Block and Mesa Area (Arcadis 2016). The HRX Well was installed into the Principal Zone to treat dissolved phase chlorinated solvents. In the vicinity of the HRX Well, the depth to the top of the Principal Zone is approximately10 to 15 ft bgs and ranges in total saturated thickness from approximately 5 to 12 ft and averages about 8 ft thick along the HRX Well alignment.

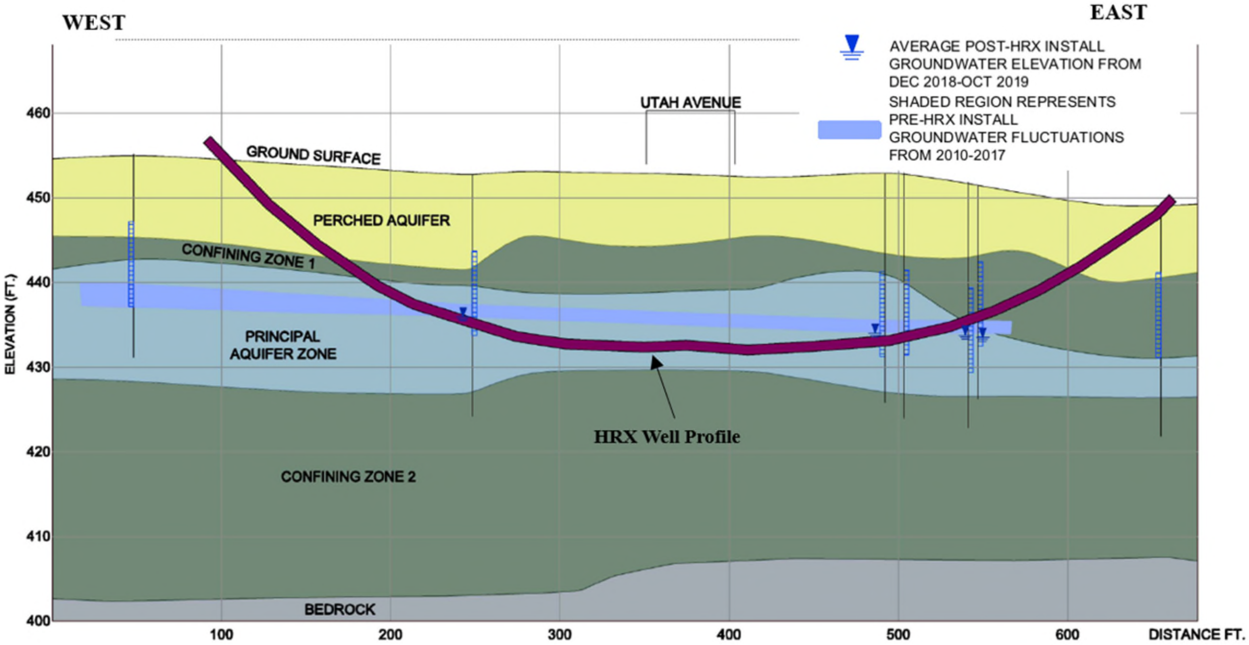

Figure 7. Geologic Cross Section Parallel to HRX Well

4.2.2 Principal Zone Hydraulic Properties

As summarized in the Treatability Test Study Report (Divine et al. 2017a) and the Demonstration Plan (Divine et al. 2018c), multiple techniques that provide results at different scales of vertical resolution were used to characterize the range of Darcy fluxes within the Principal Zone near the HRX Well. The site characterization scope of work included the following elements:

- Advancing six Hydraulic Profiling Tool (HPT) borings,
- Advancing two Soil Borings and collecting samples for laboratory grain size analysis,
- Single-Well Tracer Testing (SWTT) at three monitoring wells, and
- Installation, sampling, and analysis of passive flux meters (PFMs) at three monitoring wells.

The various methods employed in this study provided results for hydraulic conductivity (K) from HPT borings and grain size samples, or Darcy flux (q) from SWTT and PFMs. Darcy flux (q) is defined as:

$$q = Ki \tag{5}$$

where: q = Darcy flux

K = hydraulic conductivity

i = hydraulic gradient

The results of each hydraulic characterization method were compared by normalizing to Darcy flux, where necessary. This was done by applying an observed hydraulic gradient to the K results, to calculate a Darcy flux equivalent. The site-specific hydraulic gradient of 0.007 foot/foot observed during January 2016 was used when normalizing K data to Darcy flux. The Darcy flux estimates are summarized in **Table 3.**

Table 3. Summary of Darcy Flux Estimates

Method	Hydraulic Conductivity (feet per day)	Hydraulic Gradient (feet per foot)	Calculated Darcy Flux (feet per day)
Grain size distribution	0.004 – 0.4	0.007	0.00002 – 0.001
HPT logging	<0.1 – 20	0.007	<0.0007 – 0.1
SWTT	--	--	0.004 – 0.1
PFM	--	--	0.01 – 0.3

HPT = Geoprobe® Hydraulic profiling tool
SWTT = Single well tracer test
PFM = Passive flux meter
-- = SWTT and PFM provide estimates of Darcy flux

The methods provided Darcy flux estimates at different scales of resolution, nevertheless, there is general agreement between the various results. Testing at different scales allowed for estimates of not only the average Darcy flux, but also the range of Darcy fluxes present within the Principal Zone. More consideration is given to the magnitude of Darcy fluxes provided by SWTT and PFMs because these are direct measurement methods (i.e., they do not require calculations based on hydraulic gradient) and their effective measurement scale is much larger than the grain size analyses and HPT estimates discussed above. In summary, hydraulic testing by multiple methods confirmed ambient groundwater flux is relatively low at SS003 and within a range that would be expected for silt and silty/clayey fine-grained sand.

The low permeability environment near the upgradient portions of the HRX Well indicate favorable permeability contrast between the aquifer and the reactive media emplaced within the HRX Well (to promote hydraulic capture) and the relatively high permeability zone along downgradient sections will accommodate the discharge of the HRX Well. Based on the grain size analyses and single well tracer tests (which represent very localized measurements) the lower and upper bound of the hydraulic conductivity variation near the HRX Well ranging from 0.03 ft/day to 8.6 ft/day. These values are appropriately aligned with the range and median value (0.35 ft/day) noted in the preliminary site data review summarized in the Site Selection Memo (Divine et al. 2016). The additional site characterization data further validated the appropriateness of site conditions for an HRX Well application.

4.2.3 Principal Zone Groundwater Flow

The source of groundwater in the Principal Zone (and in the Shallow Perched Zone) is interpreted as infiltration of precipitation and precipitation runoff (Arcadis 2016). Leaking landscape irrigation conduits may also contribute to the SS003 groundwater budget.

The dominant groundwater gradient direction in the Principal Zone is southeast toward Oak Canyon. **Figure 6** presents the Principal Zone groundwater elevation contour map for Site SS003 from the first quarter 2016 monitoring event, prior to installation of the HRX Well. Near the HRX

Well, the horizontal hydraulic gradient is generally flatter than other portions of the site and is approximately 0.007 ft per ft between wells 3-MW-35D and 3-MW-13.

To estimate the average ambient groundwater flow rate through a vertical cross-section oriented perpendicular to flow at the HRX Well location, the following parameters were considered:

- Hydraulic conductivity measurements range from 0.01 to 11 ft/day and the geometric mean hydraulic conductivity is 0.35 ft/day;
- Horizontal hydraulic gradient of 0.007 ft per foot; and
- Capture width of 50 feet and a saturated thickness of approximately 7 ft (at 3-MW-35S/D) shown on **Figure 7**.

The estimated average volumetric flow rate across the entire width of the plume using these values is approximately 6.4 gal/day, or about 0.9 cubic foot per day (ft^3/day)

4.3 Contaminant Distribution

TCE is the primary constituent of concern at SS003. The HRX Well was designed to reduce contaminant mass discharge from the TCE "hot spot" in proximity to a suspected release point near the outfall of an auxiliary wastewater line. Concentrations at nearby wells 3-MW-35D and 3-MW-34 have historically been measured as high as 59,000 µg/L and 66,000 µg/L, respectively. **Figure 6** includes the TCE distribution in Principal Zone groundwater from samples collected during the first quarter 2016 monitoring event, prior to installation of the HRX Well in July/August 2018. The location of the existing hot spot is delineated on **Figure 6** by the purple region where TCE groundwater concentrations exceed 50,000 µg/L.

The presence of low-permeability, unconsolidated alluvial sediments suggest relatively low contaminant transport rates within the Principal Zone. The concentrations of TCE in the Principal Groundwater Zone are generally orders of magnitude higher than the concentrations of TCE in the shallow perched groundwater zone (Arcadis 2016). Transport of contaminants into the subsurface is interpreted to have occurred via percolation from the wastewater line system and vertical migration from the shallow perched zone through discontinuities in the confining layer into the Principal Zone.

5 TEST DESIGN

This section provides a detailed description of the HRX Well design and testing that were conducted during the demonstration to address the performance objectives described in Section 3.

5.1 Conceptual Experimental Design

The overall goal of ER-201631 was to complete a field demonstration to validate the HRX Well technology concept, quantify technical performance and limitations, and provide a basis for wider application at DoD and other sites. The experimental design used to evaluate the performance objectives for this project included four major tasks with several subtasks:

- Task 1 Site Selection
- Task 2 Site Characterization and Treatability Testing
    - 2A Site Characterization

  - 2B Treatability Testing
  - 2C: 3D Tank Tests and Field Scale Pilot Testing
- Task 3: Demonstration/Validation
  - 3A: Preliminary Design
  - 3B: Demonstration Plan
  - 3C: HRX Well Installation
  - 3D: HRX Well Operation and Monitoring
  - 3E: HRX Well Design Tool Validation
- Task 4 Cost, Performance, and Sustainability Analyses and Reporting

5.2 Baseline Characterization

Baseline site characterization work was performed to address data needs identified during site selection, which included further characterization of hydrogeologic conditions and the contaminant distribution in the immediate vicinity of the HRX Well (Divine et al. 2017a, 2018c). The results were used to support both the final design and performance assessment. These activities included:

- Measuring Darcy flux using a variety of methods;
- Measuring hydraulic gradients by gauging groundwater levels within monitoring wells; and
- Measuring contaminant concentrations in monitoring wells by submitting groundwater samples for laboratory analysis.

The low permeability environment near the upgradient portions of the HRX Well provides a favorable permeability contrast (to promote hydraulic capture of impacted groundwater) and the relatively high permeability zone along downgradient section accommodates the discharge of treated groundwater from the HRX Well. The grain size analyses and single well tracer tests characterize the lower and upper bound of the hydraulic conductivity variation near the HRX Well ranging from 0.03 ft/day to 8.6 ft/day. These values are appropriately aligned with the previous site data review. Overall, the site characterization data further validated the appropriateness of site conditions for an HRX Well application.

5.3 Treatability Study or Laboratory Study Results

Treatability testing, three-dimensional (3-D) Tank Tests, Field Scale pilot testing, and other project activities were completed to support the final design and field installation of the HRX Well as summarized in the following sections.

5.3.1 Treatability Testing

In preparation for the field demonstration of the HRX Well technology, treatability studies were conducted with several alternate brands of commercially available granular iron (e.g., Peerless iron, Hepure iron, and Connelly iron). A modified Point Velocity Probe (PVP) was also developed and tested as part of this task (**Figure 8**). The objective of this task was to optimize the selection of the specific ZVI material for emplacement within the HRX Well and to consider site-specific geochemical conditions to predict and optimize treatment effectiveness. The treatability testing results are summarized in the following sections. For further details on the design and testing protocol, see the Treatability Test Study Report (Divine et al. 2017a).

The measured first-order rate constants for the Connelly iron (87% iron, 13% sand) were similar to those obtained from the Peerless iron columns, ranging from 9.1 day^{-1} to 14.8 day^{-1}. Early in the column testing, the Peerless iron columns performed slightly worse than the Connelly iron columns, with slightly lower rates of TCE degradation and visually higher rates of gas production. On this basis, Connelly iron was regarded as the preferred product of the two. A third brand of iron, Hepure, was found to lose reactivity notably over the duration of the test, and was prone to significant visible gas production. None of the columns exhibited progressive, relative losses in hydraulic conductivity over the four-month time of the test, during which more than 1,000 pore volumes were pumped through the monitored sections of the columns. This result indicated that the HRX Well will not be prone to mineral buildups and clogging before many pore volumes have passed through the iron medium.

Based on these tests, Connelly iron was selected as the preferred product of the three tested iron types. Additionally, laboratory testing confirmed the modified PVP is appropriate for installation in an HRX Well and is capable of accurately and repeatedly measuring seepage velocities.

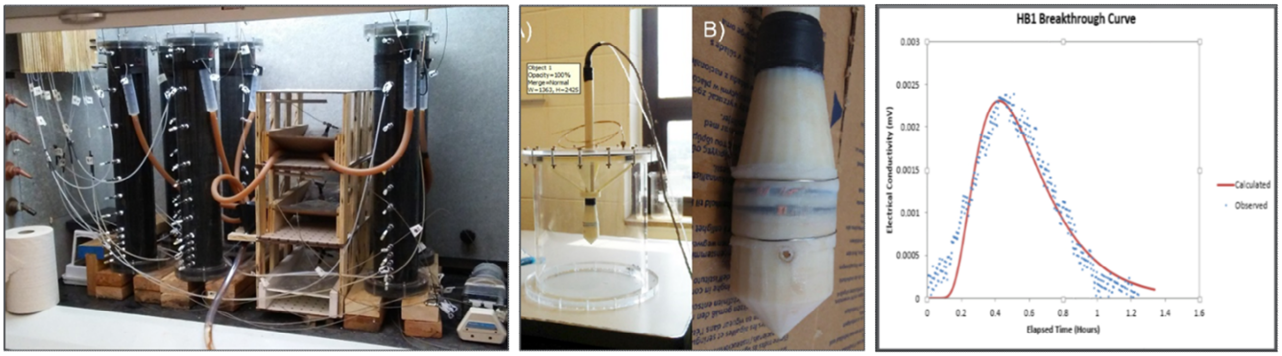

Figure 8. Treatability Testing
Treatability column setup (left), redesigned Point Velocity Probe (PVP) for in-well groundwater velocity measurement (center) and example PVP tracer breakthrough curve measuring a flow velocity of 113 centimeters/day.

5.3.2 3-D Tank Tests and Pilot Tests

Both laboratory 3-D tanks tests (**Figure 9**) and field pilot scale tests (**Figures 10** and **11**) were completed to verify the HRX Well hydraulic and treatment performance. Specifically, these activities were intended to assess the reactive transport model, simulate long-term weathering of ZVI in a 3-D transport system, and characterize any long-term hydraulic changes.

Figure 9. Laboratory Tank System
Photographs of Laboratory Tank System with HRX Well constructed within a 55-gallon drum to simulate a simple aquifer system

Results from both the laboratory 3-D tank and field pilot scale tests were highly consistent with the predicted results from numerical flow models built to design the both tests, and demonstrate that the HRX Well captured and treated contaminated water consistent with flow and transport model predictions, further validating the remediation concept and the reliability of the modeling approach to support test design. Only minor changes to flow and head measurements were measured after 100 pore volumes of throughput to simulate long-term weathering. Tracer test results from the laboratory tank demonstrate that methyl orange (the surrogate contaminant) was degraded by ZVI packed into the HRX Well, and that degradation was not negatively impacted by weathering. Hydraulic head measurements from the field pilot scale test pit indicated significant passive capture by the HRX well, with approximately 39 percent (%) of flow through the pit captured by the well, which had an area representing 0.5% of the pit's total cross-section area, corresponding well with the design model predictions.

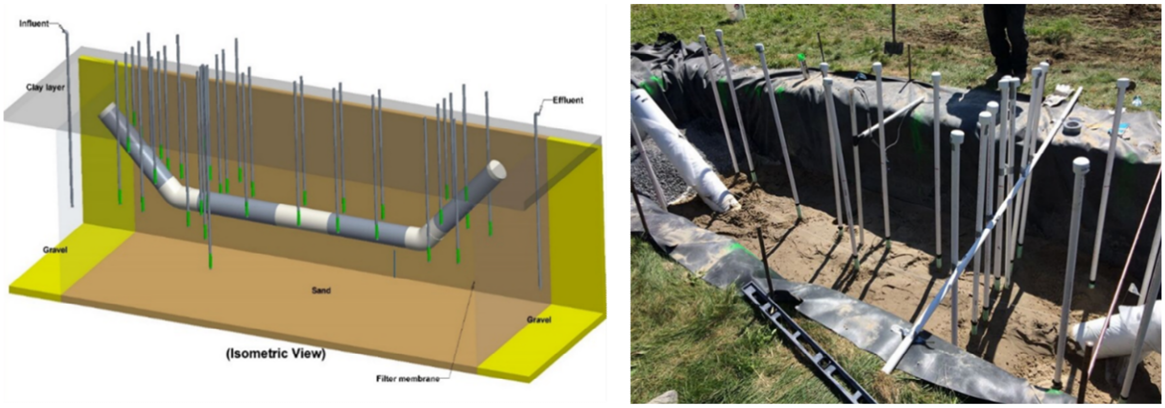

Figure 10. Pilot scale HRX Well Test Pit
Pilot scale HRX Well test pit 6 feet deep by 6 feet wide by 20 feet long. The pit is lined with an impermeable pond liner, packed with sand and a 2 foot long gravel compartments at each end. The 8-inch diameter HRX Well was filled with granular activated carbon.

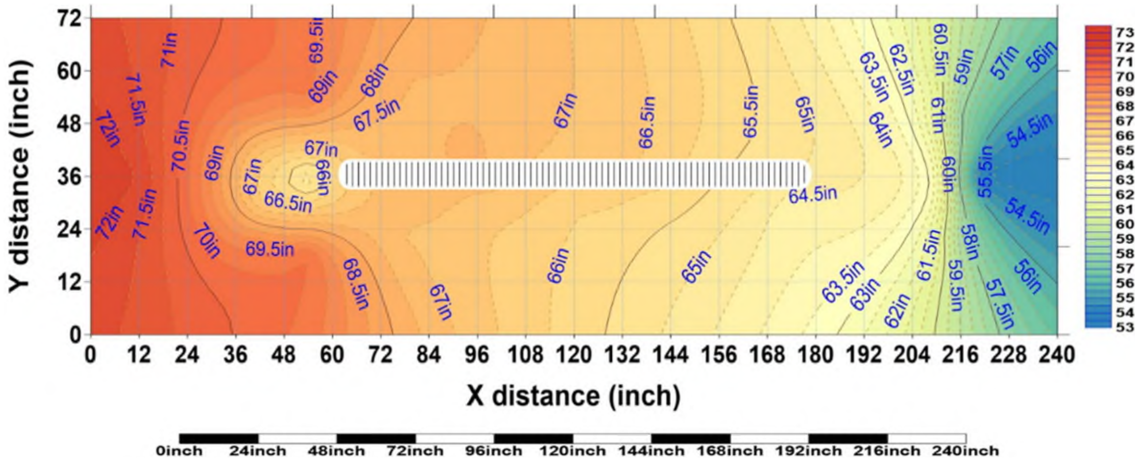

Figure 11. Contour Plot of Hydraulic Head Values Measured at 40 Points within the Test Pit
Water levels are in inches. The well capture zone is indicated by the steep gradient at the influent end of the HRX Well®, between 40 and 60 inches on the Y axis. Flow is from left to right.

5.4 Design and Layout of Technology Components

This field demonstration project entailed the installation of a single HRX Well at site SS003 (**Figure 12**). The HRX Well is approximately 565-ft long and 20-ft deep and contains segments filled with a ZVI/sand mixture that treat TCE contaminated groundwater as it is passively directly through the well. Segments at the upgradient and downgradient ends of the reactive media are used to collect data to document well performance.

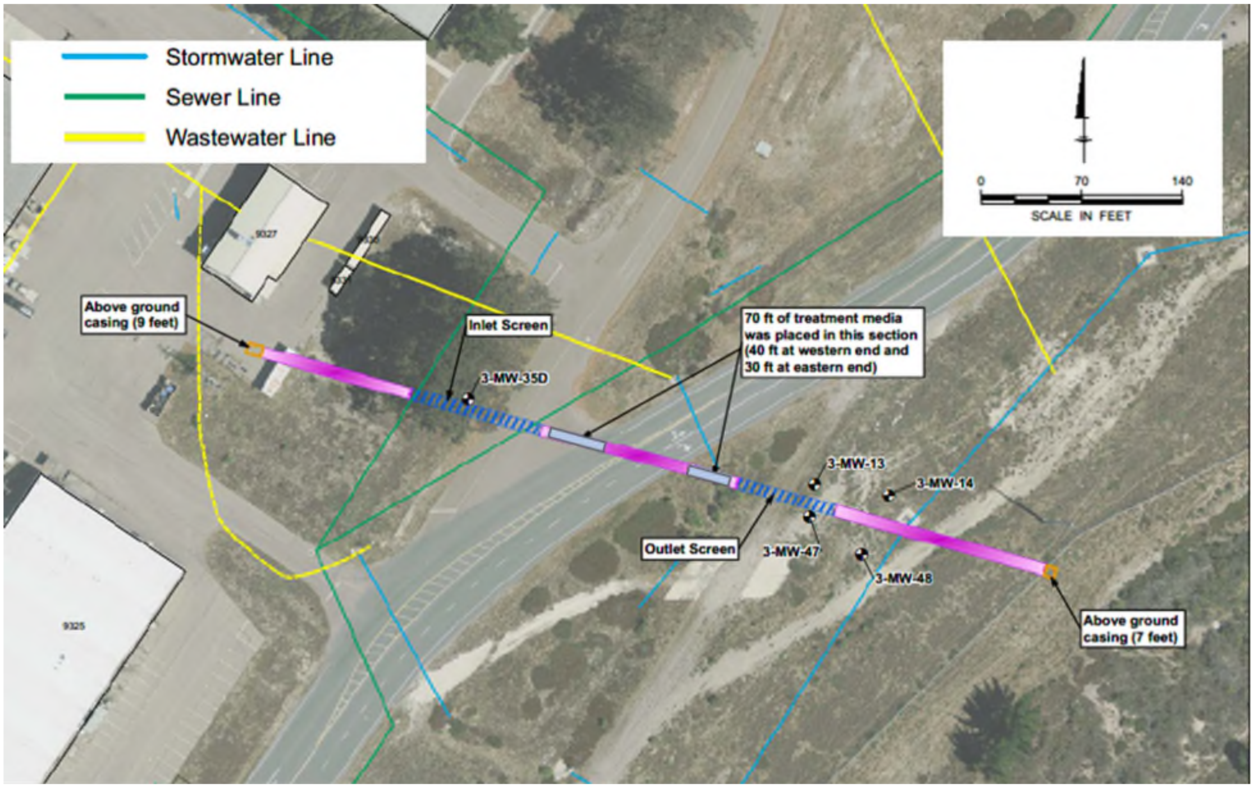

Figure 12. HRX Well As-Built Map with Performance Monitoring Well Network

To assist the HRX Well design phase and to provide a basis for performance expectations for the field demonstration, a three-dimensional groundwater flow and transport model was developed based on site-specific data (Divine et al. 2017a). The model was constructed using the United States Geologic Survey MODFLOW code (McDonald and Harbaugh 1988) to simulate the groundwater flow regime and the hydraulic capture of the proposed HRX Well. HRX Well diameters of 10 and 12 inches were evaluated using the groundwater flow model, and MODPATH (Pollock 2016) and MT3DMS (Zheng 1990) were used in conjunction with MODFLOW to predict the groundwater flow paths towards the HRX Well and to simulate the migration to and subsequent treatment of TCE in the HRX Well. Details of the original design model are provided in the previous Demonstration Plan (Divine et al. 2018c).

To support HRX Well performance assessment, the model was updated to more accurately reflect as-built specifications of the HRX Well. Details of the updated model are presented in **Appendix A**. The groundwater flow model was utilized to evaluate the hydraulic capture and residence time of the proposed HRX Well design. Various well design scenarios were simulated to optimize the well configuration to provide sufficient residence time of passively directed impacted groundwater within the treatment media. **Figure 13** presents the simulated capture width and residence time of the as-built HRX Well installed at VAFB under passive operation. As shown, the simulated capture width under the passive configuration was 52 ft with an average groundwater residence time of 9 days within the treatment media of the HRX well. Based on the previous project treatability study (Divine et al. 2017b) which measured TCE decay rates ranging from approximately 9 and 13 day^{-1} for an 85% ZVI and 15% sand mixture, a conservative TCE decay rate estimated of 1.8 day^{-1} for the 35% iron and 65% sand mixture used for the field demonstration, which suggests it will take a minimum of 4 days of contact with the ZVI for TCE to degrade from 75,000 µg/L to 50 µg/L. Therefore, the as-built passive configuration of HRX Well provides an estimated safety factor of about 2 for a treatment of TCE to less than 50 µg/L. The flushing width of treated water that exits on the downgradient side of the HRX Well was estimated to be similar to the upgradient capture width.

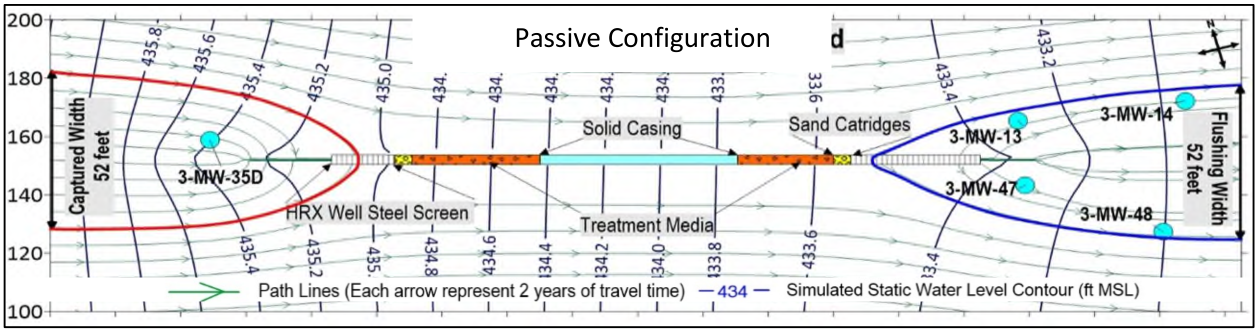

Figure 13. Simulated Groundwater Pathlines of 12 Inch Diameter HRX Well with 70 Feet of Treatment Media

The zone of hydraulic capture and treatment is defined by the flowlines that converge into the HRX Well at the upgradient side, travel through the well, and then exit and diverge out of the HRX Well on the downgradient side.

The most significant technical performance risk associated with field-scale implementation of the HRX Well is installation and construction. Specifically, the HRX Well performance is optimized when flow-focusing occurs as a result of the contrast between the higher hydraulic conductivity of the reactive media inside the well and the relatively lower hydraulic conductivity of the aquifer. During construction, media fill must be controllable and consistent along the length of the treatment zone of the HRX Well to ensure a meaningful and targeted hydraulic conductivity differential. In addition, longitudinal void spaces that would permit impacted groundwater to bypass the treatment media must be avoided during construction. To manage the risk of an underperforming well and ensure maximum well efficiency, appropriate design precautions were taken to mitigate these risks, as discussed further in the subsections below.

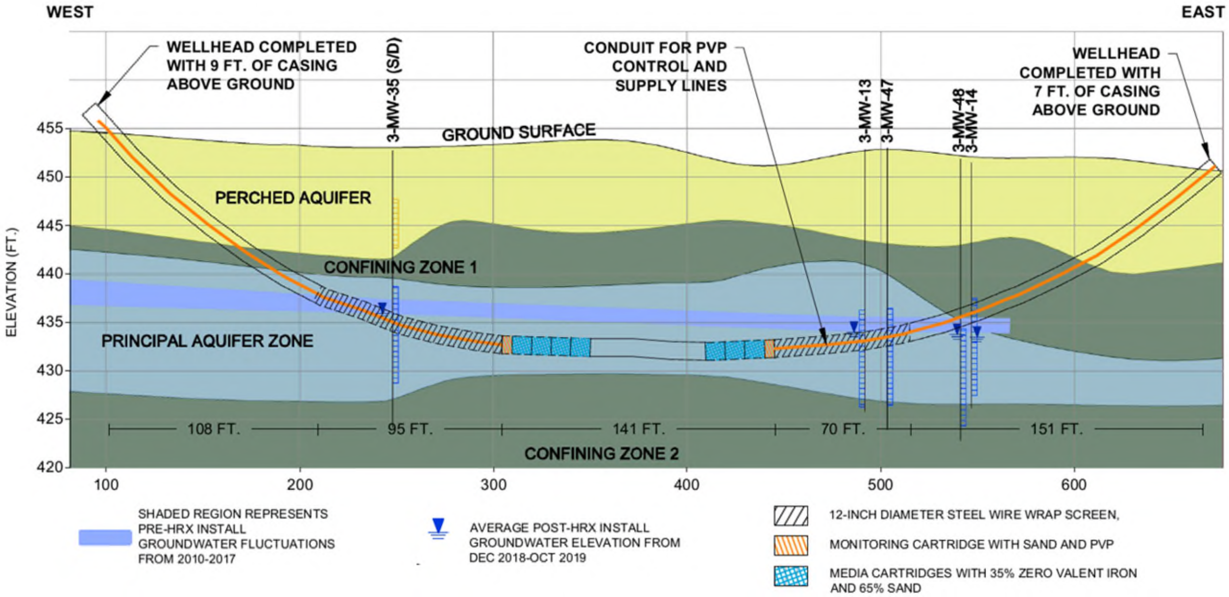

Figure 14. HRX Well As-built Schematic Cross Section Diagram with Site Hydrostratigraphy

An as-built schematic cross-section diagram is provided as **Figure 14** and shows the elements of the HRX Well and site hydrostratigraphy. The central coast region of California experienced severe drought conditions for several years prior to the field demonstration and groundwater levels during the testing period were several ft below typical historical average levels. The entry screen on the upgradient side is curved and extends above the water table to account for seasonal variability and maximize capture. The curved portion of the screen is intended to maintain capture when the water table eventually recharges. Groundwater is treated as it flows through the treatment media within the cased (not screened) central horizontal section of the well and then exits via the screened section on the downgradient side. Construction details of the HRX Well are summarized in **Table 4**.

Table 4. HRX Well Construction Details

Total well length (horizontal length)	565 ft
Total well depth	22 ft
Well casing material	12-inch diameter carbon steel
Well screen material	12-inch diameter stainless steel with 0.008-inch slots
Inlet screen length (horizontal length)	95 ft
Outlet screen length (horizontal length)	70 ft
Treatment media cartridges	7
Treatment media cartridge material	10-inch diameter HDPE
Treatment media cartridge length (each cartridge)	15 ft (10 feet filled with treatment media plus 2.5 feet of connection fittings at each end)
Treatment media	35% ZVI / 65% 16/30 sand. Measured K_{ZVI} = 200 ft/day, estimated porosity = 0.38
Treatment media length / weight / volume	Total: 70 ft / 3,972 pounds (lbs) ZVI: 1,390 lbs / 11.8 cubic ft^3 Sand: 2,582 lbs / 25.8 ft^3
PVP Monitoring cartridges	2
PVP monitoring cartridge material	10-inch diameter HDPE
PVP Monitoring cartridge length (each cartridge)	5 ft
PVP Monitoring cartridge media	100 % 16/30 sand
PVP Monitoring cartridge media length / weight / volume	Total: 10 ft / 483 lbs / 4.83 ft^3
Internal Seals between OD of cartridges and ID of steel well material (total for all cartridges)	Treatment media cartridges: • 10 expanding bentonite seals • 10 rubber seals PVP Monitoring cartridges: • 4 rubber seals
External annular grout seal between OD of steel well material and borehole	Riser grout seals at each end: • 3,196 lbs cement + 5% bentonite chips Central section: • 4,230 lbs cement + 2% bentonite

At noted in Table 4, the measured hydraulic conductivity of the ZVI/sand treatment media (K_{ZVI}) was 200 ft/day and the effective K_{HRX} was estimated at 320 ft/day by the commonly used method for estimating the effective hydraulic conductivity for heterogeneous systems with flow perpendicular to layers (e.g., McDonald and Harbaugh 1988):

$$K_{HRX} = \frac{x_{ZVI} + x_o}{\left(\frac{x_{ZVI}}{K_{ZVI}}\right) + \left(\frac{x_o}{K_o}\right)} \tag{5}$$

where x_{ZVI} and x_o are the lengths of the treatment media and open sections (80 and 61 feet, respectively) and K_o is the estimated hydraulic conductivity of the open section (estimated at approximately 2,000 ft/day).

The HRX Well comprises several subsystems, some of which were constructed offsite and then subsequently assembled onsite as part of the construction program. The construction program was initiated in mid-July 2018 and was completed on August 10, 2018, and can be described in several connected phases, as detailed in the sections below. The well completion report from Directed Technologies Drilling, Inc. is included as **Appendix B**.

5.4.1 Media Cartridge Construction

The HRX Well contains active treatment media (in this case ZVI) held in contact with groundwater that passes downgradient through a double-ended horizontal well. To maintain quality control over the volume and placement of the media within the well, a cartridge system was developed to contain the media. The media cartridges were inserted after the horizontal well and screens were installed and developed to be free of drilling fluid and in hydrological contact with the surrounding formation.

Cartridges were constructed at the Directed Technologies Drilling (DTD) shop in Mineral Wells, TX several weeks prior to project mobilization. The cartridges were constructed of high-density polyethylene (HDPE) pipe and various fittings. The objectives of the cartridge design included:

1. Constraint of media to prevent loss or contamination during installation
2. Groundwater passage through the cartridge without restriction
3. Prevention of groundwater bypassing around the media
4. Ease of placement
5. Ease of future removal
6. Ability to be instrumented for flow and/or groundwater sampling

To facilitate safe handling during installation, cartridges were designed to contain a 10-foot length of active media, with connectors or end caps extending beyond this base length. This limited the weight and size of the individual cartridge. Several cartridge types were designed and constructed, depending on where they would be placed within the treatment train. All passages and ports in the cartridges were confirmed to provide a greater cross sectional area than the equivalent media porosity across the full cartridge diameter. This was done to prevent any flow restrictions due to cartridge construction elements.

Prior to media placement within the cartridges, the proper volumes of sand and ZVI, based on treatability testing and groundwater flow model simulations, were measured into a portable cement mixer. The evenly distributed mixture was then shoveled into a cartridge body, elevated at one end. Final measurements of the length of media column, media volume and media porosity were verified prior to capping of the cartridge for transport to the site. Photographs of the treatment media cartridges are included as **Figure 15**.

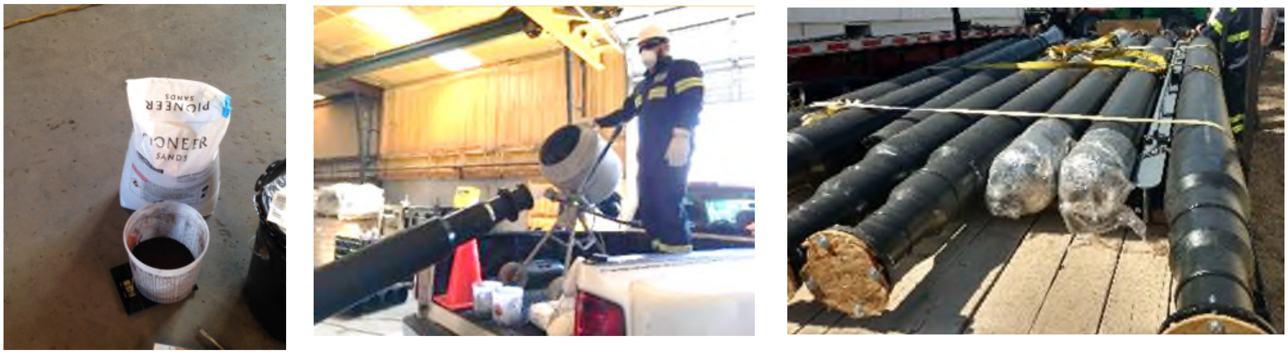

Figure 15. Treatment Media Cartridges
Specified proportions of ZVI and sand (left). Mixing to ensure even distribution of ZVI and sand prior to placing media into cartridge body (center). Fully assembled treatment media cartridges transported to the demonstration site.

The HRX Well was designed with seven treatment cartridges in the central cased horizontal section of the well, between the inlet and outlet screens. Four treatment cartridges were inserted from the inlet end of the well and three treatment cartridges were inserted from the outlet end of the well. Additional monitoring cartridges were designed, constructed, and inserted outboard of the treatment cartridges to contain PVP (see Treatability Study and Demonstration Plans for additional information on the PVPs) supplied by Kansas University, to measure groundwater velocity entering and exiting the treatment media.

Prototype treatment media cartridges were designed by the Arcadis-DTD team specifically for this project and constructed by fusion welding 10-foot lengths of 10-inch HDPE pipe to reducer fittings, bolted flanges, and end caps, in various configurations. In the field, these were bolted together and pushed into place. The PVP cartridges were constructed with 5-foot lengths of 10-inch HDPE pipe. Drawings of the cartridge configurations, which included features to prevent groundwater bypass around the media, are provided below in **Figures 16** through **19**. Domestic and international patents are pending on the cartridge design.

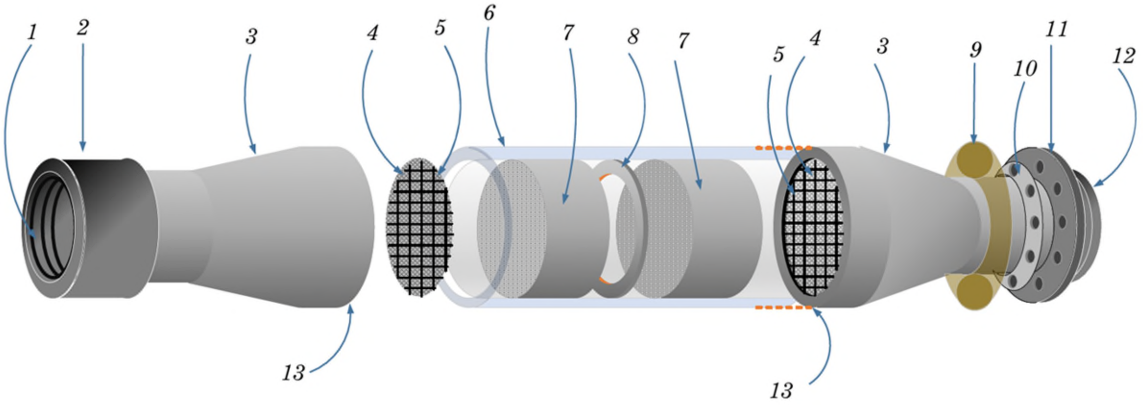

Figure 16. Media Cartridge Embodiment #1: Retrieval Connection and Connecting Flange
1) Threaded portion of drill rod connector; 2) Drill rod connector; 3) HDPE reducer; 4) Steel or plastic filter supporting grid; 5) Geotextile media retaining filter; 6) HDPE cartridge body; 7) Reactive media packed into cartridge – note the reactive media is a continuous mass separated from #8 on the diagram for clarity; 8) Interior baffle to prevent water bypass around reactive media;

9) Expanding bentonite seal; 10) Steel flange connecting plate – fasteners not shown; 11) Rubber cartridge seal; 12) HDPE flanged fitting; 13) Butt fusion connection between end assembly and cartridge body

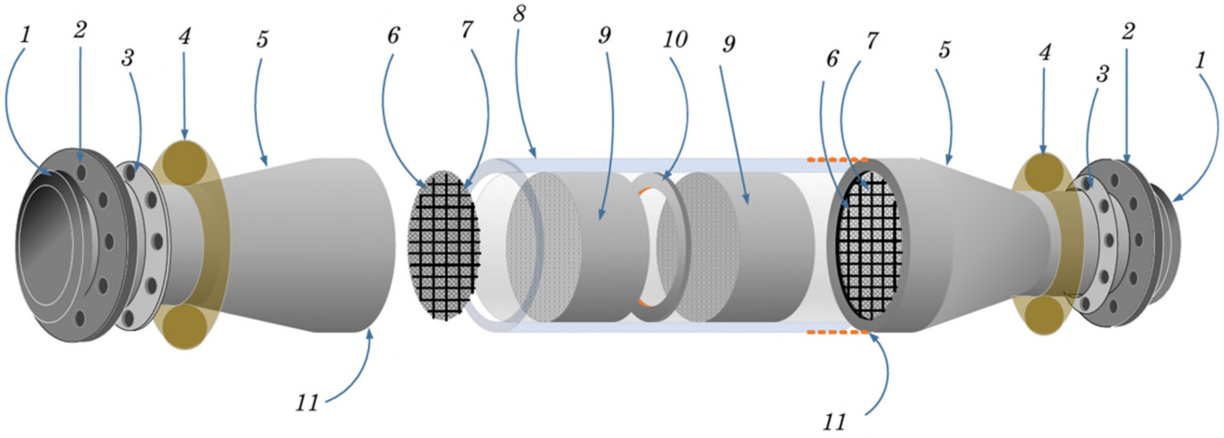

Figure 17. Media Cartridge Embodiment #2: Connecting Flanges Both Ends
1) HDPE flanged fitting; 2) Rubber cartridge seal; 3) Steel flange connecting plate – fasteners not shown; 4) Expanding bentonite seal; 5) HDPE reducer; 6) Steel or plastic filter supporting grid; 7) Geotextile media retaining filter; 8) HDPE cartridge body; 9) Reactive media packed into cartridge – note the reactive media is a continuous mass separated from #10 on the diagram for clarity; 10) Interior baffle to prevent water bypass around reactive media; 11) Butt fusion connection between flange/reducer assembly and cartridge body

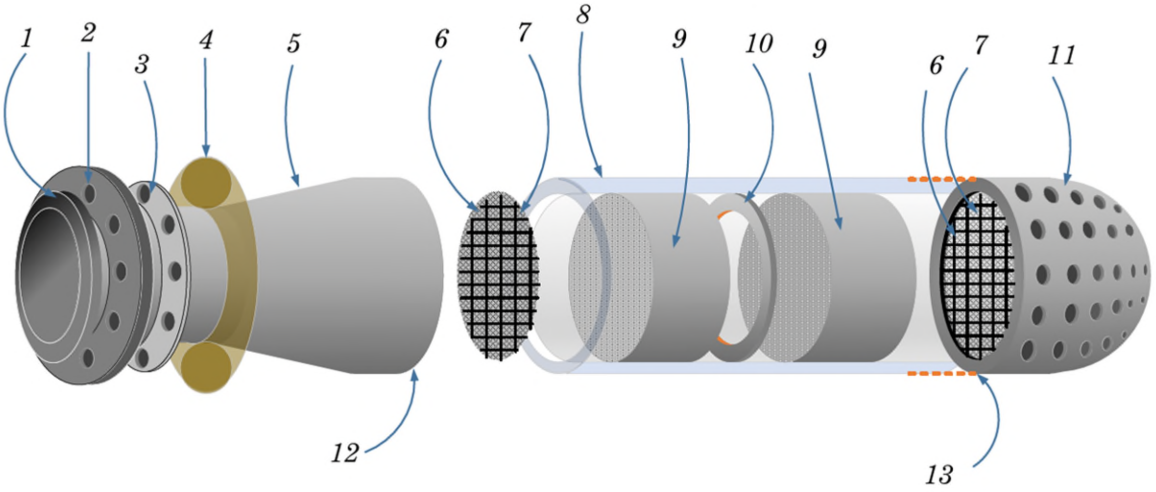

Figure 18. Media Cartridge Embodiment #3: Connecting Flange and End Cap
1) HDPE flanged fitting; 2) Rubber cartridge seal; 3) Steel flange connecting plate – fasteners not shown; 4) Expanding bentonite seal; 5) HDPE reducer; 6) Steel or plastic filter supporting grid; 7) Geotextile media retaining filter; 8) HDPE cartridge body; 9) Reactive media packed into cartridge – note the reactive media is a continuous mass separated from #10 on the diagram for clarity; 10) Interior baffle to prevent water bypass around reactive media; 11) Perforated end cap – total ratio of open area of holes exceeds the porosity of reactive media (0.38); 12) Butt fusion connection

between flange/reducer assembly and cartridge body; 13) Butt fusion connection between perforated end cap and cartridge body

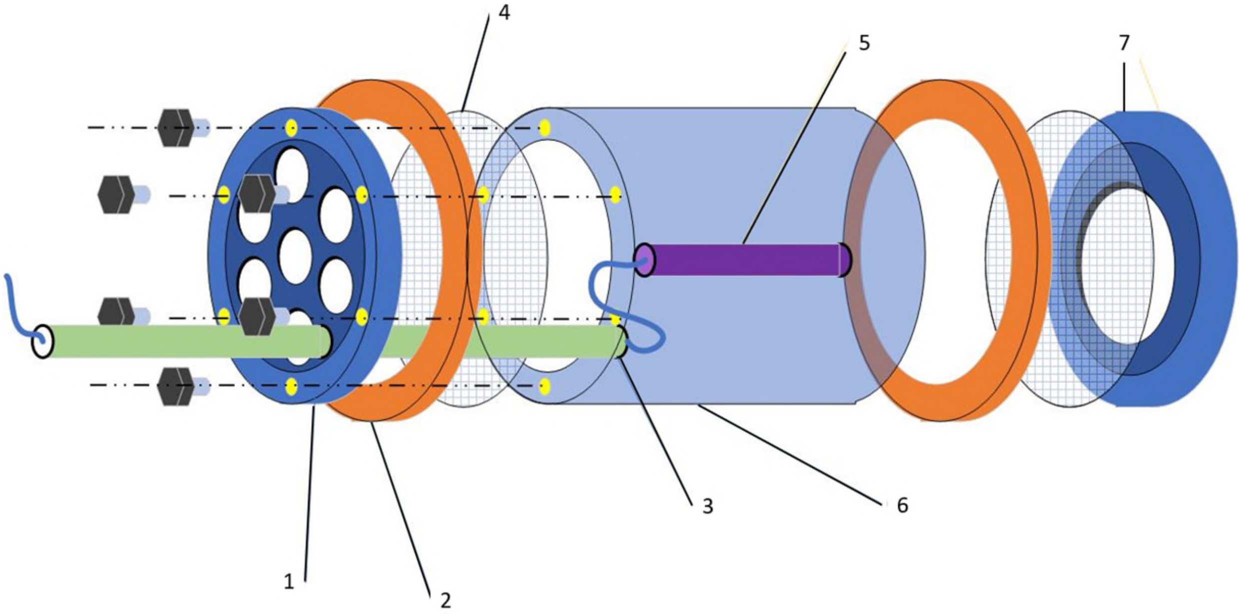

Figure 19. Monitoring Cartridge

Individual components include 1) HDPE end cap with water passages; 2) Rubber annular seal (2); 3) 1” PVC conduit with PVP cabling and injection line; 4) Sand retention mesh (2); 5) PVP; 6) HDPE cartridge body (the sand which fills the cartridge is not shown); 7) HDPE end cap with water passage

5.4.2 Drilling and Reaming Operations

The HRX Well is double-ended, meaning that a pilot bore was drilled from an entry pit to an exit pit. The pilot bore was drilled at an angle (approximately 7 degrees) to the target depth, continued horizontally, and then ascended to the surface at the exit pit. Drilling was performed with an American Augers DD10 horizontal drill rig (**Figure 20**), supported by a self-contained mud recycling system, excavator, extended reach forklift, and water truck. A biodegradable polymer drilling fluid was used during drilling operations. Additional support at the exit end of the double-ended well was supplied in the form of a large mud pump and temporary piping to convey drilling fluid back to the rig side of operations. A large generator was also staged at the well exit to support well development with a submersible pump.

Figure 20. Directional Drilling Rig and Drill Bit
American Augers DD10 directional drilling rig (left). Duckbill drill bit (right).

Drilling was performed with a 6.75-inch diameter duckbill drill bit and approximate 3.5-inch diameter drill rods. The bore alignment was surveyed and staked in advance to provide a visual alignment and stationing for drilling guidance and steering. Directional guidance for the drilling was provided by a Digital Control Inc., F5 walkover locating system. The walkover system uses a downhole transmitter that provides telemetry of bit pitch and roll measurements, combined with an electromagnetic field that is sensed at the ground surface to provide distance from the drill rig (along with rod count) and azimuth. As the bore is drilled, regular walkover measurements are taken and compared with the bore plan to confirm bit location and make steering corrections as needed. The pilot bore was drilled from July 21 through July 25, 2018.

After the pilot bore was completed, a series of reaming passes were completed to incrementally enlarge the bore diameter from the initial 6.75 inches to approximately 18 inches. Reaming was accomplished in two passes, attaching a reamer at the exit end of the bore and pulling it back towards the drill rig. Drill rods were attached behind the reamer to prevent bore loss in the event of soil collapse within the bore. A final swab pass was made with the final reamer size to clean the bore prior to well installation.

5.4.3 Well Installation

The HRX Well was constructed of a combination of carbon steel blank pipes with stainless steel wire-wrapped screen, protected inside a perforated shroud (**Figure 21**). This shielded screen offers additional strength to the relatively fragile wire-wrapped screen, allowing it to be pulled back into a horizontal well with reduced risk of screen damage. Well materials were supplied through PQ Products of Spokane, Washington. The screen is a proprietary product manufactured by Alloy Machine Works.

The well materials were supplied with plain ends and were beveled and welded together in the field prior to pullback. Due to space constraints, the string of well materials was assembled in three individual segments of a few hundred feet each. As pullback occurred, these segments were pulled into position and welded to those already pulled into place.

After reconfiguring the reaming tools, the first section of assembled well materials was attached to a swivel, which was in turn attached to the 18-inch reamer at the exit end (**Figure 22**). The materials were drawn smoothly back towards the drill rig. The first section of the well was pulled back on August 2, 2018. On August 3, pullback continued, pausing only to weld on the remaining two well segments. Pullback was completed on August 3, 2018. An artificial filter pack was not installed around the screened sections, as the horizontal orientation precludes filter sand installation procedures used for vertical wells. Instead, the well screens are in contact with the formation and a natural filter pack is developed, which is standard practice for horizontal remediation wells.

Figure 21. HRX Well Screen
Stainless Steel Wire-Wrapped Screen with External Perforated Shield (Manufactured by Alloy Machine Works)

The well assembly included 12-inch diameter riser and screen:

- Entry end riser: total 104 ft, including a section added to extend the wellhead above ground, after installation.
- Inlet screen: 95.5 ft
- Center blank section: 141 ft
- Outlet screen: 70 ft
- Exit end riser: total 161 ft, including above ground section

Figure 22. Well installation
Reaming tool attached to 12-inch diameter steel well materials prior to pullback

5.4.4 Well Grouting Operations

After the well was installed, grout was placed within the annulus of the central blank section of the well, located between the intake and outlet screens of the HRX Well. This grout seal prevents groundwater from bypassing the well though the annular space between the outer casing and the boring wall.

Prior to grouting, the volume of the bore annulus between the well screens was calculated. Half of that volume of heavy, viscous grout was evaluated to be enough to plug the central bore annulus, without risking intrusion of grout into the two adjoining well screen segments. Accordingly, the grout was mixed using a Groutmaster grout plant and injected into a tremie pipe extended to the mid-point of the central blank section, using a positive displacement pump. The tremie pipe was then removed from the bore.

The ends of the well were grouted after well development to prevent influx of surface water into the system. Tremie pipes were extended to approximately 60 ft, and a thick cement-bentonite grout was pumped until grout was observed at the surface.

5.4.5 Development

The well was developed to remove drilling fluids and promote hydraulic connection with the formation. The well development process commenced on August 6, 2018. The entry end of the well remained closed off by the steel pulling head used to install the well. A hole was cut in the well casing near the well end, and a threaded nipple was welded into place. This nipple was, in turn, connected to hose leading to a water truck staged nearby. This setup was used to flush water into the interior of the well casing. Water subsequently emerged from the screen into the bore annulus, carrying residual drilling fluid and cuttings to the surface at each well end.

Development began by flushing from the entry to the exit end of the well assembly. Approximately 5,600 gallons of water, treated with a breaker enzyme, were flushed through the well to remove mud, fines, and turbid water from the well interior. The enzyme accelerates the breakdown of the biodegradable polymer drilling fluid used to drill and ream the bore. This water issued from the exit end of the well as well as from the bore annulus. Water was captured at the exit and pumped to the containment tanks.

The exit end of the well was then capped to force all water out through the slotted sections. This water returned to both the exit and entry ends of the well (note, water flow along the central section of the bore was blocked by the previously-placed grout, as planned.) No grout was noted in the return water at either end, indicating that grout had not entered the screened zones. This effort was completed using approximately 2,400 gallons of enzyme-treated water. Of this total volume (8,000 gallons), approximately 4,200 gallons were recovered and conveyed to the mud recycler, the remainder entered the formation or remained in the well.

Following the flushing effort, DTD attached a custom-fabricated jetting tool to the string of drill rods. The jetting tool was equipped with centralizers to center it in the well screen, and multiple jets on an enlarged center section to reduce the distance from the jets to the screen slots (**Figure 23**). This was done to maximize the water jet impingement on the screen slots for more effective cleaning.

A total of four jetting passes was made through each of the screened sections, with two passes completed through the blank section. Approximately 3,800 gallons of water was used in jetting, with approximately 3,200 gallons recovered, primarily from the exit side of the well.

The final well development step was to insert a submersible pump at the exit side (**Figure 23**). The 3-phase, 400 gallons per minute (gpm) capacity pump was set to a location within the riser pipe, approximately 3 ft short of the screen (to avoid sucking sand directly through the screen). The high capacity pump removed approximately 2,400 gallons of water within a few minutes. Following this initial drawdown of the accumulated water in the well, the flow rate slowed to 16 gpm. Water was initially cloudy with light red-brown coloration, then cleared to moderately turbid, with translucent grey color. During development, water samples were collected in clear bottles. A trace of silty very fine sand sediment was noted in the recovered water at pump startup, clearing to no visible particulates in subsequent samples.

Figure 23. Well Development
Jetting tool attached to drill rods (left). Submersible pump used during final step of well development (right).

Following the initial pump startup, the well was drawn down and allowed to recover in several cycles. A summary of the field observations are provided below.

- Allowed well to recover for 10 minutes, then restarted pump. Pump required approximately 2 minutes to return water to discharge point at 16 gpm. Pumped for 10 minutes, then stopped pumping.
- Allowed well to recover 10 minutes, then restarted pump. Again, required 2-minute wait for water return, and pumped for 10 minutes at 11 gpm. Water was visibly less turbid, with no residual drilling mud or viscosity.
- Allowed to recover 10 minutes, pumped again for 10 minutes at 15 gpm. Pump cavitating. Turbidity same as last sample.

During this cycled phase, a total of approximately 800 gallons of water was recovered, in addition to the previous 2,400, for a total of approximately 3,290 gallons of water measured in the recovery tank. At this point, well development was determined to be complete.

5.4.6 Media Placement

After well development was complete, the pre-constructed media cartridges were lifted into position, bolted together, and pushed into place with the drill rig (see **Figure 24**). The entry-side cartridges were first inserted. Installation included bolting the cartridge flanges together, sandwiching a rubber annular seal between the flanges. A wire cage containing bentonite chips was then fastened over two of the flange joints to provide additional annular sealing between the cartridge assembly and the containing walls of the well. When hydrated, the bentonite chips swell and create a hydraulic seal.

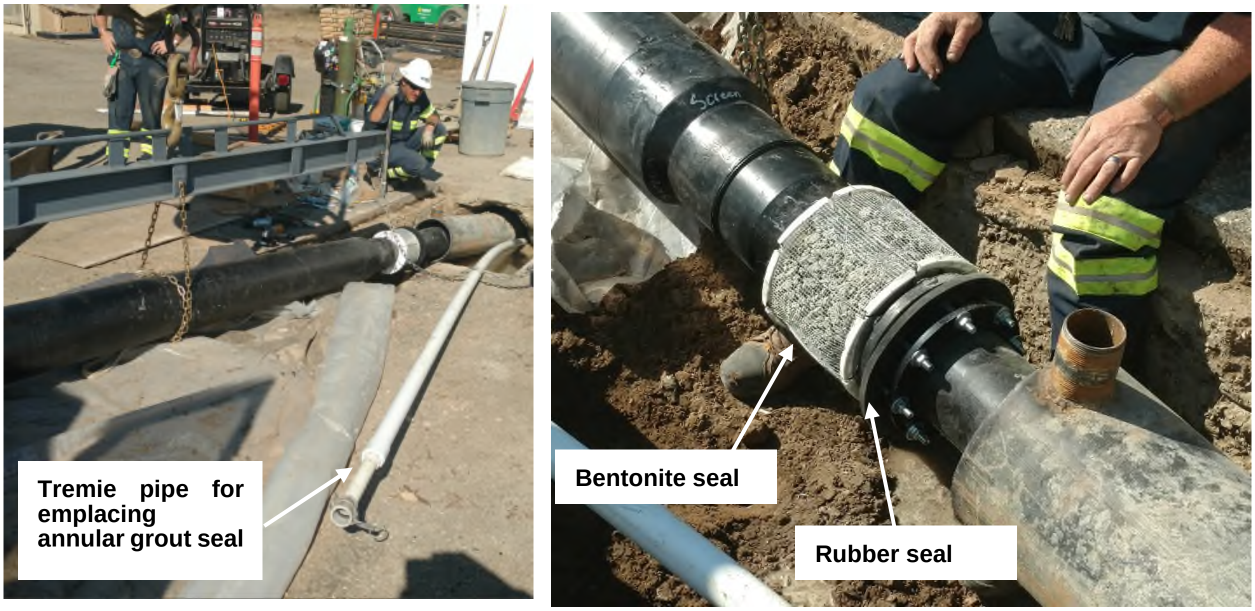

Figure 24. Treatment Media Cartridge Installation
Treatment media cartridges being pushed into the HRX Well on the entry/west side (left). Expanding bentonite seal prior to hydration and rubber seal that prevent bypass of untreated groundwater within the HRX Well (right).

Once the media was in place, the PVP monitoring cartridges were connected to their control cables and water tubing (**Figure 25**). The PVPs and attached tubing were bled with deionized water and a peristaltic pump prior to installation. The PVP control loom was then shielded inside polyvinyl chloride (PVC) pipe for the placement in the well. A custom-fabricated pushing tool was used to push the monitoring cartridges into place using the drill rig. Media and instrumentation placement were completed on August 8 (entry side) and August 9, 2018 (exit side).

Figure 25. Monitoring Cartridge Installation
PVP monitoring cartridge being pushed into the HRX Well on the exit (east) side.

5.4.7 *Wellhead Completion*

The entry and exit pits were backfilled with soil and compacted. At the entry end, saw cutting of the pavement was completed to provide a neat appearance to the site. At the exit side, lumber was used to form up a rectangular, elevated well pad. Redi-mix concrete was brought in to finish both wellheads, which were trowel-finished. A photograph of the entry-site well completion is shown in **Figure 26.**

Figure 26. Wellhead Completion
Entry (west) side well completion for the HRX Well.

5.4.8 Waste Management

Waste generated during installation of the HRX Well included general site waste (non-hazardous expendables, used personal protective equipment, etc.), solid drill cuttings, and liquid wastes from drilling and well development. The amounts of solid and liquid wastes generated during this project are summarized in **Table 5**.

Table 5. Summary of Wastes Generated During HRX Well Installation Compared to a Hypothetical PRB System

Waste stream	HRX Well (actual quantities generated)	Hypothetical PRB (estimated quantities for 50 foot long PRB trench)
Solids	50 tons	225 tons
Liquids (drilling & well development)	23,000 gallons	0 gallons

The waste drilling solids were generated during all directional drilling activities. This waste stream came directly from the mud recycling system and was transferred to lined roll-offs. Upon completion of drilling activities, the recycling system was cleaned and decontaminated. This mixture of solid and liquid waste was also placed into the lined roll-offs.

A portion of the liquid fraction that accumulated with the solids was pumped to a 21,000 gallon storage tank. The remainder of the liquids in the roll-offs were solidified prior to the transportation of the solid waste offsite for proper disposal.

In addition to the liquid fraction transferred from the solid waste roll-offs, liquid wastes were also generated during well development as described above in Section 5.4.5. Liquids were vacuumed from the storage tank into a vacuum truck and then transported off-site for proper disposal. This required multiple trips. Once the 21,000 gallon tank was emptied, cleaning of the tank generated additional liquid waste.

5.5 Field Testing

HRX Well field testing occurred approximately quarterly for a period of one year following installation of the HRX Well. Once installed, the HRX Well requires no above-ground treatment and limited ongoing maintenance. Other than the performance monitoring and testing discussed in Section 5.6, no recurring maintenance occurred the first year following installation. This ESTCP project has concluded and the Air Force has verbally agreed that the HRX Well will remain at the Site to provide continued contaminant mass discharge reduction at SS003, with written authorization pending regulatory approval of the forthcoming remedial action work plan for SS003. The actual schedule for the HRX Well installation and field testing is provided in **Figure 27**.

Task	**2018**				**2019**			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
HRX Well Installation			▨					
Start-up				▨				
Monitoring				▨	▨	▨	▨	▨

Figure 27. Completed Project Schedule

When the HRX Well needs to be decommissioned at the end of its lifecycle (anticipated to be at least 10 to 30 years based on the materials used and the 1,000 pore volumes flushed through the ZVI in the treatability testing), the well can be abandoned using conventional methods for horizontal well decommissioning. The estimated lifecycle is based on expected longevity of the treatment media and the well materials. It is not anticipated that the treatment media will need to be replaced during this 10 to 30 year time period, based on treatability testing results indicating mineral buildup and clogging did not occur on the ZVI treatment media after more than 1,000 pore volumes were passed through the test columns. In addition, the HDPE cartridges and steel well materials are expected to last for decades. The depleted cartridges would either be pushed from the well by extending drill rods downhole or pulled from the well using a cable attached to the cartridges. The cartridges would be detached from the emerging cartridge string and conveyed to an appropriate waste disposal site. A tremie tube would then be extended into the well, and an approved cement/bentonite grout slurry would be pumped in until grout is observed at both ends of the well. After a short duration to allow settlement to occur (typically overnight) the well would be topped off with grout. Optionally, the well ends could be cut back and buried, and the vaults removed, or the well ends and vaults may remain. While the abovementioned abandonment methodology represents the current state of the practice for horizontal well abandonment, if the state of the practice adapts with future optimization, the actual HRX Well abandonment procedure may be modified from this description.

5.6 Sampling Methods and Results

A sampling plan was developed to quantify the HRX Well performance and evaluate achievement of performance objectives during this field demonstration. Baseline characterization activities were completed prior to HRX well installation to support both the final design and performance assessment as summarized above in Section 5.2. Following installation, data were collected periodically over a 561-day period to validate the performance of the HRX Well. These activities included methods to measure the actual HRX Well capture and treatment widths and hydraulic performance, determine reactive media treatment efficiency, and measure contaminant mass discharge reduction.

A description of the testing that was performed during each phase of the project is provided in the following sections. A summary of the number and type of samples collected during the performance monitoring phase of the project is provided in **Table 6**. The analytical methods are summarized in **Table 7**.

Table 6. Total Number and Types of Samples Collected

Component	Matrix	Number of Samples	Analysis	Location
Pre-Demonstration Sampling (August 2017-July 2018)	Soil	2	Grain size distribution	3-MW-47 3-MW-48
	Groundwater	8 (includes 1 duplicate)	Volatile organic compounds (VOCs)	3-MW-13 3-MW-14 3-MW-35D 3-MW-47 3-MW-48
	Carbon sorbent	3	VOCs	3-MW-13 3-MW-35D 3-MW-48
Post-Installation Technology performance sampling (August 2018-October 2019	Groundwater	VOCs: 37 (includes 6 duplicates) TOC: 9	VOCs TOC	3-MW-13 3-MW-14 3-MW-35D 3-MW-47 3-MW-48 HRX Well Inlet HRX Well Outlet

Table 7. Analytical Methods

Matrix	Analysis	Method	Container	Preservative	Holding Time
Soil	Grain size	ASTM Test Method D421	1 L glass jar	None	28 days
Groundwater	VOCs	EPA 8260	40 mL glass	HCL	14 days
Groundwater	TOC	USEPA Method 5310B	250-mL plastic	HCL	28 days
Carbon sorbent	VOCs	PFM (enviroflux.com)	PFM	None	14 days

Monitoring wells were sampled using no-purge (using HydraSleeves™), low flow, or hand bailing techniques as summarized in **Table 8** below. Groundwater sampling methods for site monitoring wells were selected consistent with the State regulatory agency approved decision-making logic used for the VAFB basewide groundwater monitoring program. Low-flow groundwater samples were also collected directly from both the up- and down-gradient screened sections of the HRX Well using down-hole tubing and a peristaltic pump.

Table 8. Summary of Groundwater Sampling Methods

Monitoring Well	Screen Interval (feet bgs)	Sampling Method
3-MW-13	16.5-26.5	No purge
3-MW-14	14-24	No purge
3-MW-35D	14-24	Low flow
3-MW-47	16.5-26.5	Low flow or hand bailed when short water column and slow recharge
3-MW-48	17.5-27.5	No purge
HRX inlet screen	15-21	Low flow
HRX outlet screen	18-20	Low flow

Field water quality parameters were measured using a multimeter calibrated according to the manufacturer's specifications immediately prior to groundwater sampling. Samples were poured directly from the no-purge device into the water quality meter. Water quality parameters were measured immediately prior to groundwater sampling and are summarized in **Appendix D**.

Groundwater samples were collected in laboratory-cleaned glassware, stored on ice, and delivered under chain of custody procedure to EMAX Laboratories, Inc. of Torrance, California, an Air Force Civil Engineer Center and DoD Environmental Laboratory Accreditation Program approved laboratory. The groundwater samples were analyzed for VOCs by United States Environmental

Protection Agency (USEPA) Method 8260B. A subset of the samples were analyzed for total organic carbon (TOC) by USEPA Method 5310B. The laboratory analytical results are summarized in **Appendices E and F**.

5.6.1 Baseline Characterization

Baseline characterization activities were completed prior to HRX Well installation to support both the final design and performance assessment as summarized in Section 5.2.

5.6.2 HRX Well Performance Monitoring

Following installation, various types of data were collected for approximately a 561-day period to validate the performance of the HRX Well. These activities included methods to measure HRX Well capture width and hydraulic performance, determine reactive media treatment efficiency, and measure contaminant mass discharge reduction.

5.6.2.1 Post-Installation Groundwater Monitoring

Groundwater samples and field measurements were collected quarterly over the performance monitoring period after the HRX Well became operational in August 2018. Groundwater level measurements were recorded prior to sampling. Groundwater elevations were then calculated and used for contouring to measure the HRX Well capture width. The pre- and post-HRX well installation groundwater elevations are summarized in **Appendix C** and below on **Figure 28**. Note that water level elevation for 3-MW-47 was consistently more than a foot lower than all other nearby wells and a review of the boing and well construction logs suggest the Principal Zone aquifer is less defined at this location. Therefore, data from this well were not used to interpret groundwater elevations. After installation, the local hydraulic gradient increased significantly near the HRX Well outlet. The interpreted flow field is consistent with expectations and shows the effects of treated groundwater discharging from the HRX Well outlet.

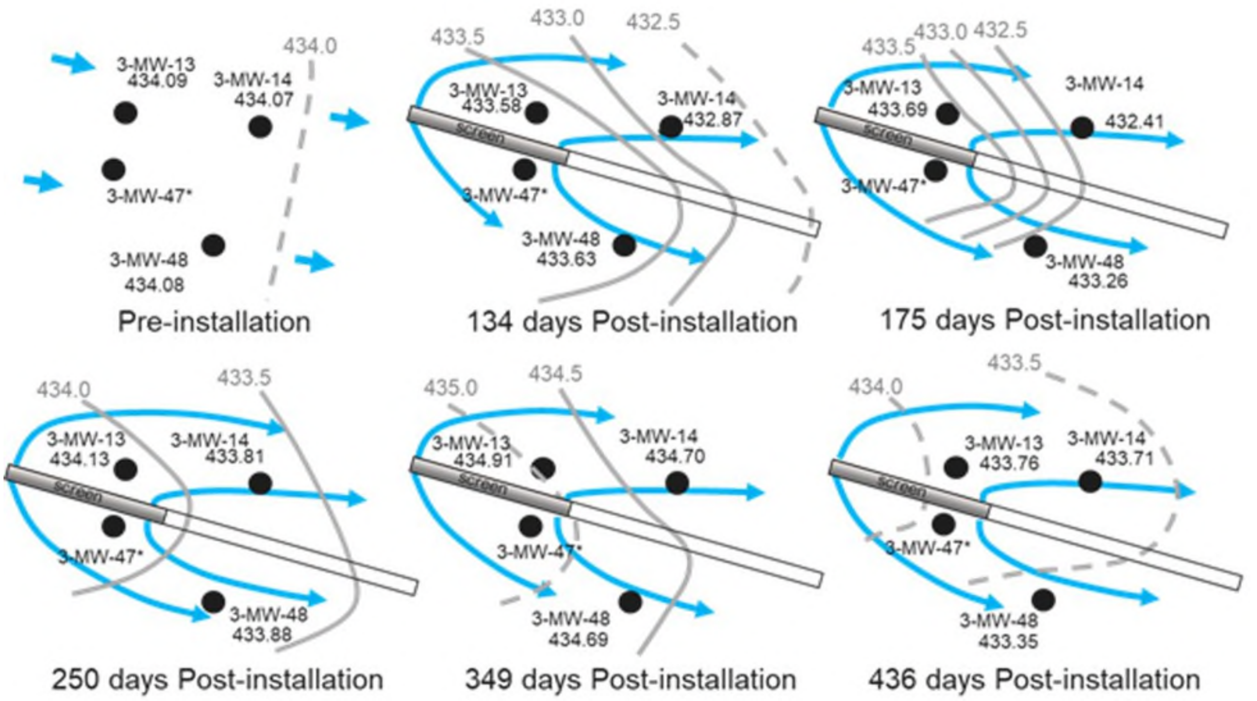

Figure 28. Groundwater Elevations and Interpreted Groundwater Flow Field at HRX Well Outlet

As discussed in significant detail in Section 6.1, groundwater concentration data show greater than 99.9% reduction in TCE concentration between the inlet and outlet of the HRX Well treatment media (see **Table 14**). The observed TCE concentration changes at downgradient groundwater monitoring wells ranged from 50 to 74% (see **Table 9**) and indicate breakthrough of treated water at approximately 50 to 200 days, consistent with expected arrival of treated water in the downgradient flushing zone (see Section 5.6.2.7 and **Table 12**). In addition, the TOC results confirm significant levels of residual biopolymer drilling fluid were present during the performance period (see **Table 14** and **Figure 29**) and served as a carbon source and electron donor, ultimately promoting biologically-mediated transformation processes. This is expected to be a short-term process relative to the expected 30-year lifecycle of the HRX Well, as discussed further in Section 6.2, it is estimated that roughly 76% of the total treatment (from 3-MW-35D to the HRX Well Outlet) is attributable to biological process and 24% to abiotic transformation by the ZVI. It is anticipated that the relative contribution of biodegradation will decrease over time as the degradable carbon is fully consumed and aquifer conditions return to more aerobic conditions.

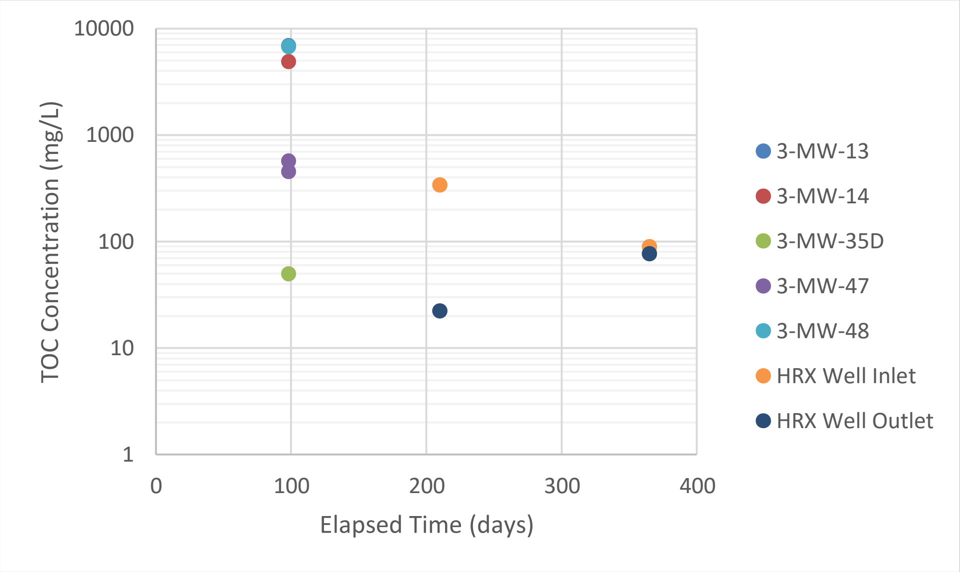

Figure 29. TOC Concentrations Versus Elapsed Time Since HRX Well Installation

Table 9. TCE Concentration Changes at Downgradient Monitoring Wells within Flushing Zone

Well ID	Baseline TCE (µg/L)	First Post-Installation Sampling Event (92 Days) (µg/L)	Final Sampling Event 436 Days (µg/L)	Change From Baseline to Final
3-MW-13	6,900 (7/10/2018)	3,800	1,800	-74%
3-MW-47	11,000 (10/2/2017)	8,600	4,500	-59%
3-MW-14	30,000 (10/2/2017)	10,000	9,500	-68%
3-MW-48	4,200 (11/30/2017)	4,200	2,100	-50%

5.6.2.2 *Flow Velocity in the HRX Well Measured by PVP Testing*

To directly measure flow velocity within the HRX Well treatment media, a custom designed PVP (Devlin et al. 2009) suitable for use in a ZVI medium was previously developed and tested as part of Tasks 2B and 2C (see the Treatability Test Report; Divine et al. 2017a, for further details on the design and testing protocol for these PVPs). The final as-build HRX Well design included PVPs installed in sand-filled cartridges on the inlet and outlet sides of the treatment media to measure seepage velocities inside the well (see **Figures 14 and 19**).

Point Velocity Probe tests were completed by connecting an air-free line attached to a 5 mL syringe filled with distilled water. The injection lines comprised 200 ft of stainless steel running from the probes to the surface. The last 20 ft of the line was constructed from polyethylene tubing because the installation of the cartridges positioned them further into the HRX Well than originally planned. The polyethylene tubing terminated at the Swagelok valve, which was attached to a short length of flexible, clear, PVC tubing suitable for attaching to a syringe tip. After the injection was complete, the Swagelok valve on the injection line was closed and a plastic pinch clamp was closed on the flexible end of the tracer injection line. Tests were initiated by injecting predetermined volumes of tracer into the injection lines, recording the time of the start of injection, and the duration of the injection phase. Injection volumes ranged from 0.5 to 5 mL, with the larger volume reserved for clearing the injection lines when needed. Injection times were generally less than 60 seconds.

The leads from the detectors on the PVPs were connected to a Campbell Scientific CR1000 datalogger equipped with a half-bridge circuit, as described in Devlin et al. (2009). This circuit registers the occurrence of distilled water (or any water more dilute in salt than the ambient groundwater) as an increasing millivolt (mV) signal, which is recorded on the datalogger. Typically, at least 30 minutes of background signals from the detectors were collected before injecting any tracer, to establish that the system was stable and recording data properly. The system was then permitted to collect data for up to several hours after tracer injection (15 to 180 minutes was generally found to be sufficient, depending on the actual velocities on the testing day) to collect a full breakthrough curve of the tracer at the PVP detectors. The data were downloaded to computers daily as a precaution against data loss. The breakthrough curves were imported into the Excel software VelProbePE (Schillig 2012) and fit with a solution to the advection-dispersion equation. Example PVP tracer curves and fitted models are shown in **Figure 30**. A photograph of the tracer injection line, data logger, battery and HRX Well outlet wellhead completion is provided in **Figure 31.**

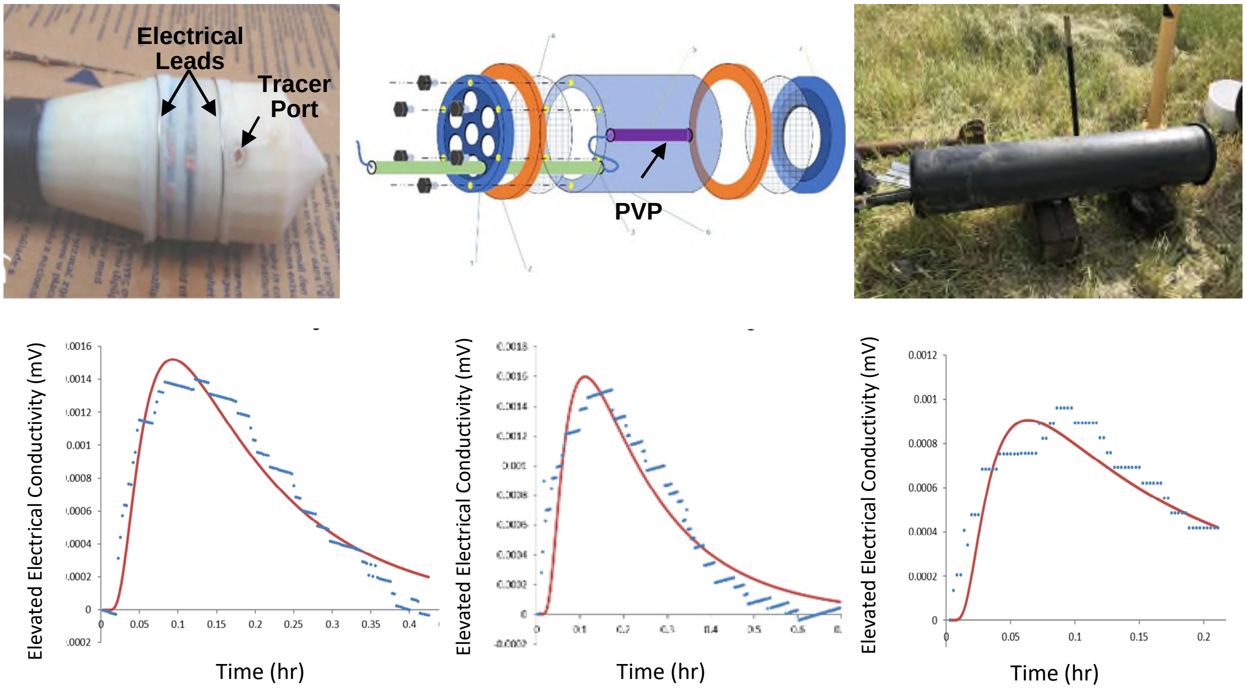

Figure 30. Redesigned PVP and Example PVP Data

Top Left: Redesigned PVP; top Center: Conceptual schematic of PVP installed in monitoring cartridge (note PVP was installed slightly off-center, in alignment casing indicated by the green cylinder); Top Right; Photograph of PVP monitoring cartridge during HRX Well installation; Bottom: example PVP data example PVP tracer curves (blue series) and fitted models (red lines).

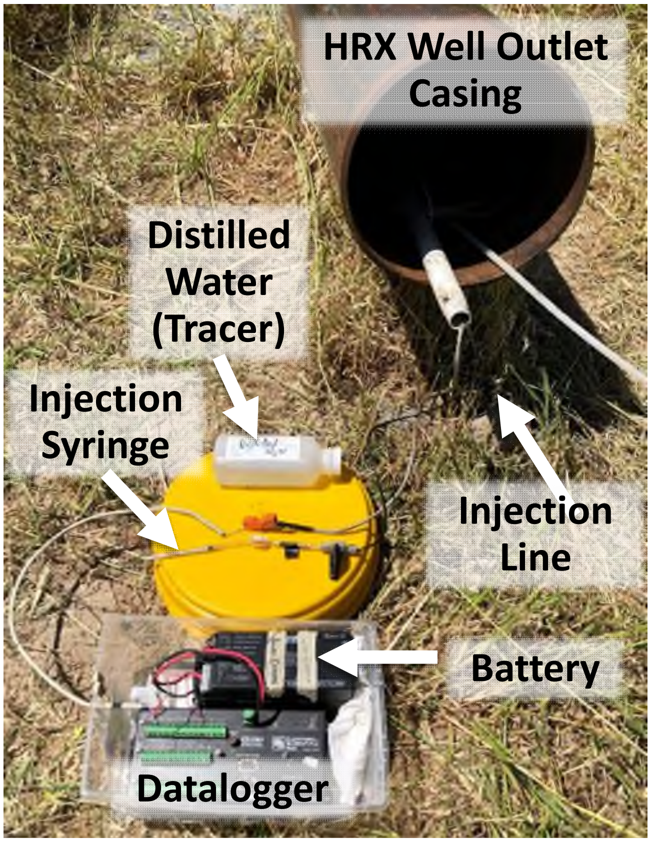

Figure 31. PVP Data Collection
Photograph of tracer injection line, data logger, battery and HRX Well Outlet wellhead Completion

During initial testing (completed December 10 to 12, 2018), it was noted that the upgradient PVP tracer line became pressurized during tracer injections. To a lesser extent, this was also true of the downgradient tracer lines. It was hypothesized that this pressure was a result of pressure or pinching of the injection line, which was later confirmed when the PVP cartridges were removed and retrofitted with an improved seal system. This observation may be important for the interpretation of the PVP signals. Normally, tracer injections were completed in time periods much less than those required for the gathering of complete breakthrough curves. Injections lasting 0.5 to 1 minute were typical and would mark the beginning of tests that last 0.5 hours or more. The pressurization of the tracer lines in the tests may have resulted in the effective tracer injection durations that were much longer than normal in duration; they continued while the lines depressurized. These depressurization times are not known exactly; however, the lines did not retain pressurization between tests, but became re-pressurized after an injection. Thus, the model used to estimate the velocity values, which assumes an instantaneously established tracer pulse centered on the injection port, may not precisely represent the boundary conditions in all tests with high accuracy, introducing uncertainty to the velocity estimates. Pulse widths estimated with VelProbePE that exceed 1 centimeter are suggestive of extended tracer injection times due to line depressurization. In order to assess this possible source of error, the data were fitted to the VelProbePE model 1) forcing the pulse size to be small, in agreement with the intended functioning of the PVP system, and 2) forcing the pulse size to be larger, more closely mimicking an extended time tracer release. In this test, which represents the most reliable results obtained in the 3-day program, the estimated velocity was found to be insensitive to the pulse size.

In general, most tests completed throughout the demonstration period produced interpretable signals. In some tests, the baseline exhibited trending and is hypothesized to be due in part to temperature fluctuations on the surface that may have affected the half-bridge circuitry. A potentiostat was used in the circuit, rather than a fixed resistor, and may have been affected by the warming and cooling cycles of the day. The potentiostat affords the flexibility to adjust the circuit to handle tests in groundwaters over a wide range of total dissolved solids. However, fixed resistors are expected to be less susceptible to temperature variations. The observed variations in baseline did not generally affect data interpretation; however, to minimize potential temperature-driven baseline variations, the testing equipment was kept in the shade.

A summary of PVP testing results is provided in **Table 10**. The average estimated flow velocity for the first testing event, 131 days after HRX Well installation, was 0.94 ft/day. While this value is notably higher than the ambient aquifer groundwater velocity (~0.1 ft/day) and indicated flow-focusing within the HRX Well, it is lower than the design model prediction of 7.6 ft/day. After careful review of the as-built details, it was recognized that, because the monitoring cartridges did not have rubber gasket or bentonite seals (like the treatment media cartridges did) and were not physically connected to the treatment media cartridges, groundwater could be short-circuiting in the void space between the inner well casing wall and the outside of the monitoring cartridge, before flowing into the treatment media cartridges (no short circuiting around the treatment media cartridges is possible because of the multiple bentonite seals installed with the treatment media cartridges). Calculations using the cubic law (which describes flow in fractures) suggested that more than half of the water flowing through the HRX Well was likely bypassing the monitoring cartridge before entering the treatment cartridge. The disparity between the model predictions and PVP results were instrumental in highlighting the monitoring cartridge design flaw. Therefore, the first set of PVP tests (131 days after HRX Well installation) are likely biased significantly low and not used for subsequent analyses.

To remedy this, both monitoring cartridges were removed, retrofitted with flange seals to prevent bypass flow (see **Figure 32**) and replaced. Unfortunately, the inlet-side PVP was damaged during monitoring cartridge re-installation and no longer produced usable tracer data; therefore, subsequent testing was limited to the outlet PVP. The average estimated flow velocities for the second (259 days), third (349 days), and fourth (561 days) PVP testing events were 9.6, 4.2, and 13 ft/day. In general, individual test results for a given testing event were consistent, with relative percent difference values ranging from 8.7 to 20%, with an average of 16%. These velocity values bracket the model prediction of 7.6 ft/day. The differences in velocities between the testing events completed after the cartridges were retrofitted with seals may partially be explained by the variations in the aquifer hydraulic gradient between the events (**Figure 33**). Based on the casing diameter (9.4 inches) and media porosity (estimated at 0.38), the estimated HRX Well flows were about 1.7, 0.9, and 2.4 ft^3/day on days 259, 349, and 561 respectively. HRX Well flows will vary as regional aquifer flows and gradients vary; however, because i_A and i_{HRX} are functionally related, HRX Well capture/treatment width is expected to be relatively insensitive to changes in the aquifer flow rates and i_A . However, the variability of these flow values is greater than the variability in observed i_A values. Using the aquifer hydraulic gradients measured at these times and rearranging **Equation 2**, the HRX Well capture and treatment widths calculated from the in-well flows measured during from PVP tests and coincident i_A values are approximately 66, 39, and 103 ft, respectively. While these values bracket the specific model predictions (52 ft) they are quite variable and suggest more transient hydraulic conditions were present than expected. In general, compared to other testing methods, PVP data identify possible short-term variations in the flow that represent maximum and minimum stresses on the treatment media.

Table 10. Summary of PVP Results

	Before Seal Installation	**After Seal Installation**		
Testing Date	December 10-12, 2018	April 17-18, 2019	July 16-17, 2019	Feb. 13, 2020
Days after HRX Well Installation	131-133	259-260	349-350	561
Inlet PVP	0.92	PVP damaged	PVP damaged	PVP damaged
	0.72			
	0.82			
Outlet PVP	1.31	9.26	4.17	18
	0.92	8.59	4.92	9.1-13
	0.95	10.46	3.60	15
	0.95	10.05		13
	0.94			16
Average	**0.94**	**9.59**	**4.23**	**13**
Relative Standard Deviation (RSD)	18%	8.7%	16%	20%

Note: Results presented in units of ft/day.

Figure 32. Photograph of Retrofitted Flange Seal on Monitoring Cartridge

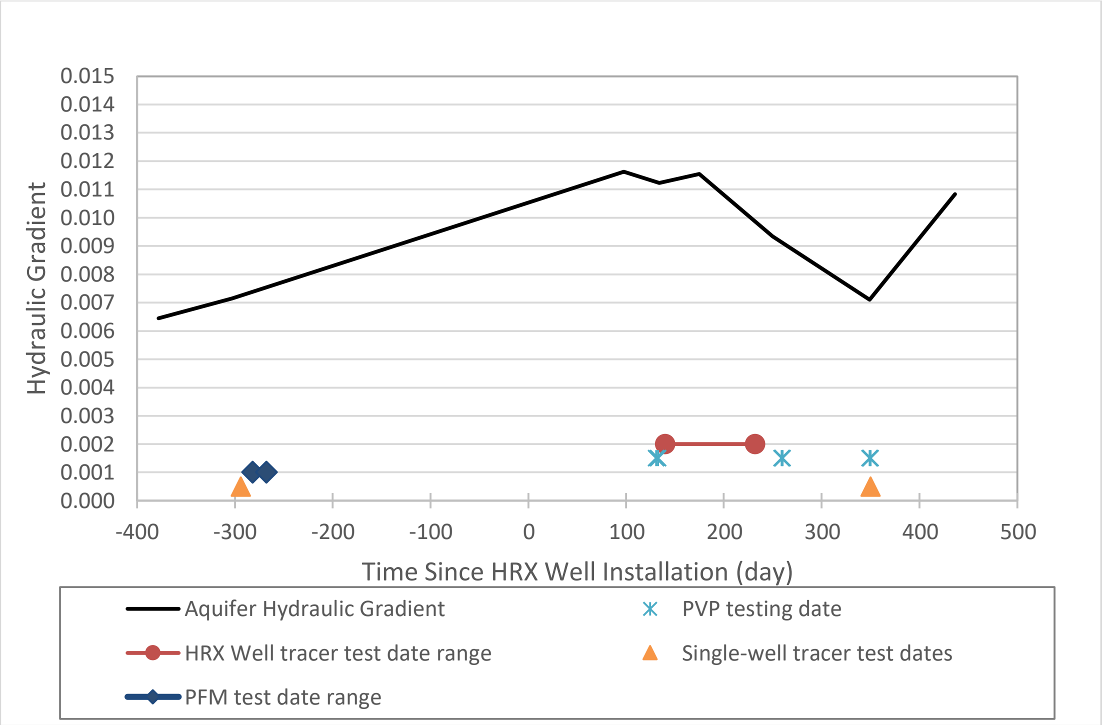

Figure 33. Aquifer Hydraulic Gradient Over Time
Shown by t (time = 0 is the date the HRX Well installation was completed; August 1, 2018). The timing of PVP, HRX Well tracer testing, single-well tracer testing, and PFM testing are also indicated at the bottom of the graph.

5.6.2.3 Flow Through the HRX Well Measured by Tracer Testing

A tracer test was initiated within the HRX Well using distilled water (which has a low specific conductance) approximately 140 days following the installation of the HRX Well as an additional method to measure residence time within the HRX Well. To support the design of this test, a model was previously completed which simulated the transport of a conservative tracer through the HRX Well (see project Demonstration Plan; Divine et al. 2018c). The purpose of this simulation was to establish a realistic tracer application rate and sampling frequency. The simulation included modeling the injection of a conservative tracer at the beginning of the treatment media and monitoring the breakthrough of the tracer at the end of the treatment media. For the test simulation, a total injection volume of 25 gallons of tracer (approximately 2% of the well volume) was injected into the HRX Well inlet screen section over 24 hours, which is equivalent to an injection rate of 1 gallon per hour (which, based on modeling, was not expected to significantly interfere with the flow rate within HRX Well treatment media). Based on the HRX Well design at the time of the design simulation, the model simulation indicated that the tracer would travel through the ZVI reactive media in 6 days, the PVP monitoring cartridges in about 1 day, and through the open cased section in about 65 days, for a total travel HRX Well time of 72 days. This equated to expected flow velocity values in the treatment media and PVP cartridges (diameter = 9.4 in, porosity = 0.38) and open section (diameter = 12 in, porosity = 1.00) of approximately 7.6 and 0.81 ft/day, respectively. Based on the design model, the tracer was expected to be detectable at the HRX Well outlet for about 2 to 3 days.

On December 18, 2019, a total injection volume of 40 gallons of distilled water tracer was injected into the HRX Well inlet screen section over 25 hours, which is equivalent to an injection rate of 1.6 gallon per hour. Tracer breakthrough was monitored by measuring relative electrical resistivity using the PVP installed at the downgradient at monitoring cartridge, immediately adjacent to the HRX Well outlet screen. As shown in **Figure 34**, relative resistivity was stable until approximately 80 days, when high relative resistivity increased notably (as expected because distilled water is more electrically resistive than native groundwater) for approximately 5 days and then it returned to baseline conditions. This longer arrival window is consistent with the 60% increase in total tracer volume injected compared to the design and is consistent with the results of a simple one-dimensional analytical transport model (Ogata and Banks, 1961) fit to the data (shown as the black line in **Figure 34**). The model assumed the relative resistivity of the distilled water tracer was approximately 1 and the background relative resistivity of groundwater was about 0.22. The fitted average velocity across the entire HRX Well was 1.6 ft/day with a fitted dispersivity of 0.4 ft.

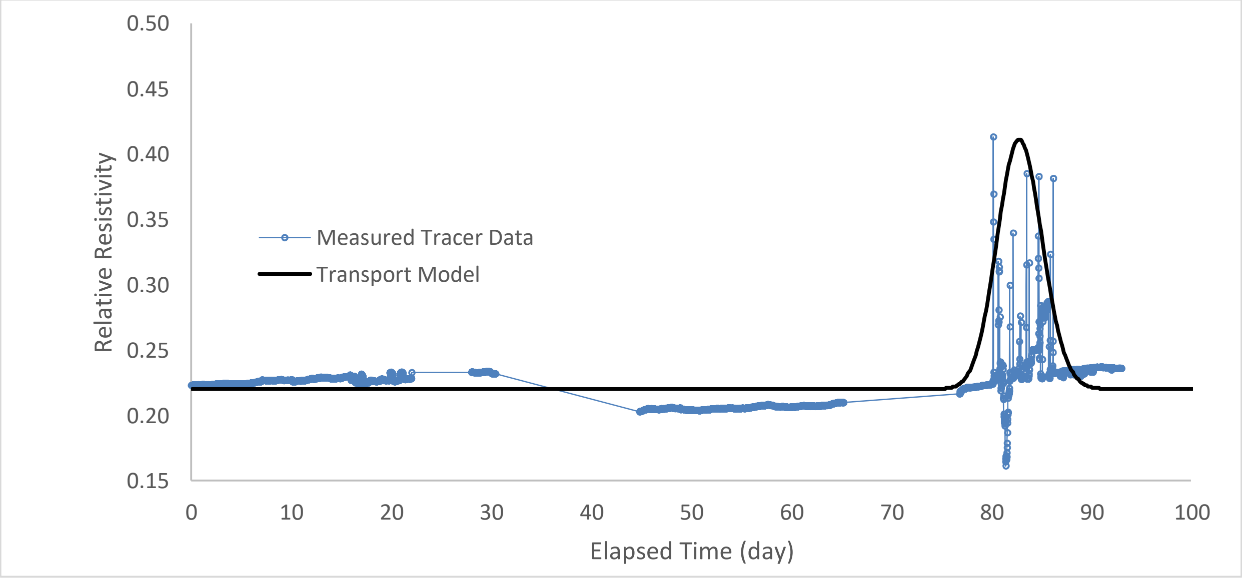

Figure 34. **HRX Well Tracer Test Breakthrough Curve**
Measured tracer data are shown in blue and the transport model is shown in black.

Based on final as-built dimensions of the HRX Well, the estimated average flow velocity values in the treatment media and open sections are calculated to approximately 7.3 and 0.74 ft/day, respectively. This results in an average flow rate during the testing period of about 1.3 ft^3/day. Using the aquifer hydraulic gradients measured at the beginning and end of the test and rearranging **Equation 2**, the estimated HRX Well capture/treatment width during the testing period was approximately 45 ft, which is consistent with the design objectives (40 to 50 ft) and agrees within about 13% of the model prediction for average capture width (52 ft). Overall, the tracer breakthrough and duration were highly consistent with model predictions and the flow velocities in the treatment media measured by the PVP testing.

5.6.2.4 Changes in Groundwater Flux Near the HRX Well Measured by Single Well Tracer Testing

As a part of the pre-design data collection activities, several different methods were employed to estimate groundwater flux in the vicinity of the planned HRX Well. In particular, SWTT and PFMs were used to measure flux at three monitoring wells (3-MW-13, 3-MW-35D, and 3-MW-48), while HPT borings and grain size analyses were used to estimate hydraulic conductivity. The hydraulic conductivity estimates were converted to equivalent Darcy flux by applying the site-specific hydraulic gradient, to allow comparison of results from all four methods. The results of this work are presented in detail in Attachment 1 of the Demonstration Plan (Divine et al. 2018c). There was general agreement between the Darcy flux values provided by all four methods. Testing at different scales allowed for estimates of not only the average Darcy flux, but also the range of Darcy fluxes present within the Principal Zone. More weight was given to the magnitude of Darcy fluxes provided by SWTT and PFMs because these are direct measurement methods (i.e., they do not require calculations based on hydraulic gradient) and their effective measurement scale is larger than the grain size analyses and HPT. In generally, PFM results likely represent flux conditions over a longer period of time (weeks) than the SWTT results (hours). Regardless, both methods confirm ambient groundwater flux is relatively low, less than 0.1 ft/day.

Because the HRX well focuses groundwater, groundwater flux in the immediate vicinity of the inlet and outlet screens increases. In an attempt to confirm and measure this phenomenon, SWTTs were repeated at the same three wells approximately 350 days after the HRX Well was installed. Because the previous PFM estimates exhibited a large uncertainty range between the upper and lower bounds of the flux estimates for each well (41 to 103 relative percent difference; RPD), PFM testing was not repeated after HRX Well installation. Using the same methods previously employed, SWTTs were performed using a tracer consisting of distilled water which had a specific conductivity contrast with test well water. The well water was amended with the tracer solution and mixed to achieve a homogeneous well water column, then allowed to washout under ambient hydraulics. The observed tracer washout data was used to estimate well water flux with an analytical model (Drost et al. 1968; Hall 1993). The aquifer flux near the tested well was estimated by accounting for groundwater flow focusing associated with well construction.

The results of the SWTTs completed pre- and post-HRX Well installation at monitoring wells 3-MW-13, 3-MW-35D, and 3-MW-48 are shown in **Figure 35**. As shown in **Figure 35**, the ambient hydraulic gradient (and therefore regional aquifer flow rate) was approximately equivalent during pre-HRX Well SWTTs and post-HRX Well SWTTs. The data suggest a slight increase in tracer washout rate is detectable at all three wells as a result of in increases in local groundwater flux. The magnitude of the flux increases is a function the distance the monitoring well is from the inlet or outlet screens (as expected). As presented in **Table 11**, the observed increases in flux measured by SWTTs range from 8 to 30%, which are lower, but consistent with the numerical model predictions of 31 to 57%. Although the observed increase in flux values are subtle and likely near or within the uncertainty range of the SWTT method, they results are consistent with the expectation that the HRX Well is enhancing groundwater flux in the immediate vicinity of the inlet and outlet screens.

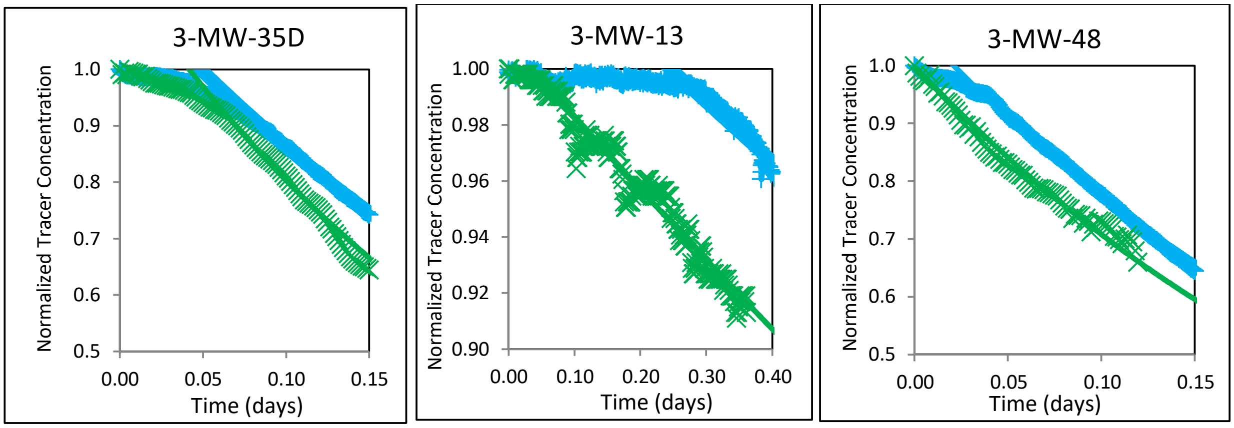

Figure 35. Single-well tracer test washout curves for monitoring wells 3-MW-35D, 3-MW-13, and 3-MW-48

Blue series represent pre-HRX Well installation test data (points) and model (solid line), green series represent post-installation test data (points) and model (solid line).

Table 11. Summary SWTT-Measured Groundwater Flux at Monitoring Wells

Well	Distance from HRX Well Inlet or Outlet (feet)	Pre-HRX Well SWTT-Measured Flux (ft/d)	Post-HRX Well SWTT-Measured Flux (ft/d)	Observed Increase	Model-Predicted Increase
3-MW-35D	48	0.053	0.069	30%	57%
3-MW-13	58	0.011	0.013	18%	39%
3-MW-48	108	0.080	0.086	8%	31%

5.6.2.5 Cartridge removal

As noted in **Section 5.6.2.2**, initial PVP test results indicated bypass flow likely resulted in biased-low results and therefore the monitoring cartridges (which contained the inlet and outlet side PVPs) were removed, retrofitted with a gasket seal (see **Figure 36**), and replaced April 8 to 9, 2019, 250 days after HRX Well completion. A small Vermeer 23 x 50 directional drilling rig was mobilized to the site and the monitoring cartridges were removed from the HRX Well. This was accomplished by attaching the pull cable on the cartridge to drill rig and then tracking the rig forward. The cartridges were removed without any apparent damage to the cartridge or the wire/cable loom attached to the PVP; however, the PVC shield pipe was broken on the inlet cartridge, just outside the cartridge body (this appeared to be prior damage that may have occurred during the original installation). After placing the cartridges on pallets, cartridge ends were retrofitted with rubber seals and HDPE clamping rings that had been prefabricated (see **Figure 36**). Immediately upon removal, it was noted that the cartridges were coated with a black film that gradually turned rusty-red after being exposed to the atmosphere. It is likely that the black film was a biogenic reduced iron sulfide that was precipitated as a result of the local reducing conditions caused by fermentation of residual biopolymer used in the drilling fluid. The drill rig was then used to push the monitoring cartridges back into place until they bumped the already in-place media cartridges and aligned with a previously placed index mark (see **Figure 36**). During reinstallation, the protective PVC pipe covering the PVP cable and tubing would periodically catch in the well (likely this was caused by the square-edged PVC couplers hanging up on weld seams). When this occurred, gentle manipulation was able to free it and allow installation to continue. The PVP wires and tubing were continually monitored to check for possible stretching, pinching, etc. and none was noted. After the cartridge was installed to depth, distilled water was injected through the PVP assembly as a check and indicated that the water supply line was neither pinched off or broken and the lines are intact. However, as noted in **Section 5.6.2.2**, subsequent data from the inlet PVP was unusable and indicated the instrument had been damaged during re-installation (it is hypothesized that the tracer injection line became disconnected from the PVP and that injected tracer no longer exits through the port on the PVP adjacent to the electrical leads). Overall, the cartridge removal and re-installation process was straightforward and suggests removal and replacement of exhausted treatment media cartridges and servicing of the monitoring cartridges can be readily accomplished. However, future HRX Wells will benefit from a more robust PVP pipe material and design.

Figure 36. Installation of monitoring cartridges retrofitted with rubber seals
Left: Exit-side monitoring cartridge after gasket seal retrofit. Right: pushing the exit-side monitoring cartridge into place during reinstallation.

5.6.2.6 ‘Active Configuration’ Pumping Test

The HRX Well installed at VAFB was designed to operate under a fully passive configuration, however, the HRX Well concept can be modified such that flows through the well (and therefore capture and treatment zone size) are enhanced through active pumping (“active configuration”). Although not originally planned for the demonstration, the HRX Well was temporarily modified to an active configuration when the monitoring cartridges were retrofitted to test and validate this operational mode. After the monitoring cartridges were removed on April 8, 2019, but before they were reinstalled, a packer was installed approximate 214 ft down the HRX Well, immediately past the inlet screen, but before the treatment media cartridges. Approximately 160 ft of intake poly tubing, secured 54 ft above the packer (to prevent well screen dewatering) was placed down the inlet site of the HRX Well and connected in-line to a high-capacity peristaltic pump and flow totalizer at the land surface. The discharge line from the flow totalizer was then placed back into the HRX Well with approximate 220 ft of PVC pipe, which was secured to the packer. **Figure 37** presents a schematic of the active configuration, showing the pump intake, pump, flowmeter, and packer components.

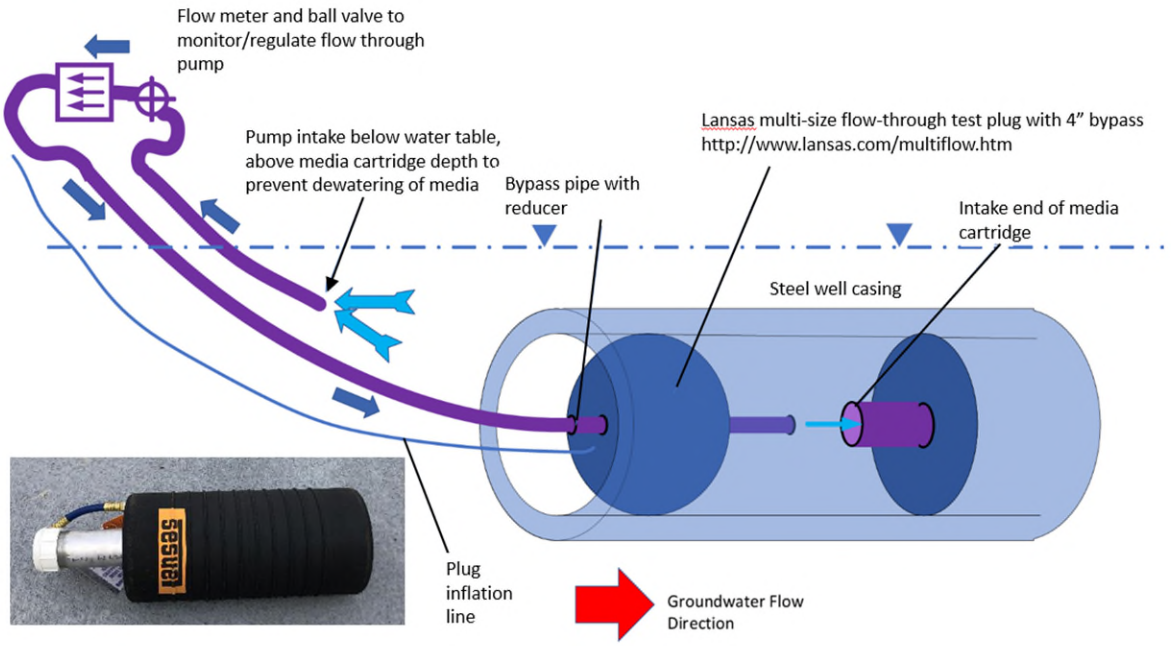

Figure 37. Schematic of the Active Configuration
Showing the pump intake, pump, flowmeter, and packer components. A photograph of the packer is shown in the lower left.

The pump was operated for approximately 20 hours, pumping a total of 266 gallons. Drawdown data obtained from pressure transducers installed in nearby wells are shown in **Figure 38**. These data were used to further calibrate the numerical model (further described **Appendix A**). This testing activity confirmed the general viability of the active configuration mode and, for the demonstration, the estimated maximum sustainable pumping rate based on aquifer yield was approximately 3 to 4 ft^3/day, two to three times the measured flow rate through the HRX Well under passive operation. Accordingly, simulations suggest that continual operation of the HRX Well under an active configuration would result in a capture and treatment zone width great of about 70 ft (**see Figure 5, Appendix A**).

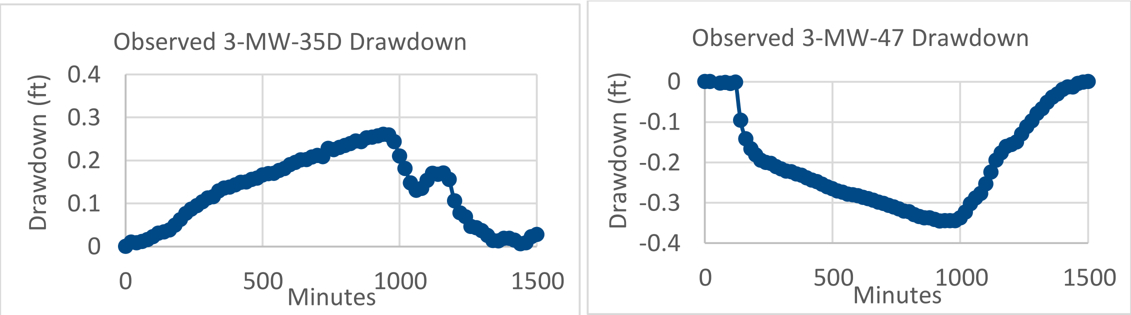

Figure 38. Observed Drawdown at Wells 3-MW-35D (left) and 3-MW-47 (right) During Pumping

Note that drawdown is defined as negative displacement.

5.6.2.7 Numerical groundwater flow model updates

To assist the preliminary HRX Well design phase at SS003 and to evaluate the field performance of HRX Well post installation, a 3-D groundwater flow model was developed based on site-specific data. The model was constructed using the United States Geologic Survey MODFLOW code (McDonald and Harbaugh 1988) to simulate the groundwater flow regime and the hydraulic capture of the HRX Well. MODPATH (Pollock 2016) were used in conjunction with MODFLOW to predict the groundwater flow paths towards the HRX Well. Details of the original design model are provided in the previous Demonstration Plan (Divine et al. 2018c). To support the HRX Well performance assessment, the model was updated to more accurately reflect as-built specifications of the HRX Well and was further calibrated based on the active configuration tested described earlier. Details of the updated model are presented in **Appendix A**.

To evaluate the performance of HRX Well, two scenarios were simulated representing both the passive and active configurations. The updated and recalibrated model predicts an HRX Well flow rate of 1.95 ft^3/day with a capture and treatment zone width of 52 ft and an average residence time within the ZVI treatment media of 9 days. The active configuration was simulated by designating extraction and injection flowrates and the entrance and exit screens. Based on the field testing, the pumping/injection rates were prescribed at 3.9 ft^3/day. The predicted capture width is approximately 70 ft with an average residence time within the treatment media of 5.5 days. Model results for these two scenarios are shown in **Figure 39**.

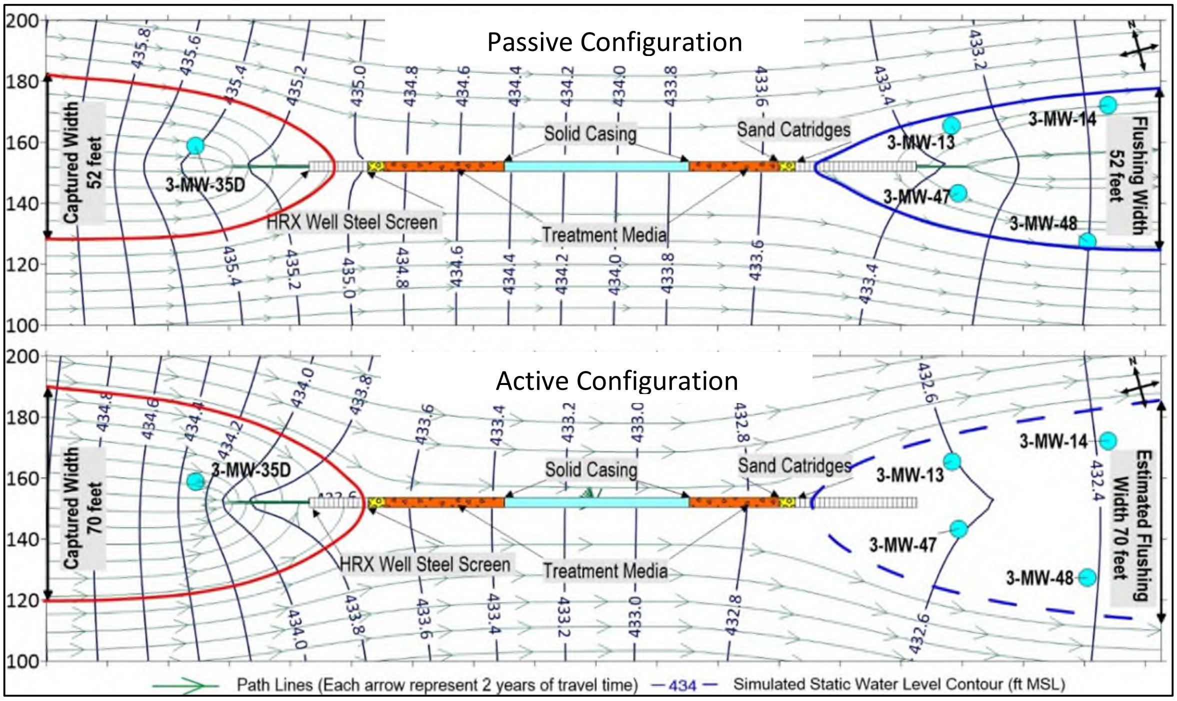

Figure 39. Updated Model Results Showing Predicted HRX Well Capture and Treatment Zones for Passive (top) and Active (bottom) Configurations

After the HRX Well installation, the observed changes in TCE and cis-1,2-DCE concentrations over time at downgradient wells (3-MW-47, 3-MW-48, 3-MW-13, and 3-MW-14) indicate that the first breakthrough of treated water ranges from approximately 50 days to 200 days at these wells. Path line analysis was performed with the model to predict the breakthrough times for these wells for comparison. As summarized in **Table 12,** estimated travel times, assuming effective (or mobile) porosity values of 1%, 5%, and 10%, are presented. The model-simulated breakthrough times for effective porosity values of 1 to 5% are generally consistent with the range of the observed breakthrough times for most wells.

Table 12. Summary of Observed and Model-Simulated First Breakthrough of HRX Well-Treated Water to Downgradient Monitoring Wells

Monitoring Well	Observed Breakthrough Time (days)		Simulated Breakthrough Time (days)		
	Observed Breakthrough (TCE)	Observed Breakthrough (cis-DCE)	10% Effective Porosity	5% Effective Porosity	1% Effective Porosity
MW-47	<92	<92	167	83	17
MW-13	<50	92-176	267	133	27
MW-48	92-157	157-250	1100	550	110
MW-14	<92	--	1000	500	100

5.6.2.8 Post-ESTCP Demonstration Sampling

Sampling of performance monitoring wells near the HRX Well will continue after the ESTCP demonstration project as part of ongoing remediation at SS003. The future sampling frequency will be negotiated with the State in accordance to existing sampling protocols at Vandenberg AFB. This post-demonstration sampling is not being funded as part of this ESTCP project.

6 PERFORMANCE ASSESSMENT

Assessment of the specific quantitative and qualitative performance objectives are discussed in detail in the following sections.

6.1 Quantitative Performance Objective #1: Quantify HRX Well Capture Width and Hydraulic Performance

This performance objective is intended to assess the overall hydraulic performance of the HRX Well and specifically to validate the size of the HRX Well capture and treatment zones and amount of flow within the HRX Well. This objective was evaluated through analysis of the hydraulic head measurements from multiple monitoring wells near the HRX Well, HRX Well flow velocity data measured with PVPs, tracer testing within the HRX Well, and the size of the treatment zone in the aquifer evidenced by performance monitoring wells. Although the model is based on necessary simplifying assumptions and there are uncertainties with its predictions, the results from these various independent tests and analyses are compared with model predictions as a way to assess consistency and reliability of both the model and the various test methods.

As previously discussed in Section 5.6.2.1, groundwater levels near the HRX Well clearly show mounding and the effects of treated water discharge, and interpreted flowlines are qualitatively similar to model predictions throughout the performance assessment period discussed in Section 5.6.2.7. However, due to local-scale heterogeneity and observed variable seasonal recharge and large-scale flow field effects, it was determined that a quantitative comparison of water levels at specific monitoring to predictions by the steady-state numerical model was not useful.

Figure 40 compares the average flow (1.95 ft^3/day) through the HRX Well predicted by the calibrated steady state-model to estimates derived from:

- The average hydraulic gradient and Darcy's Law calculations using the effective hydraulic conductivity of the treatment media (320 ft/day), and the HRX Well cartridge diameter (9.4 inches): ranges from 0.7 to 1.1 ft^3/day, average of about **0.9 ft^3/day**.
- PVP tests using the measured velocity (see Section 5.6.2.2), the assumed porosity for the treatment media (0.38), and the HRX Well diameter: ranges from 0.8 to 2.4 ft^3/day, average of **1.6 ft^3/day**.
- The results of the HRX well tracer test (see Section 5.6.2.3), the assumed porosity for the treatment media, and the HRX Well diameter: **1.3 ft^3/day**.

Figure 40. Predicted and Observed Flow through the HRX Well
Comparison of the average flow through the HRX Well predicted by the calibrated steady state-model to estimates derived from the average local aquifer hydraulic gradient and Darcy's Law, PVP tests, and the HRX Well tracer test.

The average of the results from the PVP tests and tracer test are about 26% lower than the model predictions; this is considered consistent with the success criteria of being within 25% of model predictions. The HRX Well flows calculated from the aquifer hydraulic gradient and Darcy's Law are generally lower (average 54% lower); however, these are considered more uncertain because they assume the representativeness of the regional aquifer hydraulic gradient and the hydraulic conductivity of the treatment media measured in the laboratory during the previous treatability testing. Overall, multiple methods clearly confirm flows through the HRX Well are much higher than the expected flow (0.02 ft^3/day) if there was no flow focusing effect. There is high confidence that the actual average HRX Well flow during the performance period was between 1 and 2 ft^3/day, and likely between about 1.3 and 1.6 ft^3/day, which is consistent with the success criteria of being within 25% of model predictions.

Figure 41 compares the capture zone width (52 feet) of the HRX Well predicted by the calibrated steady state-model to estimates derived from:

- The average hydraulic gradient and Darcy's law calculations using the effective hydraulic conductivity of the treatment media (320 ft/day), the average aquifer hydraulic conductivity (0.35 ft/day), the average aquifer thickness (8 feet), and the HRX Well diameter. The calculated treatment width is 34 ft.

- PVP tests using the measured velocity (see Section 5.6.2.2), an assumed porosity of 0.38 for the treatment media, the HRX Well diameter, the average aquifer hydraulic conductivity, the average aquifer thickness, and the aquifer hydraulic gradients at the times of the tests. ***The calculated treatment width ranges from 39 to 103 feet with an average of 69 ft.***
- The results of the HRX well tracer test (see Section 5.6.2.3), an assumed porosity of 0.38 for the treatment media, the HRX Well diameter, the average aquifer hydraulic conductivity, the average aquifer thickness, and the aquifer hydraulic gradient over the testing period. ***The calculated treatment width 45 ft.***

The result from the aquifer hydraulic gradient and Darcy's Law calculation is 34% lower than model predictions, the average result PVP test is about 32% higher than the model predictions, and the result from the HRX Well tracer test is 13% lower than the model predictions. Given the uncertainty and spatial variability of the underlying parameters used to calculate treatment zone widths, these results are considered relatively consistent with model predictions. Based on the average PVP results and the tracer test, there is high confidence that the actual average HRX Well capture zone width during the performance period was between 45 and 69 ft and the average of all methods is 49 ft. Overall, these results are meet the success criteria of being within 25% of model predictions (52 feet).

Figure 41. Predicted and Observed Capture by the HRX Well
Comparison of the average capture zone width of the HRX Well predicted by the calibrated steady state-model to estimates derived from the average local aquifer hydraulic gradient, PVP tests, and the HRX Well tracer test

The HRX Well treatment zone that was achieved during the performance period was also assessed. **Figure 42** shows the TCE and cis-1,2-DCE concentration trends at HRX Well performance monitoring wells (other VOCs were detected only at low concentrations). It is evident that TCE concentrations decreased at all four monitoring wells, from 50 to 74%. To quantitatively assess concentration trends and confirm treatment zone size delineated by the monitoring well network, historical data and post-installation sample data were evaluated to measure the performance objectives. The Mann-Kendall (MK) and Sen's Slope trend tests were applied to evaluate performance monitoring data for evidence of statistically significant concentration trends that are indicative of HRX Well efficacy (see **Appendix G**). These tests were applied at upgradient monitoring well 3-MW-35D and downgradient monitoring wells 3-MW-13, 3-MW-14, 3-MW-47, and 3-MW-48 using data collected over the HRX Well implementation period (August 2018 through October 2019).

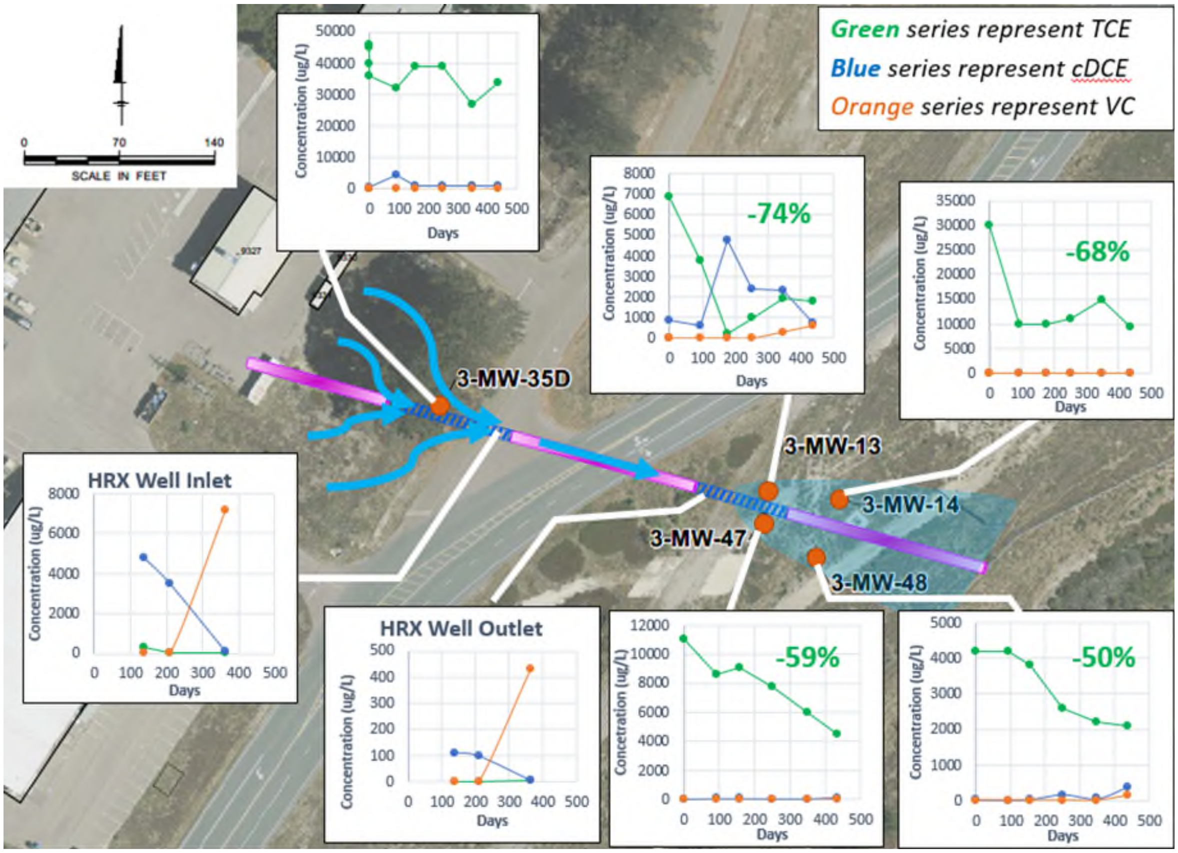

Figure 42. TCE and cis-1,2-DCE Concentration Trends at HRX Well Performance Monitoring Wells

Data are plotted as elapsed time since HRX Well installation (the most recent data prior to installation was used for Day = 0). The distance between well 3-MW-14 and 3-MW-48 is 45 ft.

At downgradient monitoring well 3-MW-13 a groundwater sample was collected approximately one month before HRX Well installation (July 10, 2018). This sample provides a baseline measurement for this downgradient well for comparison over the treatment period and was included in trend analyses. Concentrations of tetrachloroethene (PCE), TCE, cis-1,2-DCE, and vinyl chloride in micrograms per liter (µg/L) were examined, as well as the total molar concentration of these constituents in units of micromoles per liter (µmol/L). The total molar concentration was evaluated because as PCE and TCE undergo reductive dechlorination, cis-1,2-DCE and vinyl chloride are produced. Effective remediation is demonstrated by the subsequent degradation of intermediate products and decreasing trends in total molar concentration are a strong line of evidence of complete degradation.

The basic MK trend test is performed by listing the concentrations of the constituent of interest in temporal order and computing the differences between a given measurement and earlier measurements (Gilbert 1987; USEPA 2009). The MK test statistic (sum of trend [S]) is the difference between the number of strictly positive differences and the number of strictly negative differences. If S is positive, an increasing trend is indicated; if S is negative, a decreasing trend is indicated; and, if S is near zero, no trend is apparent. Trends with positive or negative S-statistics are accepted as statistically significant for p-values less than or equal to 0.1 (90% confidence level). Trends with p-values between 0.1 and 0.25 (75 to 90% confidence) were designated as potentially increasing or potentially decreasing based on the sign of the S-statistic. Where statistically significant decreasing concentration trends were found based on MK analysis, the magnitude of the change over time (the point attenuation rate constant) was determined based on the Sen's Slope analysis. For this analysis, a simple slope estimate was computed for each pair of measurements in each dataset, and then the median slope, the upper confidence limit on the median slope, and the lower confidence limit on the median slope are calculated. Trend analysis results are presented in **Table 13**.

Table 13. MK Trend Analysis Results for Total Molar Concentrations of Chlorinated Ethenes

Well Location	Well ID	Constituent	Trend Direction	Significance of Trend (90% Confidence)
Upgradient	3-MW-35D	Total Molar Concentration	Potentially decreasing	Not significant
Downgradient	3-MW-13		Decreasing	Significant
	3-MW-14		No trend	Not significant
	3-MW-47		Decreasing	Significant
	3-MW-48		Potentially decreasing	Not significant

At upgradient monitoring well 3-MW-35D, total molar and cis-1,2-DCE concentrations show potentially decreasing trends, vinyl chloride shows a potentially increasing trend, and PCE and TCE concentrations show no trend. These results suggest that there is some degree of degradation in this area associated with the residual biopolymer drilling fluid, but that the overall effect of the drilling fluid induced degradation was not the primary mechanism for TCE decreases at downgradient monitoring wells (clean water flushing is the dominant treatment process). It is expected that drilling fluid will be completely broken down over time and biologically mediated reductive dichlorination rates will further decline.

Trend analysis results at downgradient monitoring wells 3-MW-13, 3-MW-47, and 3-MW-48 provide a strong line of evidence for HRX Well influence. At monitoring well 3-MW-13, the total molar concentration shows a statistically significant decreasing trend and TCE shows a potentially decreasing trend. At monitoring well 3-MW-47, total molar and TCE concentrations each show statistically significant decreasing trends. At monitoring well 3-MW-48, total molar concentration shows a potentially decreasing trend and TCE shows a statistically significant decreasing trend. At each of these wells, concentrations of cis-1,2-DCE and/or vinyl chloride show either statistically significant or potential increasing trends. These results suggest that at least some amount of TCE degradation proceeds through these reductive dechlorination intermediate products. While the ZVI matrix used in the HRX Well may catalyze both sequential reductive dechlorination and TCE degradation through beta-elimination (which does not produce cis-1,2-DCE and vinyl chloride), it is highly likely that sequential reductive dechlorination was temporarily enhanced by the guar gum used during HRX Well installation. This is also supported by the low levels of TCE and elevated levels of cis-1,2-DCE and vinyl chloride measured at the HRX Well inlet. Because these increases are attributed to enhanced biotransformation processes driven by the residual biopolymer, they are expected to be temporary. Well 3-MW-48 is located approximately 20 feet orthogonal to the HRX Well alignment; therefore, (assuming symmetry) it is likely that the treatment zone width at day 436 was at least 40 feet. As shown in **Figure 29**, elevated TOC was present in all four downgradient performance monitoring wells 100 days after HRX Well installation. Assuming TOC represents a tracer for the treated water, these data indicate the treatment zone width was at least 45 feet. These observations are which is consistent with the results presented in **Figure 41**.

Although TCE concentrations at 3-MW-14 decreased significantly compared to baseline and historical levels, statistical trend analysis results for this well suggest that treated water discharging from the HRX Well Outlet may not have arrived during the performance monitoring period. At this location, cis-1,2-DCE concentrations (which may serve as a tracer of enhanced biodegradation driven by residual biopolymer drilling fluid) remained low; although, they showed statistically significant increasing trends. However, total molar and TCE concentrations showed no decreasing trend. The sharp initial decrease in TCE observed occurred much sooner than would be expected based on the distance of this well (180 to 470 days) and is likely the result of flow field perturbations caused by the HRX Well. However, the expected arrival time of treated water at 3-MW-14 is greater than the other wells and therefore this well may demonstrate further concentration reductions as a result of treated water arrival beyond the 1-year monitoring period for this demonstration. Concentrations at wells 3-MW-13, 3-MW-47, and 3-MW-48 are expected to continue to decline over time, consistent with the elution and clean water flushing.

In summary, multiple calculations supported by different data types and various tests and calculations confirm significant flow focusing and a resulting capture zone size that is generally consistent with model predictions and meets the success criteria of this performance objective.

6.2 Quantitative Performance Objective #2: Determine Reactive Media Treatment Efficiency

The purpose of this performance objective is to assess the reactive media treatment efficiency and whether the target contaminant (TCE) was treated to the performance goal of less than 50 µg/L, measured at the HRX Well outlet, throughout the performance assessment period. **Table 14** compares contaminant concentrations from samples obtained from the upgradient well 3-MW-35D and the HRX Well Inlet to the HRX Well Outlet and calculated the observed concentration decreases. TCE concentrations at the HRX Well Outlet ranged from non-detect (<2 µg/L) to 7.6 µg/L, lower than the performance goal of 50 µg/L. The average TCE concentration reduction compared to well 3-MW-35D and the HRX Well Outlet was about 32,700 µg/L (>99.999%) and the initial TCE concentration reduction compared to the HRX Well Inlet was 310 µg/L (99.9%).

Table 14. Comparison of Contaminant Concentrations from 3-MW-35D and the HRX Well Inlet to the HRX Well Outlet

Location	3-MW-35D (µg/L)	HRX Well Inlet (µg/L)	HRX Well Outlet (µg/L)	Reduction Compared to 3-MW35D (µg/L)	Reduction Compared to HRX Well Inlet (µg/L)	Reduction Compared to 3-MW35D	Reduction Compared to HRX Well Inlet
Date	11/7/2018	12/17/2018	12/17/2018				
Elapsed Time	98 days	138 days	138 days				
TCE	32,000	310	<1.0	32,000	310	>99.9%	99.8%
cis-1,2-DCE	4,300	4,800	110	4,190	4,690	97.4%	97.7%
Vinyl chloride	<2.5	3.7	0.8	0.45	2.9	36.0%	78.4%
Date	1/21/2019	2/27/2019	2/27/2019				
Elapsed Time	173 days	210 days	210 days				
TCE	39,000	5.1	0.21	39,000	5.1	>99.9%	95.9%
cis-1,2-DCE	1,000	3,500	97	903	3,403	90.3%	97.2%
Vinyl chloride	1.7	5.3	0.65	1	4.6	61.8%	87.7%
Date	7/18/2019	8/1/2019	8/1/2019				
Elapsed Time	351 days	365 days	365 days				
TCE	27,000	13	7.6	27,000	5.4	99.9%	41.5%
cis-1,2-DCE	880	94	6.8	873.2	87.2	99.2%	92.8%
Vinyl chloride	1.2	7,200	430		6,770	-	94.0%

Note: For results that were below the laboratory detection limit, one-half of the detection limit was used to calculate the percent reduction.

Assuming an average flow velocity in the treatment media of 7.2 ft/day, the estimated treatment media residence time is about 8 to 9 days, within the initial design goal of 6 to 20 days. Effective decays rates were calculated for TCE, cis-1,2-DCE, and vinyl chloride for dates where HRX Well Inlet concentrations were about 100 µg/L or greater (**Table 15**). The estimated first-order TCE transformation rate (0.9 day^{-1}) is about half the of the design value estimated from the treatability testing (1.8 day^{-1}), but greater than the estimated minimum rate (0.7 day^{-1}) needed to treated TCE from 35,000 µg/L to 50 µg/L, and much higher than estimated minimum rate (0.2 day^{-1}) needed to treated TCE from 310 ug/L (highest observed HRX Well Inlet concentration) to 50 ug/L. Calculated rates for cis-1,2-DCE and vinyl chloride are 50% to 66% lower than for TCE, which is commonly observed for ZVI (e.g., Tratnyek et al., 1997). It is not clear why the transformation rates in the field are lower than expected, however, the high TOC levels (and associated low redox conditions), were not represented in the treatability testing and may be influential. If this is the case, transformation rates may increase as TOC levels continued to decline. Evaluating residual drilling fluid performance on treatment media performance is an important consideration for treatability studies for future HRX Well installations.

Table 15. Effective Contaminant Transformation Rates For ZVI Treatment Media

Day	Constituent	Transformation rate (day^{-1})
92	TCE	0.9
92	1,2-cDCE	0.5
157	1,2-cDCE	0.4
351	1,2-cDCE	0.3
351	Vinyl Chloride	0.3

As shown in **Table 14**, there was a significant decrease in TCE concentration between 3-MW-35D and the HRX Well Inlet, and there was also an increase in cis-1,2-DCE and vinyl chloride concentrations (especially later in the performance period). As discussed in Section 6.1 and elsewhere, this is the result of enhanced biotransformation promoted by unrecovered residual biopolymer drilling fluid. Assuming reductions from 3-MW-35D to HRX Well Inlet are due to biotic processes and HRX Well Inlet to HRX Well outlet are primarily due to abiotic processes, the average relative contributions by these process are estimated below.

Table 16. Estimated Treatment From Biotic and Abiotic Processes

Average total chlorinated ethenes at 3-MW-35D	277
Average total chlorinated ethenes at HRX Well Inlet	68.1
Average total chlorinated ethenes HRX Well Outlet	3.0
Average total chlorinated ethenes treated by biotic processes	209
Average total chlorinated ethenes treated by biotic processes	76%
Average total chlorinated ethenes treated by biotic processes	65.1
Average total chlorinated ethenes at 3-MW-35D	277

Concentration values presented in micromoles per liter (μM/L)

Assuming the majority of treatment between 3-MW-35D and the HRX Well Inlet was biotic and the majority of treatment between the HRX Well Inlet and HRW Well Outlet was abiotic, it is estimated that roughly 76% of the total treatment (from 3-MW-35D to the HRX Well Outlet) is attributable to biological process and 24% to abiotic transformation by the ZVI. As the residual biopolymer is consumed, it is expected that redox conditions will increasingly become more aerobic and the relative contribution of biotic transformation processes will decrease over time. For downgradient wells, elution is primarily responsible for contribution reductions, however, biotic processes are indicated by the presence of daughter products and may account for about 10% of the average TCE reduction observed at the four performance monitoring wells.

The groundwater elevations (**Figure 28**) and the calculated of flow within the HRX Well (**Figure 40**), and estimated capture zone size (**Figure 41**) indicates the ZVI maintained high permeability relative to aquifer permeability over time (i.e., no evidence of significant decrease in permeability due to media plugging or fouling).

Overall, the results and analyses presented in this section indicate the success criteria was met for reactive media treatment efficiency.

6.3 Quantitative Performance Objective #3: Quantify Contaminant Mass Discharge Reduction

As discussed above, there was a significant decrease in TCE concentration between 3-MW-35D (located a few feet north of the HRX well Inlet) and the HRX Well Inlet, as a result of enhanced biotransformation promoted by unrecovered residual biopolymer drilling fluid. As the residual biopolymer is consumed, it is expected that the relative contribution of biotic transformation processes will decrease over time. Therefore the TCE concentration at 3-MW-35D is considered more representative of the total TCE in the system and was used in the contaminant mass discharge reduction estimate.

Contaminant mass discharge reduction was estimated by multiplying the difference in TCE between well 3-MW-35D (representing groundwater at the HRX Well Inlet) and the HRX Well Outlet (average of 33,000 µg/L, +/- 6,000 µg/L) by the best estimate in flow through the HRX Well (1.3 to 1.6 ft^3/day). By propagating these ranges through the calculation, the likely range for mass discharge reduction is 1.0 and 1.8 grams per day with a best estimate of 1.4 grams per day. This represents >99.99% reduction in contaminant mass discharge across a transect defined by the capture width, and meets the performance objective success metric of mass discharge reduction of more than 90%.

6.4 Quantitative Performance Objective #4: Determine PVP Performance

As discussed in detail in Section 6.1, the measurement precision, as defined by the relative standard deviation of measurements, for the four PVPs test events were 18.1%, 8.7%, 15.7%, and 20%. These results meet the success criteria of achieving a PVP measurement precision of less than 25%. For this project multiple PVP tests were able to be completed in a day and the method allows rapid flow measurements. Because individual PVP tests are completed within a couple hours or less, they represent nearly instantaneous measurements and can be used to assess the affects of temporal variations in hydraulic gradient and flow rates (as observed in this demonstration). However, PVP tests are less representative of average conditions than HRX Well tracer testing, which measures average flow conditions over several months.

6.5 Qualitative Performance Objective #1: Identify Challenges and Limitations of HRX Well Installation

There are potential implementation challenges associated with the directional drilling methods used to install HRX Wells. These potential issues are not specific to HRX Wells and would be the same for a given site if directional drilling were used to install other types of horizontal remediation wells (e.g., horizontal groundwater extraction wells). Examples include the potential for inadvertent drilling fluid returns to the ground surface along preferential pathways and electromagnetic interference with borehole navigation. The HRX Well technology uses a combination of standard commercial off the shelf materials and custom-built prototypes. Standard materials include biopolymer drilling fluid, horizontal well screen and casing, and cement-bentonite grout for the annular grout seals. Custom build prototypes for this demonstration included the media and monitoring cartridges (using standard HDPE pipe and fittings) and the PVPs suited for horizontal orientation. Based on this demonstration, challenges and limitations associated with HRX Well installation are well understood and can be readily mitigated or avoided with simple design changes, this understanding is considered sufficient to meet the success criteria for this performance objective.

6.6 Qualitative Performance Objective #2: Compare Sustainability of HRX Well Treatment Approach with Others

The sustainability impacts for three alternatives (HRX, GETS, PRB) were measured by estimating a system design to address the same contaminant plume. The analysis included three HRX Wells, GETS with 10 groundwater extraction wells, and a PRB (150 feet long, 3 feet wide, 25 feet deep). The impacts were compared across four lifecycle phases where Phase 1 was materials transport and travel, Phase 2 was materials manufacture, Phase 3 system installation, and Phase 4 operation and maintenance. In each phase, the estimated energy used, the resulting carbon dioxide emissions equivalents, nitrogen oxides, sulfur oxide, and particulate matter 10 micrometers or less in diameter emissions were all determined.

The sustainability analysis results (see Section 7.3 and Appendix H) indicated that the HRX Well sustainability performance objectives were met including that HRX Well compares favorably with the alternatives. The overall sustainability impacts were reflective of the materials or equipment used, particularly during system operation. The transportation impacts were greatest for the PRB because of the total mass of ZVI to be transported. The results were similar for materials manufacture where both PRB media placements involved a much greater mass of ZVI than the HRX Well. The installation impacts for all systems were small compared to the impacts from materials manufacture or system operation. Phase 3 impacts were greatest for the GETS system due to nearly continuous equipment operation and regular media replacements. The PRB alternative does not require equipment use during operation; however, the initial and year 15 media replacement had substantial impacts in terms of energy use and emissions. The HRX Well performed well in comparison to GETS and the PRB because the HRX Well would not require equipment operation and the mass of media used throughout the lifecycle is a fraction of that required for the other alternatives.

6.7 Qualitative Performance Objective #3: Characterize Life Cycle Costs

Section 7 provides sufficient cost information to allow a remediation professional to reasonably estimate costs for installation of a single HRX Well at a representative site. A feasibility evaluation was completed to compare the HRX Well technology to other appropriately scaled remedial technologies capable of achieving similar objectives. The HRX Well is a passive technology, appropriately suited for long-term plume treatment. Therefore, aggressive source removal/destruction technologies are not comparable, and the comparison detailed in Section 7 focuses on a GETS and a funnel and gate PRB. The remedial alternatives were evaluated by comparing six criteria, including life cycle cost. Overall, this analysis found the costs of the HRX Well technology compare favorably to other applicable technologies, as shown in **Table 17**. The HRX Well was a more cost effective option than either GETS or PRB. The efficient use of media in the HRX Well combined with passive operation resulted in lower lifecycle costs in comparison to the other alternatives. Lifecycle cost estimates included capital and operations costs. The results of this cost analysis confirm the HRX Well costs compare favorably to appropriate comparable technologies and is considered sufficient to meet the success criteria for this performance objective.

6.8 Qualitative Performance Objective #4: Finalize and Validate the HRX Well Design Tool

In order to facilitate future efficient HRX Well designs, capture lessons learned, and promote technology transfer, an Excel-based HRW Well design, cost, and sustainability tool was developed. Many HRX Well configurations are possible, but the applicability of any design is subject to site-specific factors. The tool allows the user to optimize the design based on user-provided values. Supplemental literature values can also be used as inputs to support high-level estimations. The tool predicts well length, capture width, and the number of wells required to meet target treatment goals. In addition, the associated costs and sustainability implications are calculated, which can further inform design selection. For many sites, a site-specific numerical flow and transport model may be useful for final design, as well as predicting and assessing HRX Well performance. The tool requires a series of values to be supplied and or selected by the user. Estimated values may be used in the design tool, but values from site investigations and treatability testing are ideal for high level estimation. After entering the values in the design tool, preliminary output values are calculated. The subsequent outcomes include reducing costs and increasing installation efficiency. It is important to note that the tool currently does not have restrictions on most input values; therefore, common sense should be used when reviewing the summary. For example, if the number of wells exceeds site or budget capacity, additional optimization should be completed to reduce the number of wells.

To validate the reliability and usefulness of this tool, HRX Well designs were successfully evaluated for the VAFB site as well as two additional DoD sites. The tool is summarized in **Section 8.2** and further details, user instructions and the results of the site-specific evaluations are presented in **Appendix H**. While it is anticipated that this tool will continue to be modified over time to enhance functionality and usefulness, the current version of the tool is considered sufficient to meet the success criteria for this performance objective.

7 COST ASSESSMENT

This section is intended to provide sufficient cost information so that a remediation professional could reasonably estimate costs for installation of a single HRX Well at a given site. In addition, the cost benefit of the HRX Well technology is discussed.

7.1 Cost Model

The costs unique to HRX Wells are materials and installation. The former will scale with the size of the well and treatment media used. The latter is unique because horizontal (i.e., directional), rather than vertical, drilling is required for installation and costs vary from vertical drilling that is most commonly utilized for environmental projects. All associated costs, including design, well casing and screen, treatment media, the cartridges that contained the media, installation costs, site restoration, and waste disposal were tracked during the HRX Well demonstration.

A simple cost model summarizing all expected costs associated with operation of a single HRX Well is presented in **Table 17** and serves as general guidance to estimate the cost of installing a HRX Well. The projected cost estimates (far right column) include design costs, capital costs

(costs associated with installation), operation maintenance and monitoring costs (costs associated with ongoing operations necessary to operate the remedial alternative), and present worth cost (forecasted life-cycle costs accounting for both inflation and interest). The costs were tracked through each project stage. Some costs were higher due to initial implementation challenges and site-specific logistics, which were overcome, but may not be representative of true costs at other sites.

Table 17. Cost Model for the HRX Well

Cost Element-HRX Well	Data Tracked During the Demonstration	Costs	
Treatability study	Collect site groundwater and ship to treatability lab Column tests to assess permeability, capacity, and reaction kinetics VOCs laboratory analyses	Flat rate	$15,000
Baseline characterization	Field labor & equipment costs Subcontractor costs Laboratory costs	Flat rate	$50,000
Engineering & Design	Engineering and construction, project management, contingencies	Indirect cost	$250,000
Material cost	Drilling fluid: Biopolymer	$120/bag	$28,800
	Media: Cost per pound of media	Total cost ZVI (1,390 lbs)	$2,300
		Total cost sand (2,582 lbs)	$500
	Carbon steel well casing: Cost per foot of material and total material used	12-inch diameter Carbon steel well casing; $55/feet	$22,825
	Stainless steel well screen: Cost per foot of material and total material used	12-inch diameter Stainless steel screen; $190/feet	$29,450
	Cartridge: Materials and construction	Cartridge; $9,000/each	$63,000
	PVPs:	Two PVP System (Inlet and Outlet)	$15,000
	Well ends, surface completion:	Above ground completion with bollards; $5,000/end	$10,000
	Surface wells seals: Cost for labor and materials	Entry and exit sides: $750/seal	$1,500
	Central media section well seal: Cost for labor and materials	$1,500/seal	$3,000

Cost Element-HRX Well	Data Tracked During the Demonstration	Costs	
Installation	**Drilling equipment mobilization:**	Mobilization costs; $50,000/site	$50,000
	Drilling and reaming:	Drilling; $175/feet	$99,750
	Assembly and installation:	Well assembly and installation; $70/feet	$38,290
	Well development:	Well development; $750/hour	$12,000
Waste disposal	**Waste management:** Transfer liquid and solid wastes to storage containers	Flat rate	$5,000
	Waste characterization analysis, container rental, solid and liquid waste disposal costs		$50,000
Operation and maintenance costs	Cartridge removal replacement with drill rig	Expected number of media replacements = 1	$75,000
	Media replacement & disposal	Expected number of media replacements = 1	$7,500
Long-term monitoring	Costs of quarterly groundwater monitoring events (5 monitoring wells) for one year: Field labor, laboratory costs, reporting	Annual; $20,000/year Costs projected assuming 1 sampling event per year for 30 years	$600,000
		30-year Total	$1.4 M

Notes: Forecasted lifecycle costs account assume 4% interest and 3% inflation. Capital expenses were not depreciated, either at the onset or when incurred over the lifecycle.

7.1.1 Material Costs

ZVI was used as a treatment media for this demonstration because of its applicability for TCE remediation. Other types of reactive media would be applicable for TCE or other contaminants, depending on site-specific characteristics. The capital costs and replacement frequency and associated costs will vary depending on media characteristics and site-specific contaminant mass flux.

For the HRX Well demonstration at VAFB, steel well materials were used because steel has the narrowest screen slot size available, when compared to other materials such HDPE and PVC. This will minimize the long-term operational costs at VAFB by minimizing the potential for fines to enter the HRX Well, which could reduce capture efficiency and require periodic redevelopment to restore well efficiency. Other lower cost well materials with larger minimum slot width (such as HDPE with narrowest available slot size of approximately 0.025-inch) may be suitable for sites with coarser-grained soils. The final choice of well materials should be based on a site-specific evaluation of up-front capital expenditures versus long-term maintenance costs for horizontal wells with natural filter packs.

The standard cartridge length options are 5 feet and 10 feet, with the cartridge diameter vary according to the well diameter. Therefore, costs will increase or decrease depending on specific dimensions required at a given site. Finally, the wellheads at each end were completed above grade with protective bollards. Below grade wellhead completion within a vault would result in higher costs.

All materials cost data were provided by the respective vendors and may not represent current market costs. Moreover, there is some flexibility for materials selection which could decrease costs as long as the reliability of the installation is not compromised.

7.1.2 Installation Costs

Installation costs will vary with installation time, which is a product of well length, depth, and bore and well diameter. With increasing well diameter, progressively larger equipment such as a trackhoe or crane may be required to position sections of well casing and drill pipe, which would also increase costs. Fuel costs for all equipment were included in the total cost. Drilling mud, well sealing, well development, and waste disposal costs will all increase with increasing well length and diameter. Installation costs were tracked and reported as part of this project.

7.2 Cost Drivers

The project site costs related directly to the implementation scale and materials used. Therefore, the treatment goals and target treatment area determine costs. The passive HRX Well configuration will be most efficient when 1) there is sufficiently high hydraulic conductivity contrast between the aquifer and the treatment media (generally 1,000 times or greater), and 2) when the treatment media is well suited to the contaminant such that hydraulic retention time is minimized. Increasing the length, depth, or diameter of wells, as well as the number installed, will cause costs to increase. Installation costs will also be affected by complexity of drilling operations due to subsurface composition. Operation and maintenance costs will primarily be affected by the media changeout frequency required. The frequency and lifecycle costs can be predicted on the basis of treatability testing results. Media changeout will incur drill company mobilization fees, replacement media and cartridges, and waste disposal fees.

In summary, the main cost drivers of the HRX Well technology include:

- HRX Well Length, Depth, and Diameter – Influences directional drilling costs and volume of waste generated.
- Lithology – Directional drilling costs will be lower for unconsolidated soils and higher for bedrock, consistent with the various vertical drilling methodologies that are available.
- Design costs – Detailed engineering and geological evaluations, numerical groundwater modeling, and reactive media treatability testing will typically be required to properly design

a HRX Well. A Design Tool was developed to support preliminary screening of the HRX well technology.

- Well materials – The most appropriate well materials (casing and screen) will depend on formation grain size and pipe strength required to withstand installation stresses during a given installation. The final choice of well materials should be based on a site-specific evaluation of up-front capital expenditures versus long-term maintenance costs.
- Treatment media costs – In most cases, treatment media costs are not expected to be a primary cost driver, due to efficient use of treatment media. However, if frequent media change outs or exotic treatment media are required, then media costs may become more significant.

7.3 Cost Analysis

A feasibility evaluation was completed to compare the HRX Well technology to other appropriately scaled remedial technologies capable of achieving similar objectives. The HRX Well is a passive technology, appropriately suited for long-term plume treatment. Therefore, aggressive source removal/destruction technologies are not comparable, and this comparison focuses on a GETS and a funnel and gate PRB. This feasibility cost evaluation is based on addressing the TCE groundwater plume (target plume width of 150-feet and depth of 25 feet) extending downgradient from the “hot spot”, where the HRX well was installed. The existing HRX well has a capture width of 50 feet; therefore, two additional HRX wells would be required to treat the full width of 150 feet. A typical remediation timeframe of 30 years was used for this cost comparison.

Therefore, the remedial technologies which are discussed in this feasibility evaluation are:

Alternative 1 –HRX Wells (Assumes 3 HRX wells, each with 50-foot capture width).

Alternative 2 – GETS (Assumes 10 vertical extraction wells).

Alternative 3 –Funnel and Gate PRB (Assumes PRB 150 feet long and 3 feet wide).

The remedial alternatives were evaluated by comparing six criteria (**Table 18**), which were generally based on criteria set in the Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA (USEPA 1988). The criteria are summarized below for all three alternatives:

Table 18. Summary of Criteria Used to Compare Remedial Alternatives

Criterion	**Alternative #1 - Horizontal Reactive Media (HRX) Treatment Well***	**Alternative #2 - Groundwater Extraction and Treatment System (GETS)**	**Alternative #3 - Funnel and Gate Permeable Reactive Barrier (PRB)**
Overall protection of human health and environment	Yes	Yes	Yes
Effectiveness and permanence	Moderate to High	Moderate	Moderate to High

Criterion	Alternative #1 - Horizontal Reactive Media (HRX) Treatment Well*	Alternative #2 - Groundwater Extraction and Treatment System (GETS)	Alternative #3 - Funnel and Gate Permeable Reactive Barrier (PRB)
Reductions in toxicity, mobility, and volume through treatment	Moderate to High	Moderate	Moderate to High
Implementability	Moderate	Moderate	Moderate
Sustainability	High	Low to Moderate	Moderate to High
Cost	Low to Moderate $2.6M	High $4.7M	Moderate $3.6M

**This cost evaluation is based on a target treatment width of 150 ft, requiring three HRX Wells*

Overall, this analysis found the costs of the HRX Well technology compare favorably to other applicable technologies, as shown in **Table 19**. The HRX Well was a more cost effective option than either GETS or PRB. The efficient use of media in the HRX Well combined with passive operation resulted in lower lifecycle costs in comparison to the other alternatives. Lifecycle cost estimates included capital and operations costs.

Table 19. Summary of Costs for each Remedial Alternative

Cost Element	HRX Well (3 HRX Wells)	GETS (10 vertical extraction wells)	PRB (150 foot long PRB)
Capital Costs			
Engineering & Design	$250,000	$200,000	$250,000
Treatability Study	$15,000	$0	$15,000
Baseline Characterization	$50,000	$50,000	$50,000
Installation & materials	$1,175,000	$485,000	$1,050,000
Waste Disposal	$150,000	$30,000	$115,000
Total Capital Costs	$1.6 M	$0.8 M	$1.5 M
Operation, Maintenance, & Monitoring Costs			
Operation and Maintenance (30 years)	$82,500	$3,000,000	$1,050,000
Long-term Monitoring (30 years)	$900,000	$900,000	$900,000
30-year Lifecycle Total	**$2.6 M**	**$4.7 M**	**$3.4 M**

Notes: Forecasted lifecycle costs account assume 4% interest and 3% inflation. Capital expenses were not depreciated, either at the onset or when incurred over the lifecycle.

Alternative 1 - HRX Wells

Three HRX Wells would be needed to address 150 feet of target treatment width. It is assumed all three HRX Wells would be identical to the one installed as part of this field demonstration. The cost data for one well are given in **Table 17** with an additional total for the total cost for three wells given in **Table 19**. The technology is in situ, requiring minimal operation and maintenance, making Alternative 1 more economical than Alternative 2, and the limited amount of surface disturbance makes Alternative 1 more economical than Alternative 3. Annual costs post-installation would be associated with routine groundwater sampling and a one-time media replacement assumed to occur at 15 years post-installation.

Alternative 2 – GETS

The GETS system included 10 vertical wells plus pumps with an ex situ groundwater treatment system. Costs for this technology include extraction well installation, treatment system skids, conveyance, and trenching. Capital costs were less for GETS than the HRX Wells alternative. However, operation and maintenance costs, along with costs of utilities (e.g., electricity), make Alternative 2 a less economical option than Alternative 1 over the 30-year lifecycle.

Alternative 3 – Funnel and Gate PRB

The PRB was designed to run the width of the plume (150 feet) and to an excavated depth of 40 feet. Costs for this technology include excavation, sheeting and shoring required around the excavation, offsite soil disposal, and treatment media. Although the technology is in situ, requiring minimal operation and maintenance, the costs associated with excavation and trenching make Alternative 3 a less economical option compared with Alternative 1. Annual costs post-installation would be associated with routine groundwater sampling and a one-time media replacement assumed to occur at 15 years post-installation. Although both the HRX and PRB alternatives assume media replacements occurred at the same time point, the additional ZVI required in the PRB made it a less economical option than the HRX Well. In addition, replacing the media in the PRB involved higher equipment costs. The differences in media mass used and resulting costs points to the more efficient use of media by HRX Well as compared to the PRB.

8 IMPLEMENTATION ISSUES & DESIGN TOOL

This section provides lessons learned that will be useful during future implementation of the HRX Well technology. Pertinent regulations, end-user concerns, and procurement issues are also described.

8.1 Implementation Issues

The mud rotary directional drilling method used to install HRX Wells is applicable to both unconsolidated and fractured bedrock aquifer settings. Therefore, HRX Well implementation challenges associated with lithology and hydrogeology will have more to do with performance risks than inability to complete installation. The majority of horizontal remediation wells are installed to a depth of less than 100 feet, with lengths ranging from a few dozen feet to over 1,500 feet. Site lithology and hydrogeology can pose performance risks for the HRX Well technology. In high hydraulic conductivity settings the HRX Well can be operated in a pumping “active configuration”, however, high flow rates through the well and shorter residence times in the treatment media could become a limiting factor.

There are potential implementation challenges associated with the mud rotary directional drilling method used to install HRX Wells. These potential issues are not specific to HRX Wells and would be the same for a given site if directional drilling were used to install other types of horizontal remediation wells (e.g., horizontal groundwater extraction wells). Examples include the potential for inadvertent drilling fluid returns to the ground surface along preferential pathways and electromagnetic interference with borehole navigation. The reader is referred to horizontal well guidance documents (USEPA 2017; DTD 2004) for a more thorough discussion of the advantages and disadvantages of directional drilling.

Environmental regulations and necessary permits required for a HRX Well are expected to be consistent with those required for vertical well remediation projects, and will vary by jurisdiction. For example, if a given locality requires a permit for injection of ZVI or a carbon based amendment, then it is expected the same permit would be required for installation of a HRX Well with ZVI treatment media. Utility clearance will be required prior to drilling and many states require a licensed well driller for installation of remediation wells. Drilling waste will require characterization and disposal in accordance with local rules and regulations.

The HRX Well technology uses a combination of standard commercial off the shelf materials and custom-built prototypes. Standard materials include biopolymer drilling fluid, horizontal well screen and casing, and cement-bentonite ground for the annular grout seals. As noted in this demonstration, recovery of the biopolymer drilling fluid may be incomplete, and subsequent fermentation of this carbon source will affect local redox conditions and electron acceptor concentrations. At VAFB, this effect resulted in a beneficial complimentary biotic treatment processes; however, these geochemical conditions might not be desirable for some treatment strategies (e.g., slow-release chemical oxidation treatment media). Custom build prototypes for this project included the media and monitoring cartridges (using standard HDPE pipe and fittings) and the PVPs suited for horizontal orientation.

Finally, it should be noted that the HRX Well concept is a patented technology and patents are pending for the treatment cartridges; therefore, licensing requirements must be considered before implementation.

8.2 Lessons Learned

The HRX Well achieved the demonstration objectives, as discussed in Section 6. However, as with any new technology being implemented for the first time, there were lessons learned that can be applied during future HRX Well installations. The first is that residual carbon-based biopolymer drilling fluid remaining after well development stimulated reductive dechlorination of TCE by native subsurface bacteria. The biodegradation is expected to be a temporary relative to the 30-year projected lifecycle of this HRX Well and the results from the performance monitoring period indicate this process is beginning to diminish, but could persist for a few more years. For chemicals subject to biodegradation, the performance monitoring plan should include biodegradation indicator parameters such as TOC, so that the short-term influence of residual drilling fluid can be separated from the treatment process associated with the HRX Well treatment media (in this case chemical reduction of TCE by ZVI). The potential influence of residual drilling fluid on treatment media performance (e.g., treatment rates, efficiency, capacity) should be considered in treatability testing and incorporated in HRX Well design.

Another lesson learned is the importance of the internal and external seals to prevent bypass of impacted groundwater either around the treatment media inside the well, or along the borehole annulus outside the well. PVP testing indicates that minor gaps could have a significant impact in low permeability settings. Bypass of untreated water from the upgradient end of the HRX Well to the downgradient end was not observed; however, the annular grout seals are not typically installed in the center section of horizontal wells, so this requires special consideration and field methods for emplacing grout to further distances than typical. For higher permeability settings where a downhole pump will be used to increase capture width, the significance of the center grout seal will be further evaluated for future designs under the pumping scenario.

One final lesson learned is that the volatility in the price of steel caused well material costs to increase significantly between the planning and installation stages. Steel well materials were selected for this demonstration due to site lithology, however, HRX Wells can be constructed with other common well materials such as HDPE, which may be appropriate for other settings.

8.3 Design Tool

The HRX Well design tool was developed to provide preliminary site design estimates to practitioners considering implementation of the HRX Well. Complete user instructions and design tool examples are included in **Appendix H**. The Microsoft Excel-based HRX Well Design Tool version 1.0 will be available for download from the ESTCP ER-201631 project website.[2]

Many HRX Well configurations are possible but the applicability of any design is subject to site-specific factors. The tool allows the user to optimize the design based on user-provided values and using the equations described in Divine et al. (2018c). Supplemental literature values can also be used as inputs to support high-level estimations. The tool predicts well length, capture width, and the number of wells required to meet target treatment goals. In addition, the associated costs and sustainability implications are calculated, which can further inform design selection. For many sites, a site-specific numerical flow and transport model may be useful for final design, as well as predicting and assessing HRX Well performance.

The tool requires a series of values to be supplied and or selected by the user. Estimated values may be used in the design tool, but values from site investigations and treatability testing are ideal for high level estimation. After entering the values in the design tool, preliminary output values are calculated. In addition, an option was included to add a pump rate or to incorporate mix-in media to increase capture width and reduce the number of wells. If the capture width is too low or number of wells exceeds site or budget capacity, additional optimization should be completed to reduce the number of wells.

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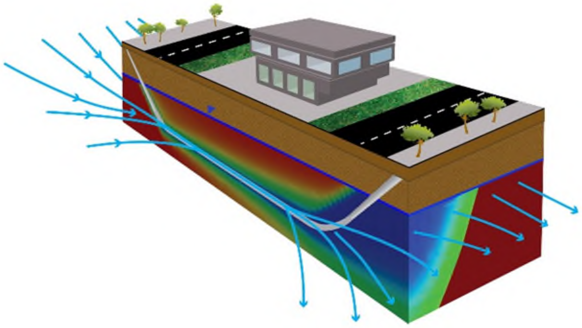
Appendix A

Model Evaluation of HRX Well Performance

APPENDIX A: MODEL EVALUATION OF HRX WELL PERFORMANCE

DEMONSTRATION AND VALIDATION OF THE HORIZONTAL REACTIVE MEDIA TREATMENT WELL (HRX Well®) FOR MANAGING CONTAMINANT PLUMES IN COMPLEX GEOLOGIC ENVIRONMENTS



ESTCP Project ER-201631

February 2020

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1 INTRODUCTION

In collaboration with the Environmental Security Technology Certification Program (ESTCP), Arcadis U.S., Inc. (Arcadis) installed and field-validated the Horizontal Reactive Media Treatment Well (HRX Well$^{®)}$ technology, a new in situ remediation approach for managing dissolved contaminants from source zones in complex geological settings (Divine et al. 2013). The overall project objective is to complete a field demonstration of this technology to quantify technical performance, assess limitations of the technology, and provide a basis for wider application at United States Department of Defense and other sites. Based on application of the site selection criteria at two candidate sites (Divine et al. 2016), Installation Restoration Program Site 3 (SS003; the Site) located within the Cantonment Area at Vandenberg Air Force Base (VAFB) was selected as the demonstration site to perform further treatability study of HRX Well technology.

To assist the preliminary HRX Well design phase at SS003 and to evaluate the field performance of the HRX Well post installation, a three-dimensional groundwater flow model was developed based on Site-specific data. The model was constructed using the United States Geologic Survey (USGS) MODFLOW code (McDonald and Harbaugh 1988) to simulate the groundwater flow regime and the hydraulic capture of the proposed HRX Well. MODPATH (Pollock 2016) were used in conjunction with MODFLOW to predict the groundwater flow paths towards the HRX Well. This document summarizes the development of the flow model at the Site and related modeling results, which consists of the following section:

- A brief review of the conceptual site model (CSM);
- Construction and calibration of the groundwater flow model;
- Predictive hydraulic capture of the HRX Well; and
- Project clean water breakthrough time in monitoring wells downgradient of the HRX Well.

2 SITE DATA REVIEW/CSM DEVELOPMENT

SS003 has been divided into three adjoining geographical areas including the 9300 Block, the Mesa Area, and the Canyon Area as shown on **Figure 1**. Note that the proposed location of the HRX Well is within the Mesa Area. Three saturated zones in the subsurface have been identified onsite: (1) the laterally discontinuous shallow perched zone; (2) the contiguous Principal Zone; and (3) the discontinuous deep saturated zone.

The approximate location of the planned HRX Well is within the Principle Zone, which consists of silt with occasional fine-grained sands overlaying a continuous greenish/olive gray clay. The hydraulic slug tests and 72-hour constant rate test conducted at adjacent Site SS050 indicate the unconsolidated alluvial material within the Principal Zone have moderately low hydraulic conductivity values ranging from 0.01 feet per day (ft/d) at well 50-MW-8 to 11 ft/d at well 156-MW-13 with a geometric mean hydraulic conductivity value of 0.35 ft/d from all test results.

Divine et al. 2016 and Divine et al. 2017a summarize the saturated thickness ranges from approximately 12 feet in the vicinity of well 3-MW-35D to approximately 8 feet immediately upgradient of well 3-MW-13 in the vicinity of the HRX Well (**Figure 1**). The dominant groundwater gradient direction in the Principal Zone is southeast toward Oak Canyon. The horizontal hydraulic gradient is generally flatter than other portions of the Site and historically ranged approximately 0.007 to 0.012 feet per foot (ft/ft) between wells 3-MW-35D and 3-MW-14.

Additional Site characterization work was performed from August to November 2017 with details described in the Draft Treatability Test Report (Divine et al. 2017b). Site characterization included the following elements to refine the understanding of groundwater and contaminant fluxes in the vicinity of the proposed HRX Well.

- Advancing six hydraulic profiling tool (HPT) borings;
- Advancing two soil borings that were then completed as monitoring wells;
- Sampling five monitoring wells;
- Single-Well Tracer Testing at three monitoring wells; and
- Installation, sampling, and analysis of passive flux meters (PFMs) at three monitoring wells.

Figure 1 shows the spatial location of the newly installed HPT borings and monitoring wells near the HRX Well. Based on the HPT logging data, a continuous zone of higher permeability (indicated by lower corrected pressure and estimated hydraulic conductivity) was identified within the Principal Zone between 3-SB-34 and 3-SB-37 (**Figure 2**). The thickness of this higher permeability zone ranges from 2 to 4 feet with a range of hydraulic conductivity of from 0.1 to 20 ft/d. The groundwater flux measured from PFMs are also low, ranging from 0.1 to 0.2 ft/d. The difference in groundwater flux estimation might relate to the sensitivity limitations of the techniques and/or the different scales of vertical resolution provided by these techniques when characterizing the hydraulic parameters. HPT borings provide hydraulic conductivity at the highest vertical resolution (1 measurement every 0.05 foot), the PFMs provide intermediate resolution (approximate 0.5 foot interval, PFM results pending), and the single well tracer tests provide an average across the monitoring well screen interval (10-foot interval). Regardless, both methods confirm ambient groundwater flux is low.

On July 16, 2018, Directed Technologies Drilling Inc. (DTD) began the installation prototype HRX well at Site 003 on VAFB in California. The pilot bore was completed with a total length of 657 feet. Data from the locating procedure was summarized and documented in the Well Completion Report (DTD 2018). The HRX Well assembly included:

- Entry end riser: 12-inch pipe – total 103.9 feet, including a section added to extend the wellhead above ground, after installation;
- Inlet screen - 95.5 feet;
- Center blank section - 140.9 feet;
- Outlet screen: 70.3 feet; and

- Exit end riser: 160.8 feet.

The HRX Well bore path extends from a paved parking area, adjacent to a small building, crosses beneath a landscaped area, paved street, and then returns to the surface in an undeveloped grassy/brushy area, south of the street. The depth of the horizontal section of the HRX Well is designed at approximately 432 feet above mean sea level (amsl). HRX Well treatment media and instrumentation placement was completed on August 9, 2019. Note that the effective radius of the treatment media is nominally 10 inches with a nominal 1-inch thick cartridge wall.

3 GROUNDWATER FLOW/TRANSPORT MODEL DEVELOPMENT

3.1 Model Code Selection

The MODFLOW code, a publicly-available groundwater flow simulation program developed by the USGS, was used to construct the groundwater flow model at the Site. It is thoroughly documented; widely used by consultants, government agencies, and researchers; and is consistently accepted by the regulatory and scientific community. The flow model was used in conjunction with the MODPATH code to delineate the hydraulic effectiveness or effective capture width of the HRX Well and to predict the residence time of groundwater entering the HRX Well.

3.2 Finite-Difference Grid Discretization

The model domain extents were designed to reflect all relevant hydraulic features within the surrounding area of the HRX Well and were located a sufficient distance from the HRX Well to reduce the potential for boundary effects on simulated results.

The model was rotated 15.4 degrees counterclockwise to align an axis of the model with the HRX Well orientation at the Site. **Figure 3** shows the extent of horizontal model grid developed for the groundwater flow model, which extends approximately 850 feet along the groundwater flow direction and approximately 300 feet perpendicular to the groundwater flow direction. The model grid was refined to a very fine 5-inch by 5-inch grid cell spacing in the vicinity of the HRX Well to enhance model accuracy and precision. Outside of the area of interest, the model cell spacing gradually increases to a maximum spacing of 5 feet by 5 feet.

Based on the CSM development and a comprehensive review of the additional Site characterization work, the top of the Principle Zone generally occurs between 10 to 15 feet below grade. The saturated portion of the Principal Zone ranges from approximately 423.3 feet amsl to 440.0 feet amsl with variable aquifer thickness along the HRX Well. The model was vertically discretized into 11 model layers with a 5-inch layer thickness representing the HRX Well from layers 6 to 7 and that gradually increased up to a maximum layer thickness of 2.0 feet at the top of the model (layers 1 to 3) and 1.2 feet maximum layer thickness at the bottom of the model (layers 8 to 10). Note that a variable thickness was assigned to model layer 11 based on the boring logs to depict the varying bottom elevation of the Principle Aquifer.

Overall, the finite-difference grid constructed for the model consists of 894 columns and 258 rows with 11 layers for a total of 2,537,172 grid cells.

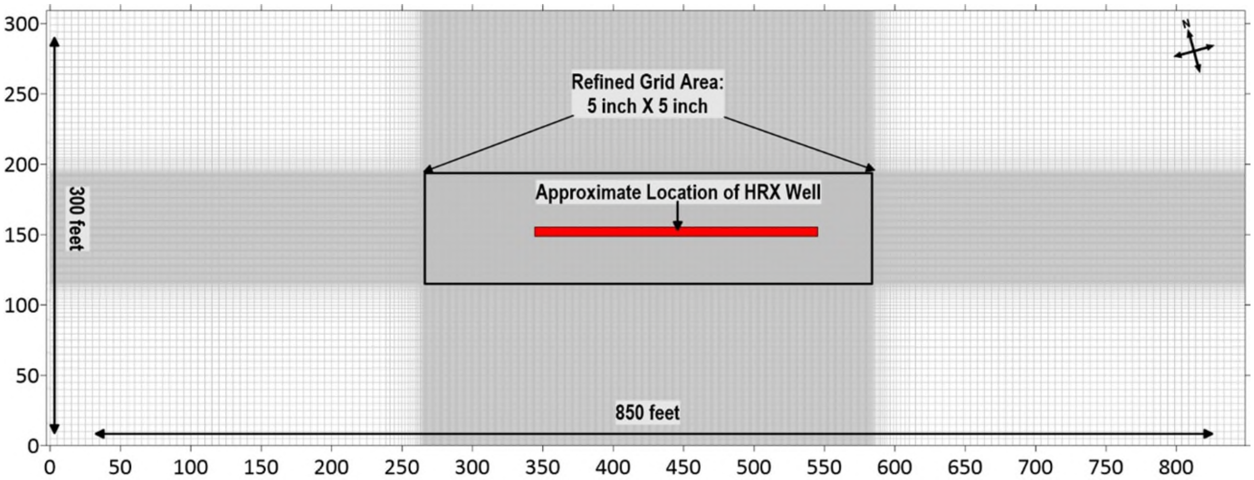


Figure 3. Model Grid Layout

3.3 Boundary Conditions

No-flow boundaries were also assigned to model grid cells along the northeastern and southwestern edges of the model to represent the inferred groundwater flow lines across the Site (i.e., no groundwater flux occurs perpendicular to the groundwater flow path line). To eliminate boundary effects, a pre-HRX Well model was developed by setting constant head boundaries at upgradient and downgradient model boundaries with a constant groundwater elevation of 440.0 feet amsl and 431.50 feet amsl, respectively to maintain the average site gradient of 0.01 ft/ft measured between wells 3-MW-35D and 3-MW-14 (an average of measurements during 2017 and 2018). Groundwater recharge at the Site was considered minimal and was not simulated.

To eliminate the artificial boundary effect of enhanced domain flow during HRX Well simulation as a result of a constant head boundary, a background model (i.e., without representation of HRX Well property) was firstly simulated with constant head boundary value discussed above. Then the calculated groundwater flux values were extracted at the constant head location from the water budget file of the background model. The extracted groundwater flux was then simulated with the HRX Well package in MODFLOW as prescribed flux values to ensure the regional groundwater flows in the model during HRX Well simulations were fixed and consistent, preventing the erroneous boundary effects.

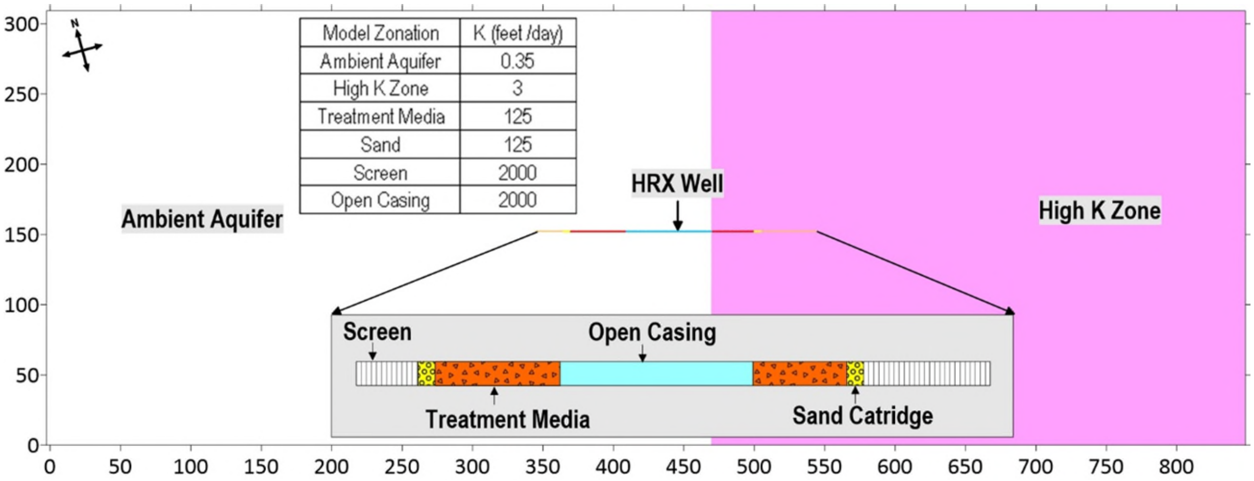
3.4 Hydraulic Conductivity Zonation

Three hydraulic conductivity zones were delineated to represent the principal aquifer material, the HRX Well media, and the higher permeability zone. Based on the results of the slug tests and pumping test, a uniform hydraulic conductivity was used to represent the average hydraulic condition in principal aquifer material in all model layers. The higher permeability zone presented from layers 1 to 10. Along the groundwater flow direction, this zone is horizontally bounded by 3-SB-34 and 3-SB-37 where high hydraulic conductivity value has been observed in the HPT logging data.

The other hydraulic conductivity zones were delineated to represent the treatment media consists of iron and sand, inlet screen/outlet screen, and center blank section.

Devlin (2018) performed permeameter tests to measure the hydraulic performance of iron-sand mixtures (i.e., HRX Well treatment media). #16 sand was mixed with Connelly granular iron such that the final mixture was 10.7% iron, or 35% iron. Each type of iron-sand mixture was packed in plastic columns and conducted permeameter test. The permeameter tests yielded a hydraulic conductivity value of approximately 60 meter per day (196 ft/day). However, to compensate for dimensional limitations of the finite difference grid to exactly represent the radial geometry of the HRX Well, an equivalent hydraulic conductivity value of 125 ft/d was used for the HRX Well treatment media zone. **Figure 4** presents the hydraulic conductivity zonation in model layer 6.

On April 8, 2019, pumping test was completed in the HRX Well by installing packer system to extract from inlet screen and pumped 263 gallons through treatment media for 20 hours and discharged to outlet the screen. HRX well became dry at the end of the pumping test. The pumping test last 20 hours and transducer were installed at upgradient monitoring well 3-MW-35D and downgradient monitoring wells 3-MW-47. The groundwater model hydraulic conductivity values were transiently calibrated to match the transducer data during pumping data at 3-MW-35D and 3-MW-47. **Figure 4** presents the calibrated hydraulic conductivity values for ambient aquifer, high K zone, and treatment media to be 0.35 ft/d, 3.0 ft/d, and 125 ft/d, respectively. **Figure 5** shows the simulated groundwater levels at 3-MW-35D and 3-MW-47 matches the observed transducer data reasonably well given the uncertainties (e.g., well bore storage effects, flow rate measurement) associated with the pumping test.



Model Zonation	K (feet /day)
Ambient Aquifer	0.35
High K Zone	3
Treatment Media	125
Sand	125
Screen	2000
Open Casing	2000

Figure 4. Model Hydraulic Conductivity Zonation

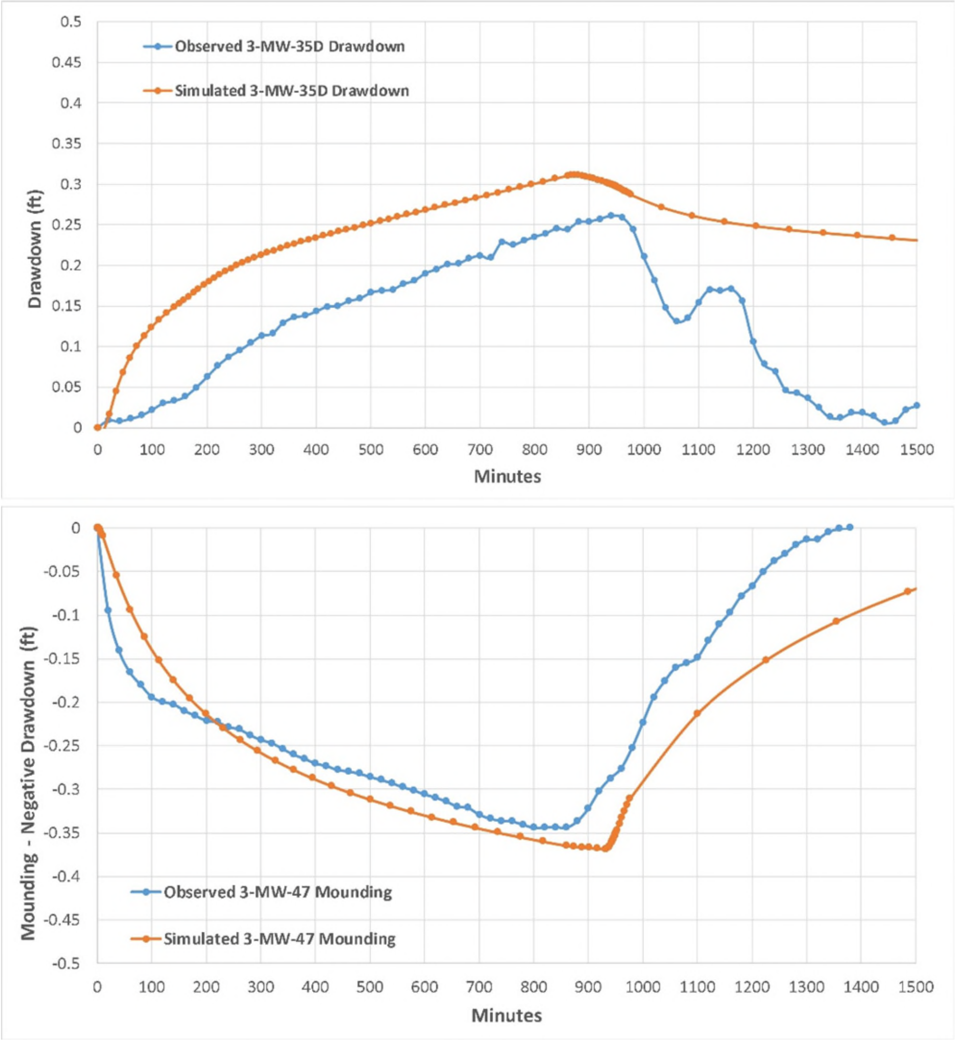


Figure 5. Transient Calibration Hydrograph of 3-MW-35D and 3-MW-47

4 HRX PERFORMANCE EVALUATION

To evaluate the field performance of the HRX Well, two scenarios were designed to simulate the effective capture and treatment zone width of the HRX Well and the potential for enhanced-capture condition. Scenario 1 ("passive configuration") is the base line scenario where an 12-inch diameter HRX Well consists of 5 feet of sand cartridges, following 40 feet of treatment media with 60 feet of open casing in the middle and another 30 feet of treatment media with 5 feet of sand-filled monitoring cartridges at the end was simulated with the calibrated groundwater model. The calibrated model has an ambient aquifer zone hydraulic conductivity of 0.35 ft/d and higher permeability zone of 3.0 ft/d. Scenario 2 ("active configuration") is designed to simulate enhanced groundwater flow through the HRX Well by placing a pump in the upgradient entrance screen section, and immediately connect to a simulated injection pump that discharges the pumped water downgradient to the exit screen. The extraction pump and injection pump are separated by a packer system to prevent hydraulic interference. The pumping/injection rates were tested and capped at 3.90 cubic feet per day (ft^3/d), which is approximately equal to the average sustainable flow rate observed during the pumping test and two times of groundwater flow in the passive configuration scenario (1.95 ft^3/d).

4.1 HRX Well Capture Evaluation

Figure 6 present the simulated capture width and residence time in Scenarios 1 and 2 in model layer 6. As shown, the simulated capture width under the passive configuration in Scenario 1 was 52 feet with an average groundwater residence time of 9 days within the treatment media of HRX well. This simulation best represents the operation and performance of the as-built HRX Well installed at VAFB. Based on the previous project treatability study (Divine 2017b) the trichloroethene (TCE) decay rate was estimated at 1.81^{-1} decay rate for a 35% iron and 65% sand mixture, which suggests it will take a minimum of 4 days of contact with the zero valent iron for TCE to degrade from 75,000 parts per billion (ppb) to 50 ppb. Therefore, the as-built passive configuration of HRX Well would provide an estimated safety factor of 2 for a treatment of TCE to less than 50 ppb. The flushing width of treated water that exits on the downgradient side of the HRX Well was estimated to be similar to the upgradient capture width.

In active configuration evaluated in Scenario 2, which simulates continual pumping at the estimated maximum aquifer sustainable yield, the results show a larger capture zone due to the enhanced flow condition through the HRX Well. The predicted capture width is approximately 70 feet, which is approximately 35% larger than the passive configuration scenario. The average residence time within the treatment media is 5.5 days, which is theoretically sufficient to achieve less than 50 ppb treatment goal.

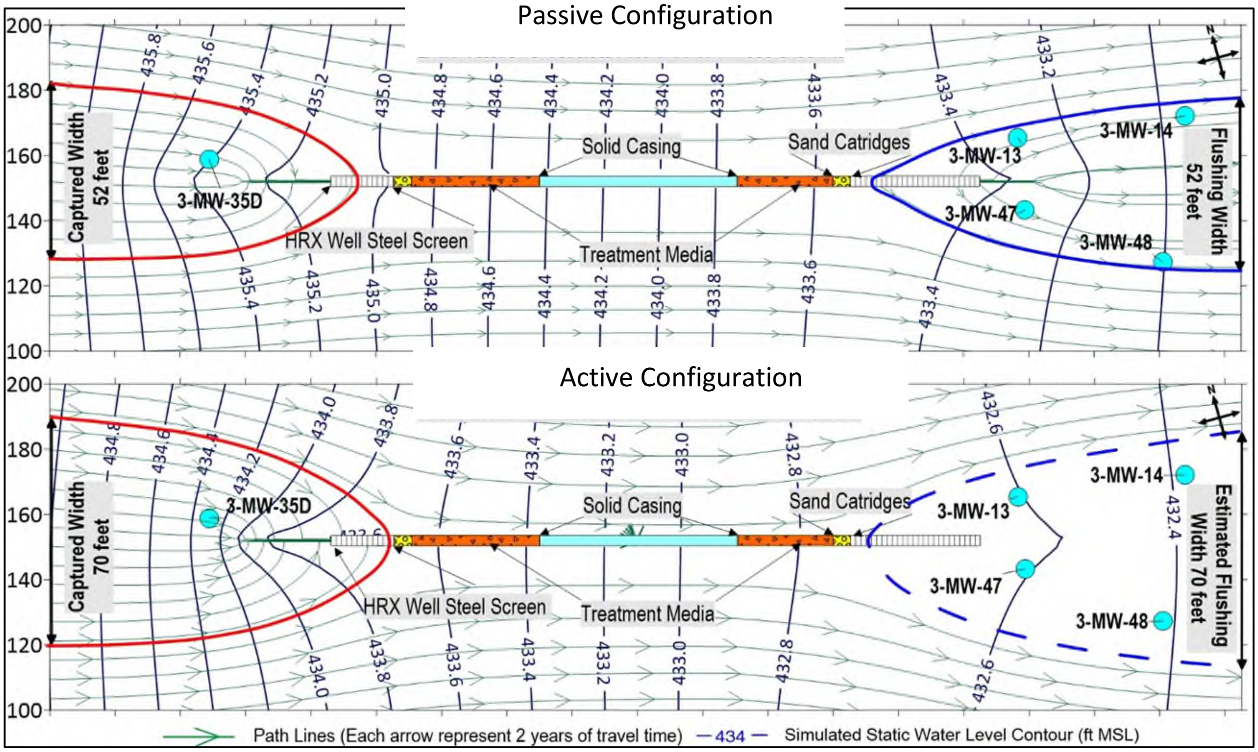


Figure 6. Simulated Capture Extent and Pathline in Baseline Scenario and Enhanced Scenario

4.2 HRX Well Treatment Evaluation

After the HRX Well installation, groundwater quality data were collected at downgradient monitoring wells to evaluate the treatment performance of the HRX Well. The observed changes in TCE and cis-1,2-dichloroethene (cis-1,2-DCE) concentrations over time at all downgradient wells (3-MW-47, 3-MW-48, 3-MW-13, and 3-MW-14) indicate that the first breakthrough of treated water ranges from approximately 50 days to 200 days. Path line analysis was performed using the calibrated groundwater model to estimate the breakthrough time (i.e., travel time) from the HRX Well outlet to downgradient monitoring wells. **Table 1** summarizes the estimated travel time by simulating effective porosity values of 1%, 5% and 10% for the Principal Aquifer. The model simulated breakthrough time are generally within the range of the observed breakthrough time of TCE and cis-DCE.

Table 1. Observed and Simulated Breakthrough Time

Monitoring Well	Observed Breakthrough Time (days)		Simulated Breakthrough Time (days)		
	Observed Breakthrough - TCE	Observed Breakthrough cis-1,2-DCE	10% Effective Porosity	5% Effective Porosity	1% Effective Porosity
MW-47	<92	<92	167	83	17
MW-13	<50	92-176	267	133	27
MW-48	92-157	157-250	1100	550	110
MW-14	<92	--	1000	500	100

5 SUMMARY

The groundwater modeling results indicate that the HRX Well will provide long-term hydraulic capture and mass discharge reduction at Site SS003 at VAFB. A capture width of 52 feet was calculated for the passive configuration and 70 feet for the active configuration. Under passive and the simulated residence time within the treatment media for the passive configuration is approximately 9 days, which is sufficient to achieve the treatment goal (< 50 ppb) for TCE and represents a safety factor of approximately 2. Based on the observed TCE and cis-1,2-DCE concentrations in monitoring wells following HRX Well installation, the breakthrough of treated water at downgradient monitoring wells ranges from 50 to 200 days, which is consistent with the simulated breakthrough times, which further confirms the treatment effectiveness of the HRX well.

6 REFERENCES

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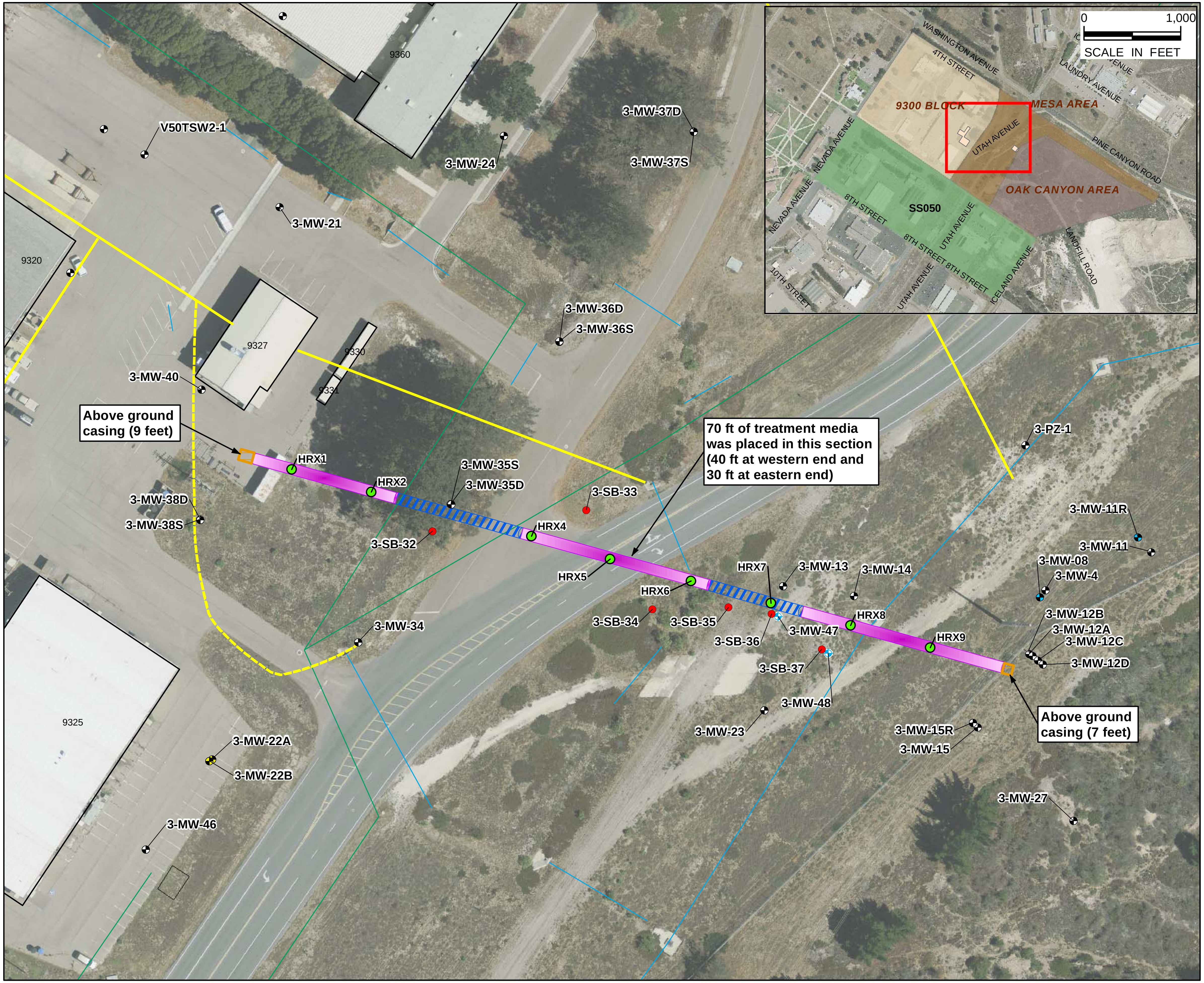
Figures



Legend

● HRX Point Location

Existing Locations

- Principal Zone Monitoring Wells
- Deep Saturated Zone Monitoring Wells
- Monitoring Well Locations

Task 2A Site Characterization Locations

- New Soil Boring/MW
- ● HPT Boring Location

Proposed HRX Well

- Well Screen
- Well Casing
- ☐ Above Ground Casing
- ☐ Building
- ▨ Demolished Building
- Stormwater Line
- Sewer Line
- Wastewater Line

Notes:

1. Dashed wastewater line is based on Tetra Tech observation in the field.
2. Monitoring wells with -S and -D suffixes (in example, 3-MW-32S and 3-MW-32D) are nested wells designated in the Shallow Zone and Principal Zone, respectively. "Shallow Zone Monitoring Well" symbols are hidden at these locations by corresponding Principal Zone nested wells' symbols. 3-MW-22A and 3-MW-22B are both Shallow Zone.

0 70 140

SCALE IN FEET

* Tetra Tech 2008. Final Site 3 Geophysical Survey Technical Memorandum. Site 3 Vandenberg Air Force Base. April.

FOR OFFICIAL USE ONLY

Source: Basemap data layers were provided by Vandenberg Air Force Base, September 2014.

VANDENBERG AIR FORCE BASE CALIFORNIA
FINAL REPORT - APPENDIX A

SITE LOCATION AND HRX WELL AS-BUILT MAP

ARCADIS Design & Consultancy for natural and built assets

FIGURE
1

PATH: Z:\GISProjects_ENV\USAFB\VandenbergAFB\GIS\ArcMap_MXD\Site_SS003\GW_FTM_SummaryMemoFig1_SS003_HRX_and_HTP_Well_LayoutMap.mxd 9/18/2019 1:42:29 PM Last saved by: mestifanos

CITY:ROSEVILLE DIV/GROUP:ENVCAD DB:ENVCAD PM:(Reqd)
C:\Users\barobita\OneDrive - ARCADIS\BIM 360 Docs\U_S_ARMY_HUMPHREYS ENGINEERING CENTER SUPPORT ACTIVITY\USACE-HORIZONTAL REACTIVE MEDI\2018\CI001924.0001\01-DWG\CI0019240001 Cross Sections v3.dwg LAYOUT: A-A SAVED: 2/22/2018 10:58 AM PLOTSTYLETABLE: PLTFULL.CTB
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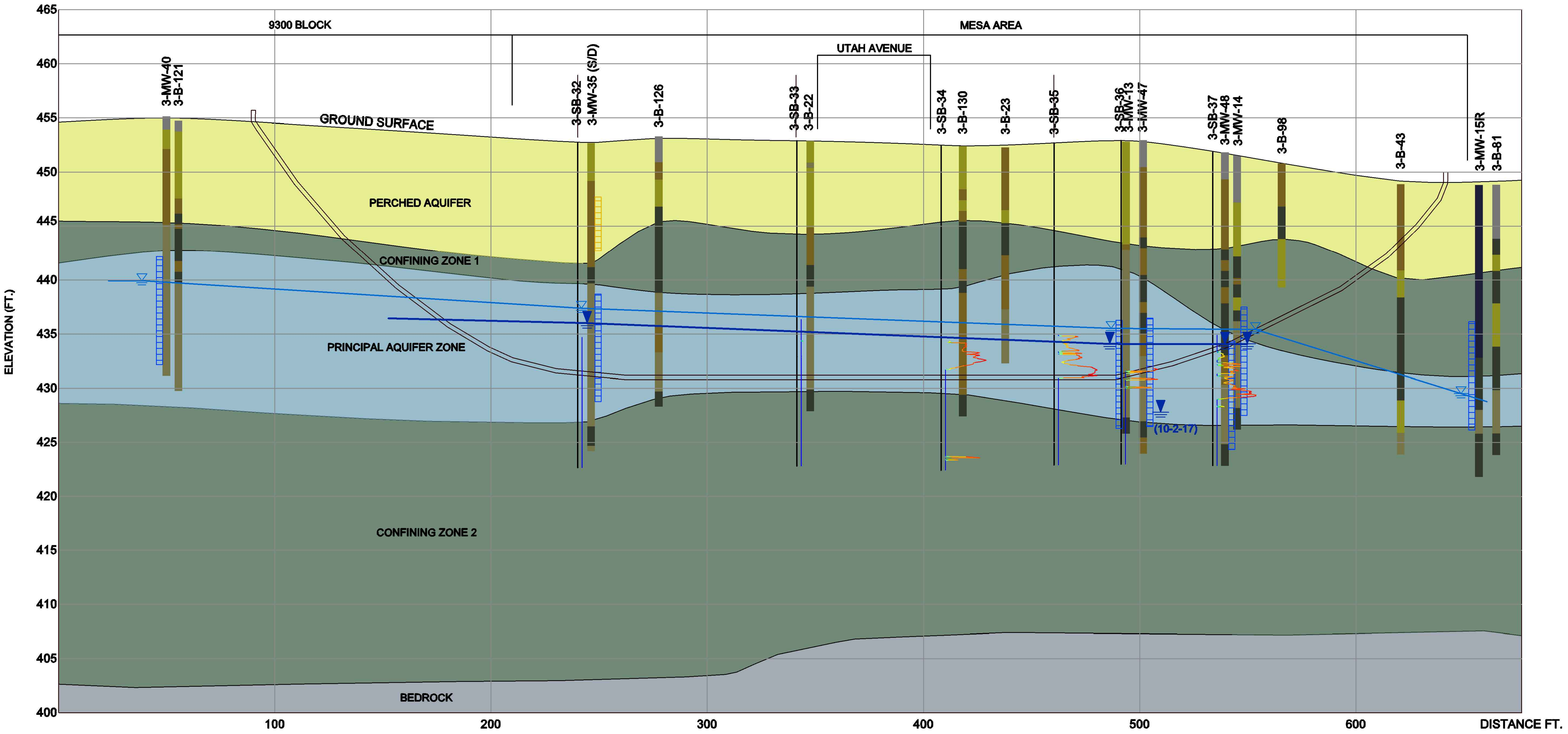

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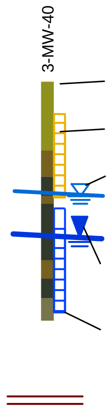


WELL/BORING IDENTIFICATION
SOIL BORING
SCREEN (PERCHED ZONE)
GROUNDWATER ELEVATION (FEET ABOVE MEAN SEA LEVEL) (JUNE 2010)
GROUNDWATER ELEVATION (FEET ABOVE MEAN SEA LEVEL) (OCTOBER 2017)
SCREEN (PRINCIPAL ZONE)
HRX WELL ALIGNMENT

BOREHOLE LITHOLOGY

■	FILL
■	CLEAN SANDS AND GRAVELS
■	SILTY AND CLAYEY SANDS AND GRAVELS
■	SILTS
■	SILTS WITH CLAYS
■	CLAYS
■	BEDROCK
■	NO RECOVERY

TCE CONCENTRATION

■	> 100,000 µg/L
■	> 50,000 µg/L
■	> 10,000 µg/L
■	> 1,000 µg/L
■	> 100 µg/L
■	> 5 µg/L

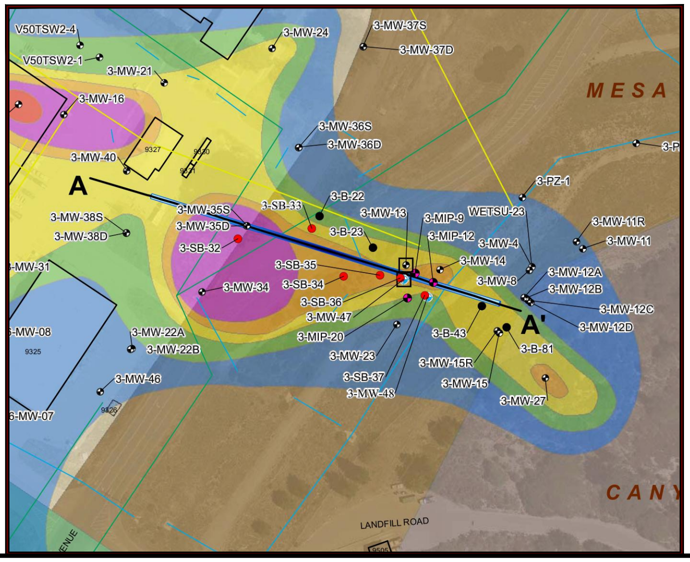
HYDROSTRATIGRAPHIC UNITS

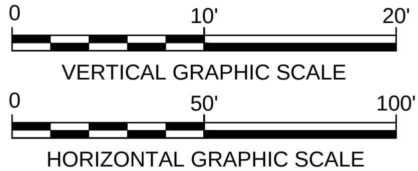
■	PERCHED AQUIFER
■	CONFINING ZONE 1
■	PRINCIPAL AQUIFER ZONE
■	CONFINING ZONE 2
■	BEDROCK

HPT HYDRAULIC COND (K)

19 FT/DAY
10 FT/DAY
3 FT/DAY
1 FT/DAY
0.3 FT/DAY
0.1 FT/DAY

NOTE:
K = HYDRAULIC CONDUCTIVITY (FT/DAY)





VERTICAL EXAGGERATION = 5X HORIZONTAL

VANDENBERG AIR FORCE BASE CALIFORNIA
FINAL REPORT - APPENDIX A

GEOLOGIC CROSS SECTION (A-A') ORIENTED ALONG HRX WELL ALIGNMENT

ARCADIS Design & Consultancy for natural and built assets

FIGURE
2

Appendix B

DTD Well Completion Report

Directed Technologies Drilling
Incorporated

August 13, 2018

Craig Divine
Arcadis US
320 Commerce
Suite 2000
Irvine, CA 92602
craig.divine@arcadis.com

RE: Draft Well Completion Report – HRX Well Pilot – Site 3 – Vandenberg AFB

Dear Craig:

Thank you to you and Arcadis for teaming with DTD on the installation of the prototype Horizontal Reactive Media Treatment (HRX) well at Site 3 on Vandenberg Air Force Base in California. As you know, the installation appears to have been successful, which will hopefully be confirmed as monitoring data becomes available. As described below, there were some necessary changes made to the bore profile and the point velocity probe installation required some modification to install into the well. Other than these changes, the well installation proceeded as planned.

I have documented construction details in the table below. The bore profile, as determined from a combination of pitch and depth data from our walkover locating system is provided as an attachment. The X-Y locations of the locating points were marked in the field with pin flags or paint; DTD did not survey these points.

Well Construction Details – HRX-1

Well Length: Total well length (including stickup at each end) 665.0 feet

Screened Intervals: Inlet 95.4' Outlet 70.3'

Riser Lengths: Entry end 103.9' total – including added above-ground stickup.
Exit end 160.8

Screen Lengths: Inlet: 95.5'
Outlet: 70.3'

Central Blank: 140.9'

Screen Elevation: Start of Inlet – 437.9' End of Outlet – 434.0'

Screen Material: 12-inch Alloy 304L SS wire wrap with .375" wall round-hole perforated carbon steel shield.

Slot Specifications (as installed) "tight" 0.008" wire wrap.

Riser and Central Piping: nominal 12-inch, 0.375" wall' carbon steel pipe.

Drilling Fluid: Baroid BioBore biodegradable biopolymer

Well Development additives: CETCO LEB-CD enzyme breaker

Mobilization and Setup

DTD mobilized a 7-person crew to VAFB on Monday, July 16, 2018. The crew reported to the VAFB visitor center for site access badging and then proceeded to the Arcadis site trailer for site orientation and health and safety briefings. The crew then received equipment and supplies at Site 3 to begin setup for drilling and started to assemble and weld well screen and casing.

Several logistical details were identified.

- The conceptual bore profile needed to be adjusted to provide enough vertical clearance between a 4-foot diameter sewer line and the bore. In doing so, the well length had to be extended beyond a fence that defines the boundary for the landfill that is south of the well. Also, it was necessary to clear brush and other vegetation below the exit point of the well to provide work space for staging the well materials and for trailing/supporting drill rods during the reaming and pullback process. Some of this work was accomplished while drilling of the pilot bore was underway.
- DTD worked with Arcadis, who in turn secured the necessary authorizations from VAFB to extend the bore beyond the fence line and to clear brush. Additional contact with VAFB was made to verify minimum allowable clearance between the drill tooling and the sewer line.
- Hot work permits were also obtained, and the fire department approved the areas for welding the casing and at the entry end of the well for miscellaneous activities requiring welding or torch work. Welding commenced on July 17 and continued for several days to assemble casing and screen sections. Due to the limited space available (~200 feet) for assembly, the well materials were welded into three segments, which were subsequently joined together during the well pullback operation.
- A means to transfer drilling fluid from the exit collection pit back to the drill rig was identified. This required placement of a high capacity pump at the exit side and stringing 4-inch diameter hose back to the mud system. Arcadis identified a culvert that passed beneath New Mexico Street, which allowed DTD to push a 4-inch HDPE pipe through with connections to the hose at each end. This setup allowed uninterrupted transfer of drilling fluid from the exit side to the rig side during reaming and pullback.
- Traffic control procedures were established to stop traffic on New Mexico Street when off-road construction equipment was shuttled over the road.

Drilling and Reaming Operations

Drilling for the pilot bore commenced on Saturday, July 21 and continued through Wednesday, July 25. Drilling operations were interrupted by VAFB rocket launch operations, which required a 40-hour shutdown of all invasive ground construction operations, including drilling or reaming, prior to launch. One shutdown was scheduled during drilling of the pilot bore, and another during the reaming operations.

Drilling was performed with a 6.75-inch duckbill (jetting) drill bit. No major difficulties were encountered in advancing the bore, although mitigation of drilling fluid leaks to the ground surface (described below) did slow operations.

The pilot bore was completed on July 25, to a total length of 657 feet. Data from the locating procedure was compiled into a spreadsheet and the bore profile and pertinent stationing and elevations generated from the worksheet are provided as attachments.

Inadvertent Return of Drilling Fluid

While drilling the pilot bore, several inadvertent returns (IR) of drilling fluid to the ground surface occurred and required cleanup. A zone of IR surfacing occurred near a drainage ditch that parallels New Mexico Street, near the bore entry. At this location, a combination of loose soil, the depth of the ditch, and the relative shallowness of the bore at this point along the profile resulted in recurrent IR events. A vacuum trailer and the large exit side pump were employed to contain the surfaced drilling fluid and convey it back to the mud system. This zone of IR reactivated at various times during drilling and reaming, but eventually healed, with no further fluid loss seen during pullback or well development.

A second zone of IR occurred at the exit end of the bore, where the exit curve of the bore brought high-volume mud flow near the ground surface. At this location, small channels were excavated to direct mud flow back to the exit pit, where it collected to be pumped back to the mud system.

Upon completion of the well installation, both zones were restored. Dried drilling fluid (essentially sand) was pushed to the exit pit, or returned from the ditch to the mud system, and the ground was lightly graded during the demobilization process.

Reaming Operations

The 6.75-inch pilot bore was reamed to its final diameter in two operations. First the bore was enlarged with a 14-inch reaming tool, then a second reaming pass enlarged the diameter to 18 inches. Before pullback, the 18-inch reamer was pulled through the bore a second time in a "swab pass" to remove drill cuttings and prepare the bore for pullback. Reaming commenced on July 26 and was completed with the final swab pass on August 2.

A combination of "push" or forward reaming and "back" reaming was employed to economize on the work effort and to control mud flow from the bore. The smaller, 14-inch reaming pass was completed by attaching the reaming tool at the drill rig and advancing it forward toward the exit. The reamer was attached by breaking the rods adjacent to the drill rig and inserting the reamer into the drill string. This resulted in drill rods advancing through the bore ahead of the reamer. The rods were controlled by attaching the string via a swivel to a trackhoe, which backed down away from the exit, keeping the string in tension. As the trackhoe reached the end of the prepared work area, the rods would be broken into sections of ~200 feet. Close coordination by radio was maintained to synchronize efforts and assure safety at both ends of the bore.

When the forward reaming pass was completed, a larger reamer was attached at the exit end and pulled back toward the rig, trailing rods behind it. These were also controlled with a trackhoe at the exit end.

During reaming, intermittent IR occurred in the previously noted zones. These continued to be contained and/or diverted back to the exit pit.

Well Installation

After reconfiguring the reaming tools, the first section of assembled well materials was attached to a swivel, which was in turn attached to the 18-inch reamer at the exit end. The materials were drawn smoothly back towards the drill rig. The first section of the well was pulled back on August 2. On August 3, pullback continued, pausing only to weld on the remaining two well segments. Pullback was complete at 1648 on August 3.

The well assembly included:

- Entry end riser: 12-inch pipe – total 103.9 feet, including a section added to extend the wellhead above ground, after installation.
- Inlet screen - 95.5'
- Center blank section - 140.9'
- Outlet screen: 70.3'
- Exit end riser: 160.8'

Well materials were supplied through PQ Products of Spokane, Washington. The screen is a proprietary product manufactured by Alloy Machine Works.

Center Section Grouting

After the well was installed, the next critical task was to grout the central, blank section of the well. This is a crucial step to prevent groundwater from bypassing the well though the larger bore and higher permeability zone adjacent to the well casing.

During assembly of the well materials, DTD designed and attached two steel tremie pipes with rearward-facing ports at the center point of the center well section. These pipes, measuring about 30 feet in length, were welded to the blank section of the well assembly, and extended towards the exit end of the well. HDPE tubing was connected to the ends of the two steel pipes in sufficient length to reach the ground surface.

During pullback, these HDPE pipes were damaged by movement of the 12-inch diameter well casing. One pipe was completely severed and the other was pinched flat, rending them both unusable for grouting. An unsuccessful attempt was made to insert a tremie pipe manually from the center section. Upon procurement of 2-inch diameter PVC, a tremie was successfully installed from the entry end, half way through the central blank section.

The volume of the bore annulus between the well screens was calculated. Half of that volume of heavy, viscous grouted was evaluated to be enough to plug the central bore annulus, without risking intrusion of grout into the two adjoining well screen segments. Accordingly, the grout was mixed using a Groutmaster grout plant and injected into the tremie using a positive displacement pump. The tremie pipe was then removed from the bore.

Well Development

Upon installation of the well casing and screen, DTD undertakes a well development process to ensure effective communication between the well and the surrounding geologic formation. DTD began the well development process on August 6, 2018. The entry end of the well was still closed by the pulling head used to install the well. A hole was cut in in the well casing near the well end, and a threaded nipple was welded into place. This nipple was, in turn, connected to hose leading to the water truck. This setup was used to flush water into the interior of the well casing – it subsequently emerges from the screen into the bore annulus, carrying residual drilling fluid and cuttings to the surface at each well end.

Development began by flushing from the entry to the exit end of the well assembly. Approximately 5,600 gallons of water, treated with a breaker enzyme, were flushed through the well to remove mud, fines, and turbid water from the well interior. This water issued from the exit end of the well as well as from the bore annulus. Water was captured at the exit and pumped to the containment tanks.

The exit end of the well was then capped to force all water out through the slotted sections. This water returned to both the exit and entry ends of the well (note, water flow along the central section of the bore was blocked by the previously-placed grout, as planned.) No grout was noted in the return water at either end, indicating that grout had not entered the screened zones. This effort was completed using approximately 2,400 gallons of enzyme-treated water. Of this total volume (8,000 gallons), approximately 4,200 gallons were recovered and conveyed to the mud recycler, the remainder entered the formation or remained in the well.

Following the flushing effort, DTD attached a custom-fabricated jetting tool to the string of drill rods. The jetting tool was equipped with centralizers to center it in the well screen, and multiple jets on an enlarged center section to reduce the distance from the jets to the screen slots. This was done to maximize the water jet impingement on the screen slots for more effective cleaning.

A total of four jetting passes was made through each of the screened sections, with two passes completed through the blank section. Approximately 3,800 gallons of water was used in jetting, with ~3,200 gallons recovered, primarily from the exit side of the well.

The final well development step was to insert a submersible pump at the exit side. The 3-phase, 400 gpm capacity pump was set to a location within the riser pipe, ~ 3 feet short of the screen (to avoid sucking sand directly through the screen). The high capacity pump removed ~ 2,400 gallons of water within a few minutes. Following this initial drawdown of the accumulated water in the well, the flow rate slowed to 16 gpm. Water was initially cloudy with light red-brown coloration, then cleared to moderately turbid, with translucent grey color. During development, DTD collected water samples in clear bottles. A trace silty v. fine sand sediment was noted in the recovered water at pump startup, clearing to no visible particulates in subsequent samples.

Following the initial pump startup, and in communication with Arcadis (Jesse Wright), the well was drawn down and allowed to recover in several cycles.

- Allowed well to recover for 10 minutes, then restarted pump. Pump required ~ 2 minutes to return water to discharge point, at 16 gpm. Pumped for 10 minutes, then stopped pumping.
- Allowed well to recover 10 minutes, then restarted pump. Again, required 2-minute wait for water return, and pumped for 10 minutes at 11 gpm. Water visibly less turbid, with no residual drilling mud or viscosity.
- Allowed to recover 10 minutes, pumped again for 10 minutes at 15 gpm. Pump cavitating. Turbidity same as last sample.

During this cycled phase, a total of ~800 gallons of water was recovered, in addition to the previous 2,400, for a total of ~3290 gallons of water measured in the recovery tank. At this point, in communication with Arcadis, well development was agreed to be complete.

Media Placement

After well development was complete, the pre-constructed media cartridges were lifted into position, bolted together, and pushed into place with the drill rig. The entry-side cartridges were first inserted. Installation included bolting the cartridge flanges together, sandwiching a rubber annular seal between the flanges. A wire cage containing bentonite chips was then fastened over two of the flange joints to provide additional annular sealing between the cartridge assembly and the containing walls of the well.

Once the media was in place, the PVP instrumentation cartridges were connected to their control cables and water tubing. This critical operation was time-consuming, and required splicing of tubing and/or wiring to assure sufficient length was available to reach the wellhead. All modifications/extensions to the PVP controls were made in communication with Rick Devlin at Kansas University. The PVPs and attached tubing were bled with deionized water and a peristaltic pump in coordination with Arcadis (Jesse Hinkle) prior to installation. The PVP control loom was then shielded inside PVC pipe for the placement in the well. DTD used a custom-fabricated pushing tool to push the instrumentation cartridges into place using the drill rig.

Media and instrumentation placement was completed on Thursday, August 8 (entry side) and Friday, August 9 (exit side). While cartridges were being placed, additional efforts included welding an extension onto the entry side wellhead to bring it above ground, overall site restoration, and preparation of equipment for demobilization.

Wellhead Completion

The wellheads were completed by introducing a thick grout mix to a depth of approximately 30 feet, letting it set, and then grouting back to the ground surface. After this was completed, the entry and exit pits were backfilled with soil and compacted. At the entry end, saw cutting of the pavement was completed to provide a neat appearance to the site. At the exit side, lumber was used to form up a rectangular, elevated well pad. Redi-mix concrete was brought in to finish both wellheads, which were trowl-finished.

The construction work for the well installation was completed by Friday, August 10. Some light work remained to continue demobilization, with a limited DTD crew on site until the following week to load the drill rig and finalize demobilization.

Sincerely,

Directed Technologies Drilling, Inc.

Michael D. Lubrecht

Michael D. Lubrecht
Project Manager / Senior Geologist

Cc:
Jesse Wright – Arcadis
Hoa Voscott – Arcadis
Dan Ombalski – Directed Technologies Drilling, Inc.
Luke Anderson – Directed Technologies Drilling, Inc.

Attachment: Bore profile – HRX well

Client Name:	ARCADIS	
Job Name:	ESTCP Pilot HRx Project	
Well Name:	HRx - 01	
Location:	VAFB, CA	
Drill Rig:	DD 10	
Drill bit:	6.75" Duckbill	
Well Screen:	WW 304L CS shield	
Well Casing:	12" CS	
Length of Drill Rods:	20	ft
Length of Borehole:	564.0	ft (Horizontal Distance)
Length of Well:	567.0	ft
Entry Casing Length:		ft
Screen Length:		ft
Exit Casing Length		ft

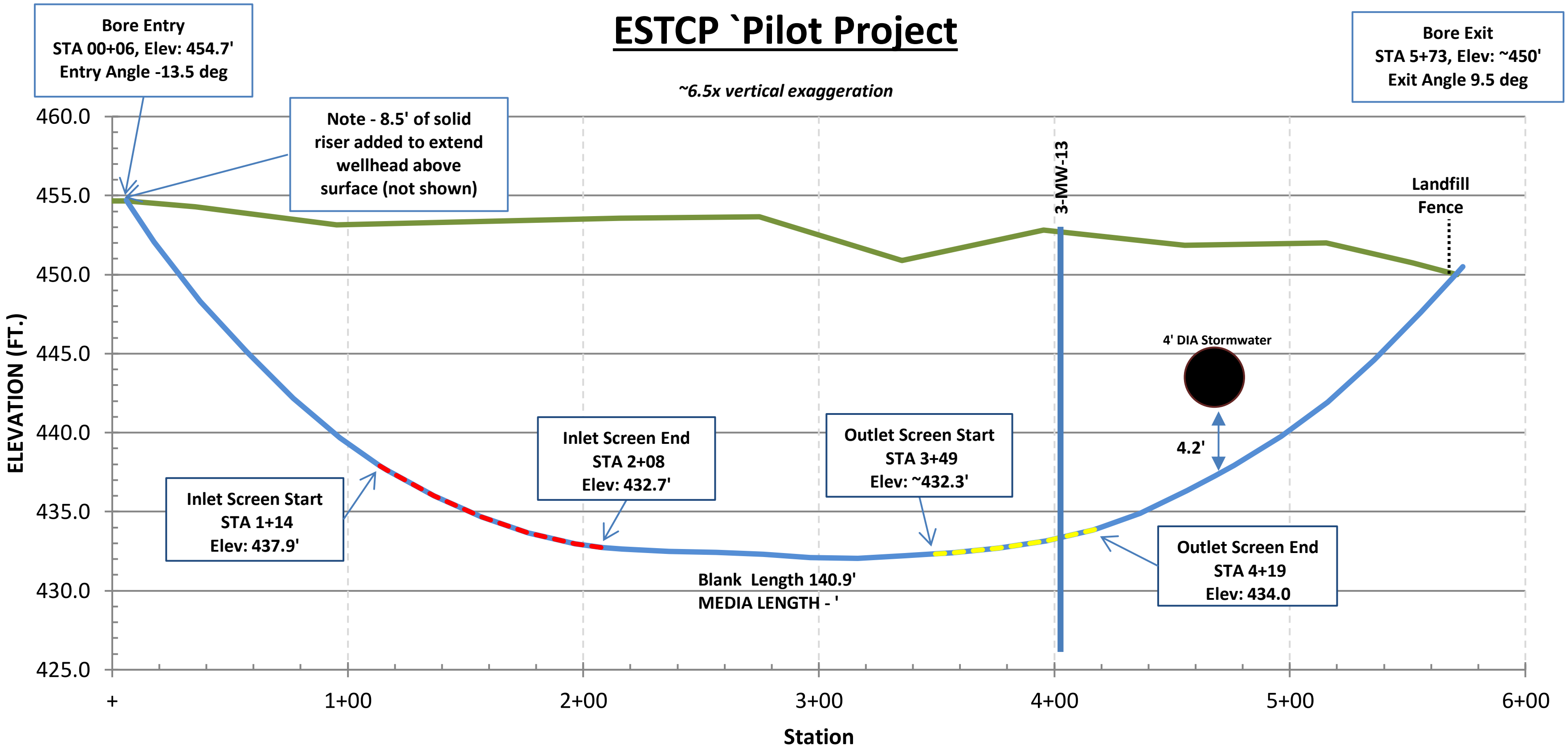
Directed Technologies Drilling Incorporated

Rig Entry Angle	-13.5	degrees
Elevation at Point of Entry	454.7	ft
Station at Point of Entry	+6	station
Horz distance from Transmitter to Point of Entry	8	ft
Height of Transmitter above Point of Entry	0	ft

Rod	Rod Distance from Vices (ft)	Station (#+##)	Description	Bore Elevation (ft amsl)	Percent Slope (%)	Vertical Angle (degrees)	Horizontal Distance (cumulative ft)	Calculated Depth (ft below entry)
Point of Entry	8	+6	Blank Riser	454.7	-24.0 %	-13.5	0.0	0.0
1	20	+18	Blank Riser	452.1	-21.3 %	-12.0	11.7	2.6
2	40	+37	Blank Riser	448.3	-16.7 %	-9.5	31.4	6.4
3	60	+57	Blank Riser	445.1	-15.8 %	-9.0	51.1	9.6
4	80	+77	Blank Riser	442.2	-13.9 %	-7.9	70.9	12.5
5	100	+97	Blank Riser	439.7	-11.4 %	-6.5	90.7	15.0
5.85	117	1+14	inlet screen start @ Elev 4	437.9	-9.5 %	-5.4	107.6	16.8
6	120	1+17	inlet screen - 437.95	437.6	-9.1 %	-5.2	110.6	17.1
7	140	1+37	inlet screen - 436.3	436.0	-7.2 %	-4.1	130.5	18.7
8	160	1+57	inlet screen - 434.1?	434.7	-5.9 %	-3.4	150.5	20.0
9	180	1+76	inlet screen - 433.89	433.7	-4.4 %	-2.5	170.5	21.0
10	200	1+96	inlet screen - 433.0	433.0	-2.6 %	-1.5	190.5	21.7
10.6	212	2+08	inlet screen end @Elev 43	432.7	-1.6 %	-0.9	202.5	22.0
11	220	2+16	Blank - 432.36	432.6	-0.7 %	-0.4	210.5	22.1
12	240	2+36	Blank - 432.15	432.5	-0.7 %	-0.4	230.5	22.2
13	260	2+56	Blank - 432.43	432.4	0.0 %	0.0	250.5	22.3
14	280	2+76	Blank	432.3	-1.0 %	-0.6	270.5	22.4
15	300	2+96	Blank - 432.08	432.1	-1.2 %	-0.7	290.5	22.6
16	320	3+16	Blank - 432.02	432.0	0.9 %	0.5	310.5	22.7
17	340	3+36	Blank - 432.15	432.2	0.9 %	0.5	330.5	22.5
17.65	353	3+49	outlet start screen	432.3	0.7 %	0.4	343.5	22.4
18	360	3+56	outlet screen - 432.55	432.4	1.4 %	0.8	350.5	22.3
19	380	3+76	outlet screen - 432.88	432.7	1.7 %	1.0	370.5	22.0
20	400	3+96	outlet screen - 433.26	433.1	2.6 %	1.5	390.5	21.6
21	420	4+16	outlet screen - 433.2??	433.8	4.4 %	2.5	410.4	20.9
21.15	423	4+19	outlet end screen	434.0	4.4 %	2.5	413.4	20.7
22	440	4+36	Blank Riser - 435.19	434.9	6.5 %	3.7	430.4	19.8
23	460	4+56	Blank Riser - 436.49	436.3	7.9 %	4.5	450.4	18.4
23.6	472	4+68	Blank Riser - storm sta 46	437.3	7.9 %	4.5	462.3	17.4
24	480	4+76	Blank Riser - 437.82	437.9	8.7 %	5.0	470.3	16.8
25	500	4+96	Blank Riser - 440.38	439.8	9.6 %	5.5	490.2	14.9
26	520	5+16	Blank Riser - 441.92	441.9	12.3 %	7.0	510.1	12.8
27	540	5+36	Blank Riser	444.6	14.6 %	8.3	529.9	10.1
28	560	5+56	Blank Riser	447.6	15.8 %	9.0	549.7	7.1
28.75	575	5+70	Blank Riser	450.0	16.7 %	9.5	564.5	4.7
28.9	578	5+73	Blank Riser	450.5	16.7 %	9.5	567.5	4.2

HRx Well As-Built
ARCADIS - Vandenberg AFB site
ESTCP `Pilot Project

~6.5x vertical exaggeration



BORE NOTES:
Bore Length 567'
Horizontal Length 564'
Inlet Screen Length 95.4'
Outlet Screen Length 70.3'

MEDIA NOTES:
Inlet Media Length
60' total length + 5' PVP cartridge
(40' total HRX media)
Outlet Media Length
45.1 total
(30' total HRX media)

Approx Ground Surface ● Stormwater As-Built Inlet Screen Outlet Screen

Appendix C

Summary of Groundwater Elevation Data

Appendix C - Groundwater Elevations
ESTCP Draft Final Report
Demonstration and Validation of the Horizontal Reactive Media Treatment Well
for Managing Contaminant Plumes in Complex Geologic Environments

Well ID	Gauging Event	Measurement Date	TOC (ft amsl)	Depth to Water (ft below TOC)	Groundwater Elevation (ft amsl)
3-MW-13	Pre-Installation	10/2/2017	452.36	18.27	434.09
3-MW-14		10/2/2017	451.81	17.74	434.07
3-MW-35D		10/2/2017	452.59	16.52	436.07
3-MW-47		10/2/2017	452.99	25.19	427.80
3-MW-48		10/2/2017	451.86	17.78	434.08
3-MW-13	134 days Post-Installation	12/13/2018	452.36	18.78	433.58
3-MW-14		12/13/2018	451.81	18.94	432.87
3-MW-35D		12/13/2018	452.59	17.07	435.52
3-MW-47		12/13/2018	452.99	22.92	430.07
3-MW-48		12/13/2018	451.86	18.23	433.63
3-MW-13	175 days Post-Installation	1/24/2019	452.36	18.67	433.69
3-MW-14		1/23/2019	451.81	19.40	432.41
3-MW-35D		1/21/2019	452.59	17.14	435.45
3-MW-47		1/21/2019	452.99	22.90	430.09
3-MW-48		1/23/2019	451.86	18.60	433.26
3-MW-13	250 days Post-Installation	4/8/2019	452.36	18.23	434.13
3-MW-14		4/8/2019	451.81	18.00	433.81
3-MW-35D		4/8/2019	452.59	16.40	436.19
3-MW-47		4/8/2019	452.99	21.20	431.79
3-MW-48		4/8/2019	451.86	17.98	433.88
3-MW-13	349 days Post-Installation	7/15/2019	452.36	17.45	434.91
3-MW-14		7/15/2019	451.81	17.11	434.70
3-MW-35D		7/16/2019	452.59	16.41	436.18
3-MW-47		7/16/2019	452.99	20.19	432.80
3-MW-48		7/16/2019	451.86	17.17	434.69
3-MW-13	436 days Post-Installation	10/11/2019	452.36	18.60	433.76
3-MW-14		10/11/2019	451.81	18.10	433.71
3-MW-35D		10/11/2019	452.59	16.25	436.34
3-MW-47		10/11/2019	452.99	20.21	432.78
3-MW-48		10/11/2019	451.86	18.51	433.35

TOC = top of casing
ft amsl = feet above sea level

Appendix D

Field Water Quality Readings

Appendix D - Field Water Quality Readings
ESTCP Draft Final Report
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	Sample Location	3-MW-13	3-MW-13	3-MW-13	3-MW-13	3-MW-13
	Sample Number	SS003-3-MW-13(1Q18)	SS003-3-MW-13(3Q18)	SS003-3-MW-13(4Q18)	SS003-3-MW-13(1Q19)	SS003-3-MW-13(2Q19)
	Sample Date	1/4/2018	7/10/2018	11/7/2018	1/24/2019	4/8/2019
Chemical	**Units**					
Conductivity	uS/cm	6844	8388	4116	7949	7182
Dissolved Oxygen	mg/l	1.18	0.39	1.09	2.57	1.32
Oxidation Reduction Potential	mV	-17.6	142	-213.6	-239.6	-209.1
pH	pH units	7.56	7.19	5.05	7.43	7.02
Specific Conductivity	umhos/cm	NA	NA	NA	NA	NA
Specific Conductivity	uS/cm	NA	NA	NA	NA	NA
Temperature	C	21.3	23.7	22.7	21.4	22.4
Turbidity	ntu	23	13	1000	412	271

Attachment D - Field Water Quality Readings
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	Sample Location	3-MW-13	3-MW-13	3-MW-14	3-MW-14	3-MW-14
	Sample Number	SS003-3-MW-13(3Q19)	SS003-3-MW-13(4Q19)	SS003-3-MW-14(4Q18)	SS003-3-MW-14(1Q19)	SS003-3-MW-14(2Q19)
	Sample Date	7/15/2019	10/11/2019	11/7/2018	1/23/2019	4/8/2019
Chemical	**Units**					
Conductivity	uS/cm	8198	1511	3980	6840	6767
Dissolved Oxygen	mg/l	1.35	1.11	1.42	1.74	1.62
Oxidation Reduction Potential	mV	-268.3	-31.6	-150.7	-89.7	-82.8
pH	pH units	8.01	6.9	4.13	5.37	5.24
Specific Conductivity	umhos/cm	NA	NA	NA	NA	NA
Specific Conductivity	uS/cm	NA	NA	NA	NA	NA
Temperature	C	23.2	18.7	22.1	19.7	20.9
Turbidity	ntu	99	38	1000	241	1000

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Sample Location Sample Number Sample Date		3-MW-14 SS003-3-MW-14(3Q19) 7/15/2019	3-MW-14 SS003-3-MW-14(4Q19) 10/11/2019	3-MW-35D SS003-3-MW-35D(1Q18) 1/3/2018	3-MW-35D SS003-3-MW-35D(4Q18) 11/7/2018	3-MW-35D SS003-3-MW-35D(1Q19) 1/21/2019
Chemical	**Units**					
Conductivity	uS/cm	7608	1346	2169	7879	8893
Dissolved Oxygen	mg/l	4.83	0.84	2.11	2.53	1.77
Oxidation Reduction Potential	mV	-195.6	-61.4	-29.5	-44.8	-258.4
pH	pH units	8.07	7.1	7.1	5.89	6.02
Specific Conductivity	umhos/cm	NA	NA	NA	NA	NA
Specific Conductivity	uS/cm	NA	NA	NA	NA	NA
Temperature	C	20.4	18.4	19.6	19.8	16.4
Turbidity	ntu	281	31	36	194	87

Attachment D - Field Water Quality Readings
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	Sample Location Sample Number Sample Date	3-MW-35D SS003-3-MW-35D(2Q19) 4/8/2019	3-MW-35D SS003-3-MW-35D(3Q19) 7/18/2019	3-MW-35D SS003-3-MW-35D(4Q19) 10/11/2019	3-MW-47 SS003-3-MW-47(4Q18) 11/7/2018	3-MW-47 SS003-3-MW-47(1Q19) 1/21/2019
Chemical	**Units**					
Conductivity	uS/cm	8144	4022	1486	3951	5518
Dissolved Oxygen	mg/l	1.35	1.75	1.87	1.07	1.06
Oxidation Reduction Potential	mV	110.2	28.1	39.1	-143.2	-380.9
pH	pH units	4.97	6.7	6.84	5.27	6.29
Specific Conductivity	umhos/cm	NA	NA	NA	NA	NA
Specific Conductivity	uS/cm	NA	NA	NA	NA	NA
Temperature	C	19.8	18.6	18.4	22.2	19.8
Turbidity	ntu	48	12	13	1000	96

Attachment D - Field Water Quality Readings
ESTCP Draft Final Report
Demonstration and Validation of the Horizontal Reactive Media Treatment Well for Managing Contaminant Plumes in Complex Geologic Environments

	Sample Location	3-MW-47	3-MW-47	3-MW-47	3-MW-48	3-MW-48
	Sample Number	SS003-3-MW-47(2Q19)	SS003-3-MW-47(3Q19)	SS003-3-MW-47(4Q19)	SS003-3-MW-48(4Q18)	SS003-3-MW-48(1Q19)
	Sample Date	4/8/2019	7/16/2019	10/11/2019	11/7/2018	1/23/2019
Chemical	**Units**					
Conductivity	uS/cm	3907	4959	1391	4583	7228
Dissolved Oxygen	mg/l	2.54	1.07	0.71	2.11	1.06
Oxidation Reduction Potential	mV	112.6	95.3	-26.1	-211.7	-134.6
pH	pH units	5.75	6.93	6.81	5.27	5.5
Specific Conductivity	umhos/cm	NA	NA	NA	NA	NA
Specific Conductivity	uS/cm	NA	NA	NA	NA	NA
Temperature	C	20.5	20.2	18.2	21.1	21.8
Turbidity	ntu	152	10	12	1000	1000

Attachment D - Field Water Quality Readings
ESTCP Draft Final Report
Demonstration and Validation of the Horizontal Reactive Media Treatment Well for Managing Contaminant Plumes in Complex Geologic Environments

	Sample Location	3-MW-48	3-MW-48	3-MW-48
	Sample Number	SS003-3-MW-48(2Q19)	SS003-3-MW-48(3Q19)	SS003-3-MW-48(4Q19)
	Sample Date	4/8/2019	7/16/2019	10/11/2019
Chemical	**Units**			
Conductivity	uS/cm	6708	7247	1390
Dissolved Oxygen	mg/l	3.78	2.94	1.64
Oxidation Reduction Potential	mV	83.2	-29.7	-37.1
pH	pH units	5.65	6.65	7.1
Specific Conductivity	umhos/cm	NA	NA	NA
Specific Conductivity	uS/cm	NA	NA	NA
Temperature	C	20.2	18.9	18.3
Turbidity	ntu	592	32	23

Appendix E

VOCs Groundwater Analytical Results

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Sample Location			**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**
Sample ID			**SS003-3-MW-13(3Q17)**	**SS003-DUP1(3Q17)**	**SS003-3-MW-13-100217**	**SS003-DUP1-100217**	**SS003-3-MW-13(1Q18)**	**SS003-3-MW-13(3Q18)**	**SS003-3-MW-13(4Q18)**	**SS003-3-MW-13(1Q19)**
Sample Date			**7/17/2017**	**7/17/2017**	**10/2/2017**	**10/2/2017**	**1/4/2018**	**7/10/2018**	**11/7/2018**	**1/24/2019**
Parameter	**CAS**	**Units**								
1,1,1,2-Tetrachloroethane	630-20-6	ug/l	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U	< 2.5 U	< 0.50 U
1,1,1-Trichloroethane	71-55-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,1,2,2-Tetrachloroethane	79-34-5	ug/l	< 1.0 U	< 1.0 U	**0.69 J**	**0.84 J**	**1.2**	**1.9**	**3.1 J**	< 1.0 U
1,1,2-trichloro-1,2,2-trifluoroethane	76-13-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,1,2-Trichloroethane	79-00-5	ug/l	**4.1**	**3.9**	**4.8**	**4.6**	**4.9**	**5.6**	**5.2**	**0.81 J**
1,1-Dichloroethane	75-34-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,1-Dichloroethene	75-35-4	ug/l	< 1.0 U	< 1.0 U	**0.69 J**	**0.65 J**	< 1.0 U	**0.37 J**	< 5.0 U	**6.7**
1,1-Dichloropropene	563-58-6	ug/l	**0.17 J**	**0.18 J**	**0.20 J**	**0.22 J**	**0.16 J**	**0.15 J**	< 5.0 U	< 1.0 U
1,2,3-Trichlorobenzene	87-61-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,2,3-Trichloropropane	96-18-4	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 10 U	< 2.0 U
1,2,4-Trichlorobenzene	120-82-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,2,4-Trimethylbenzene	95-63-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,2-Dibromo-3-chloropropane	96-12-8	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 10 U	< 2.0 U
1,2-Dibromoethane	106-93-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,2-Dichlorobenzene	95-50-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,2-Dichloroethane	107-06-2	ug/l	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U	**0.16 J**	**0.14 J**	< 2.5 U	**3.2**
1,2-Dichloropropane	78-87-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,3,5-Trimethylbenzene	108-67-8	ug/l	< 1.0 U	< 1.0 U	**0.19 J**	**0.19 J**	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,3-Dichlorobenzene	541-73-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,3-Dichloropropane	142-28-9	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
1,4-Dichlorobenzene	106-46-7	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
2,2-Dichloropropane	594-20-7	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
2-Butanone (MEK)	78-93-3	ug/l	< 10 U	< 10 U	**12**	**12**	< 10 U	**8.3 J**	**190**	**180**
2-Chloroethyl vinyl ether	110-75-8	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
2-Chlorotoluene	95-49-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
4-Chlorotoluene	106-43-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
4-Methyl-2-Pentanone	108-10-1	ug/l	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 50 U	< 10 U
Acetone	67-64-1	ug/l	**72**	**73**	**110**	**110**	**210**	**73**	< 50 U	**150**
Benzene	71-43-2	ug/l	**2.6**	**2.6**	**2.9**	**2.9**	**2.6**	**2.5**	**1.8 J**	**2.4**
Bromobenzene	108-86-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Bromochloromethane	74-97-5	ug/l	**0.28 J**	**0.30 J**	**0.48 J**	**0.52 J**	**1.0**	**0.41 J**	**0.57 J**	< 1.0 U
Bromodichloromethane	75-27-4	ug/l	**0.17 J**	**0.17 J**	**0.24 J**	**0.26 J**	**0.19 J**	**0.16 J**	< 5.0 U	< 1.0 U
Bromoform	75-25-2	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Bromomethane	74-83-9	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Carbon Disulfide	75-15-0	ug/l	**1.2**	**1.1**	**1.4**	**1.4**	**2.2**	**1.1**	**5.3**	**5.2**
Carbon Tetrachloride	56-23-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
CFC-11	75-69-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U

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		Sample Location	3-MW-13	3-MW-13	3-MW-13	3-MW-13	3-MW-13	3-MW-13	3-MW-13	3-MW-13
		Sample ID	SS003-3-MW-13(3Q17)	SS003-DUP1(3Q17)	SS003-3-MW-13-100217	SS003-DUP1-100217	SS003-3-MW-13(1Q18)	SS003-3-MW-13(3Q18)	SS003-3-MW-13(4Q18)	SS003-3-MW-13(1Q19)
		Sample Date	7/17/2017	7/17/2017	10/2/2017	10/2/2017	1/4/2018	7/10/2018	11/7/2018	1/24/2019
Parameter	CAS	Units								
CFC-12	75-71-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Chlorobenzene	108-90-7	ug/l	< 1.0 U	< 1.0 U	**0.21 J**	**0.21 J**	< 1.0 U	**0.25 J**	< 5.0 U	**0.18 J**
Chlorodibromomethane	124-48-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Chloroethane	75-00-3	ug/l	**0.68 J**	**0.72 J**	**0.55 J**	**0.52 J**	**0.77 J**	**0.54 J**	< 5.0 U	**0.53 J**
Chloroform	67-66-3	ug/l	**15**	**15**	**17**	**17**	**17**	**20**	**8.9**	**0.26 J**
Chloromethane	74-87-3	ug/l	**22**	**23**	**19**	**18**	**71 J**	**19**	**52**	**1.4**
cis-1,2-Dichloroethene	156-59-2	ug/l	**780**	**810**	**990 D**	**950 D**	**750**	**870**	**620**	**4800**
cis-1,3-Dichloropropene	10061-01-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Cymene (p-Isopropyltoluene)	99-87-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	**0.18 J**
Dichloromethane	75-09-2	ug/l	**9.1**	**9.4**	**12**	**11**	**15**	**12**	**14**	**13 J**
Dichloromonofluoromethane	75-43-4	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
Di-isopropyl ether	108-20-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Ethyl tert-butyl ether	637-92-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Ethylbenzene	100-41-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	**1.3 J**	**0.96 J**
Hexachloro-1,3-butadiene	87-68-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Isopropylbenzene	98-82-8	ug/l	**0.36 J**	**0.36 J**	**0.48 J**	**0.50 J**	**0.12 J**	**0.27 J**	< 5.0 U	**0.17 J**
m&p-Xylenes	ARC-mpXyl	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	**3.8 J**	**1.7 J**
Methyl N-Butyl Ketone (2-Hexanone)	591-78-6	ug/l	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 50 U	< 10 U
Methyl-tert-butylether	1634-04-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Naphthalene	91-20-3	ug/l	< 2.0 U	< 2.0 U	**1.0 J**	**1.1 J**	**0.57 J**	**0.41 J**	< 10 U	**0.55 J**
n-Butylbenzene	104-51-8	ug/l	**0.43 J**	**0.44 J**	**0.51 J**	**0.52 J**	**0.26 J**	**0.29 J**	< 5.0 U	**0.20 J**
n-Propylbenzene	103-65-1	ug/l	**0.45 J**	**0.47 J**	**0.58 J**	**0.59 J**	**0.34 J**	**0.38 J**	< 5.0 U	**0.21 J**
o,p-Xylene	136777-61-2	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
o-Xylene	95-47-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	**1.6 J**	**0.65 J**
sec-Butylbenzene	135-98-8	ug/l	**0.50 J**	**0.51 J**	**0.61 J**	**0.62 J**	**0.31 J**	**0.38 J**	< 5.0 U	**0.21 J**
Styrene (Monomer)	100-42-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
tert-Amyl methyl ether	994-05-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
tert-Butyl alcohol	75-65-0	ug/l	< 10 U	< 10 U	**16**	**16**	**510 J**	**14**	< 50 U	**40**
tert-Butylbenzene	98-06-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Tetrachloroethene	127-18-4	ug/l	**18**	**18**	**19**	**18**	**15**	**22**	**8.6**	**0.66 J**
Toluene	108-88-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 UB	< 1.0 U	**0.34 J**	< 1.0 U	< 5.0 U	**0.12 J**
trans-1,2-Dichloroethene	156-60-5	ug/l	**450**	**440**	**530 D**	**500 D**	**390**	**420**	**250**	**270**
trans-1,3-Dichloropropene	10061-02-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 1.0 U
Trichloroethene	79-01-6	ug/l	**6200**	**6000**	**6900 D**	**6600 D**	**4300**	**6900**	**3800**	**190 J**
Vinyl acetate	108-05-4	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 10 U	< 2.0 U
Vinyl chloride	75-01-4	ug/l	**0.44 J**	**0.46 J**	< 0.50 U	< 0.50 U	**0.42 J**	**0.45 J**	< 2.5 U	**2.4 J**

		Sample Location	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-14**	**3-MW-14**
		Sample ID	**SS003-DUP4(1Q19)**	**SS003-3-MW-13(2Q19)**	**SS003-DUP1(2Q19)**	**SS003-3-MW-13(3Q19)**	**SS003-DUP1(3Q19)**	**SS003-3-MW-13(4Q19)**	**SS003-3-MW-14(3Q17)**	**SS003-3-MW-14-100217**
		Sample Date	**1/24/2019**	**4/8/2019**	**4/8/2019**	**7/15/2019**	**7/15/2019**	**10/11/2019**	**8/8/2017**	**10/2/2017**
Parameter	**CAS**	**Units**								
1,1,1,2-Tetrachloroethane	630-20-6	ug/l	< 0.50 U	< 0.50 U	< 0.50 U	**0.38 J**	**0.42 J**	< 0.50 U	< 2.5 U	< 2.5 U
1,1,1-Trichloroethane	71-55-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,1,2,2-Tetrachloroethane	79-34-5	ug/l	**0.69 J**	**0.33 J**	**0.36 J**	**0.38 J**	< 1.0 U	**0.90 J**	**280**	**360**
1,1,2-trichloro-1,2,2-trifluoroethane	76-13-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,1,2-Trichloroethane	79-00-5	ug/l	**0.95 J**	**1.2**	**1.2**	**3.3**	**3.5**	**4.2**	**6.5**	**8.1**
1,1-Dichloroethane	75-34-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,1-Dichloroethene	75-35-4	ug/l	**6.0**	**2.2**	**2.2**	**2.4**	**2.7**	**6.1**	< 5.0 U	< 5.0 U
1,1-Dichloropropene	563-58-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	**0.31 J**	**0.32 J**	**0.28 J**	< 5.0 U	< 5.0 U
1,2,3-Trichlorobenzene	87-61-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,2,3-Trichloropropane	96-18-4	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 10 U	< 10 U
1,2,4-Trichlorobenzene	120-82-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,2,4-Trimethylbenzene	95-63-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,2-Dibromo-3-chloropropane	96-12-8	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 10 U	< 10 U
1,2-Dibromoethane	106-93-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,2-Dichlorobenzene	95-50-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,2-Dichloroethane	107-06-2	ug/l	**3.1**	**2.1**	**2.1**	**1.6**	**1.5**	< 0.50 U	**0.67 J**	**0.76 J**
1,2-Dichloropropane	78-87-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,3,5-Trimethylbenzene	108-67-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,3-Dichlorobenzene	541-73-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,3-Dichloropropane	142-28-9	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
1,4-Dichlorobenzene	106-46-7	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
2,2-Dichloropropane	594-20-7	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
2-Butanone (MEK)	78-93-3	ug/l	**150**	**37**	**39**	**21**	**21**	< 10 U	**13 J**	**30 J**
2-Chloroethyl vinyl ether	110-75-8	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
2-Chlorotoluene	95-49-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
4-Chlorotoluene	106-43-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
4-Methyl-2-Pentanone	108-10-1	ug/l	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 50 U	< 50 U
Acetone	67-64-1	ug/l	**130**	**56**	**50**	**29**	**28**	**3.9 J**	**240**	**380**
Benzene	71-43-2	ug/l	**2.2**	**1.6**	**1.6**	**2.4**	**2.4**	**2.5**	< 5.0 UB	**1.5 J**
Bromobenzene	108-86-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Bromochloromethane	74-97-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	**3.7 J**	**2.9 J**
Bromodichloromethane	75-27-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	**1.6 J**	**0.67 J**
Bromoform	75-25-2	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	**11**	< 5.0 U
Bromomethane	74-83-9	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Carbon Disulfide	75-15-0	ug/l	**4.5**	**2.3**	**2.3**	**1.9**	**1.7**	**1.8**	< 5.0 U	< 5.0 U
Carbon Tetrachloride	56-23-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
CFC-11	75-69-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U

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		Sample Location	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-13**	**3-MW-14**	**3-MW-14**
		Sample ID	**SS003-DUP4(1Q19)**	**SS003-3-MW-13(2Q19)**	**SS003-DUP1(2Q19)**	**SS003-3-MW-13(3Q19)**	**SS003-DUP1(3Q19)**	**SS003-3-MW-13(4Q19)**	**SS003-3-MW-14(3Q17)**	**SS003-3-MW-14-100217**
		Sample Date	**1/24/2019**	**4/8/2019**	**4/8/2019**	**7/15/2019**	**7/15/2019**	**10/11/2019**	**8/8/2017**	**10/2/2017**
Parameter	**CAS**	**Units**								
CFC-12	75-71-8	ug/l	< 1.0 U	< 1.0 UJ	< 1.0 UJ	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Chlorobenzene	108-90-7	ug/l	**0.16 J**	**0.11 J**	**0.12 J**	**0.15 J**	**0.18 J**	**0.15 J**	< 5.0 U	< 5.0 U
Chlorodibromomethane	124-48-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	**1.2 J**	< 5.0 U
Chloroethane	75-00-3	ug/l	**0.44 J**	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Chloroform	67-66-3	ug/l	**0.39 J**	**0.67 J**	**0.68 J**	**1.0**	**1.0**	**5.0**	**37**	**44**
Chloromethane	74-87-3	ug/l	**0.71 J**	**1.5 J**	< 1.0 UJ	< 1.0 U	< 1.0 U	< 1.0 U	**26**	**31**
cis-1,2-Dichloroethene	156-59-2	ug/l	**4500**	**2400**	**2600**	**2300**	**2200**	**720**	**71**	**90**
cis-1,3-Dichloropropene	10061-01-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Cymene (p-Isopropyltoluene)	99-87-6	ug/l	**0.15 J**	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Dichloromethane	75-09-2	ug/l	**9.9 J**	**5.6**	**5.5**	**7.3**	**7.1**	**3.6**	**210**	**230**
Dichloromonofluoromethane	75-43-4	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
Di-isopropyl ether	108-20-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Ethyl tert-butyl ether	637-92-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Ethylbenzene	100-41-4	ug/l	**0.78 J**	**0.20 J**	**0.22 J**	**0.25 J**	**0.27 J**	**0.11 J**	< 5.0 U	< 5.0 U
Hexachloro-1,3-butadiene	87-68-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Isopropylbenzene	98-82-8	ug/l	**0.12 J**	< 1.0 U	< 1.0 U	**0.15 J**	**0.17 J**	**0.19 J**	< 5.0 U	< 5.0 U
m&p-Xylenes	ARC-mpXyl	ug/l	**1.1 J**	**0.44 J**	**0.50 J**	**0.50 J**	**0.52 J**	< 2.0 U	< 10 U	< 10 U
Methyl N-Butyl Ketone (2-Hexanone)	591-78-6	ug/l	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 50 U	< 50 U
Methyl-tert-butylether	1634-04-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Naphthalene	91-20-3	ug/l	**0.44 J**	**0.39 J**	**0.35 J**	**0.50 J**	**0.59 J**	**0.54 J**	< 10 U	< 10 U
n-Butylbenzene	104-51-8	ug/l	**0.17 J**	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
n-Propylbenzene	103-65-1	ug/l	**0.17 J**	< 1.0 U	< 1.0 U	**0.18 J**	**0.18 J**	**0.20 J**	< 5.0 U	< 5.0 U
o,p-Xylene	136777-61-2	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
o-Xylene	95-47-6	ug/l	**0.44 J**	**0.16 J**	**0.19 J**	**0.23 J**	**0.25 J**	**0.11 J**	< 5.0 U	< 5.0 U
sec-Butylbenzene	135-98-8	ug/l	**0.19 J**	< 1.0 U	< 1.0 U	**0.16 J**	**0.18 J**	**0.18 J**	< 5.0 U	< 5.0 U
Styrene (Monomer)	100-42-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
tert-Amyl methyl ether	994-05-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
tert-Butyl alcohol	75-65-0	ug/l	**30**	**24**	**22**	**33**	**31**	**28**	**24 J**	**40 J**
tert-Butylbenzene	98-06-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Tetrachloroethene	127-18-4	ug/l	**0.88 J**	**2.0**	**2.0**	**3.6**	**4.1**	**6.1**	**30**	**38**
Toluene	108-88-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	**0.10 J**	< 1.0 U	< 5.0 U	< 5.0 U
trans-1,2-Dichloroethene	156-60-5	ug/l	**240**	**150**	**170**	**320**	**290**	**250**	**13**	**15**
trans-1,3-Dichloropropene	10061-02-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 5.0 U	< 5.0 U
Trichloroethene	79-01-6	ug/l	**310 J**	**970**	**990**	**1900**	**1700**	**1800**	**21000**	**30000 D**
Vinyl acetate	108-05-4	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 10 U	< 10 U
Vinyl chloride	75-01-4	ug/l	**1.7 J**	**1.8 J**	< 0.50 UJ	**300**	**250**	**590**	< 2.5 U	< 2.5 U

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		Sample Location	**3-MW-14**	**3-MW-14**	**3-MW-14**	**3-MW-14**	**3-MW-14**	**3-MW-35D**	**3-MW-35D**	**3-MW-35D**
		Sample ID	**SS003-3-MW-14(4Q18)**	**SS003-3-MW-14(1Q19)**	**SS003-3-MW-14(2Q19)**	**SS003-3-MW-14(3Q19)**	**SS003-3-MW-14(4Q19)**	**SS003-3-MW-35D(3Q17)**	**SS003-3-MW-35D-100217**	**SS003-3-MW-35D(1Q18)**
		Sample Date	**11/7/2018**	**1/23/2019**	**4/8/2019**	**7/15/2019**	**10/11/2019**	**7/19/2017**	**10/2/2017**	**1/3/2018**
Parameter	**CAS**	**Units**								
1,1,1,2-Tetrachloroethane	630-20-6	ug/l	< 5.0 U	< 0.50 U	< 2.5 U	< 0.50 U	< 0.50 U	< 5.0 U	< 2.5 U	< 5.0 U
1,1,1-Trichloroethane	71-55-6	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,1,2,2-Tetrachloroethane	79-34-5	ug/l	**110 J**	**260**	**340**	**360**	**340**	< 10 U	< 5.0 U	< 10 U
1,1,2-trichloro-1,2,2-trifluoroethane	76-13-1	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,1,2-Trichloroethane	79-00-5	ug/l	**2.4 J**	**4.7**	**4.4 J**	**7.3**	**14**	**5.3 J**	**5.6**	**4.1 J**
1,1-Dichloroethane	75-34-3	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,1-Dichloroethene	75-35-4	ug/l	< 10 U	**0.14 J**	< 5.0 U	**0.17 J**	< 1.0 U	**1.6 J**	**1.8 J**	**2.0 J**
1,1-Dichloropropene	563-58-6	ug/l	**2.2 J**	**4.5**	**2.8 J**	**6.1**	**6.9**	< 10 U	< 5.0 U	< 10 U
1,2,3-Trichlorobenzene	87-61-6	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,2,3-Trichloropropane	96-18-4	ug/l	< 20 U	< 2.0 U	< 10 U	< 2.0 U	< 2.0 U	< 20 U	< 10 U	< 20 U
1,2,4-Trichlorobenzene	120-82-1	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,2,4-Trimethylbenzene	95-63-6	ug/l	< 10 U	**0.12 J**	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,2-Dibromo-3-chloropropane	96-12-8	ug/l	< 20 U	< 2.0 U	< 10 U	< 2.0 U	< 2.0 U	< 20 U	< 10 U	< 20 U
1,2-Dibromoethane	106-93-4	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,2-Dichlorobenzene	95-50-1	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,2-Dichloroethane	107-06-2	ug/l	< 5.0 U	**0.43 J**	< 2.5 U	**0.38 J**	**0.39 J**	< 5.0 U	< 2.5 U	< 5.0 U
1,2-Dichloropropane	78-87-5	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,3,5-Trimethylbenzene	108-67-8	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,3-Dichlorobenzene	541-73-1	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,3-Dichloropropane	142-28-9	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
1,4-Dichlorobenzene	106-46-7	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
2,2-Dichloropropane	594-20-7	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
2-Butanone (MEK)	78-93-3	ug/l	< 100 U	**13**	**28 J**	**150**	**130**	< 100 U	< 50 U	< 100 U
2-Chloroethyl vinyl ether	110-75-8	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
2-Chlorotoluene	95-49-8	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
4-Chlorotoluene	106-43-4	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
4-Methyl-2-Pentanone	108-10-1	ug/l	< 100 U	< 10 U	< 50 U	< 10 U	< 10 U	< 100 U	< 50 U	< 100 U
Acetone	67-64-1	ug/l	< 100 U	**40**	**270**	**1300**	**790**	< 100 U	< 50 U	**240**
Benzene	71-43-2	ug/l	< 10 U	**1.0**	**0.74 J**	**0.83 J**	**0.82 J**	< 10 U	< 5.0 U	< 10 U
Bromobenzene	108-86-1	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Bromochloromethane	74-97-5	ug/l	< 10 U	**1.7**	**1.3 J**	**1.2**	**1.3**	< 10 U	< 5.0 U	< 10 U
Bromodichloromethane	75-27-4	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Bromoform	75-25-2	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Bromomethane	74-83-9	ug/l	**2.3 J**	**1.4**	**0.94 J**	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Carbon Disulfide	75-15-0	ug/l	< 10 U	**1.9**	**3.4 J**	**4.4**	**7.2**	< 10 U	< 5.0 U	< 10 U
Carbon Tetrachloride	56-23-5	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	**0.52 J**	< 10 U
CFC-11	75-69-4	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U

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		Sample Location	3-MW-14	3-MW-14	3-MW-14	3-MW-14	3-MW-14	3-MW-35D	3-MW-35D	3-MW-35D
		Sample ID	SS003-3-MW-14(4Q18)	SS003-3-MW-14(1Q19)	SS003-3-MW-14(2Q19)	SS003-3-MW-14(3Q19)	SS003-3-MW-14(4Q19)	SS003-3-MW-35D(3Q17)	SS003-3-MW-35D-100217	SS003-3-MW-35D(1Q18)
		Sample Date	11/7/2018	1/23/2019	4/8/2019	7/15/2019	10/11/2019	7/19/2017	10/2/2017	1/3/2018
Parameter	CAS	Units								
CFC-12	75-71-8	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Chlorobenzene	108-90-7	ug/l	< 10 U	**0.22 J**	< 5.0 U	< 1.0 U	**0.20 J**	< 10 U	< 5.0 U	< 10 U
Chlorodibromomethane	124-48-1	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Chloroethane	75-00-3	ug/l	< 10 U	**0.72 J**	< 5.0 U	**0.98 J**	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Chloroform	67-66-3	ug/l	**7.3 J**	**20**	**17**	**18**	**17**	**42**	**46**	**33**
Chloromethane	74-87-3	ug/l	**25**	**37**	**27**	**30**	**28**	< 10 U	< 5.0 U	< 10 U
cis-1,2-Dichloroethene	156-59-2	ug/l	**16 J**	**36**	**27**	**36**	**47**	**260**	**210**	**390**
cis-1,3-Dichloropropene	10061-01-5	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Cymene (p-Isopropyltoluene)	99-87-6	ug/l	< 10 U	**0.15 J**	< 5.0 U	< 1.0 U	**0.27 J**	< 10 U	< 5.0 U	< 10 U
Dichloromethane	75-09-2	ug/l	**46 J**	**140**	**110**	**130**	**110**	< 20 UB	< 10 UB	< 20 J
Dichloromonofluoromethane	75-43-4	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
Di-isopropyl ether	108-20-3	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Ethyl tert-butyl ether	637-92-3	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Ethylbenzene	100-41-4	ug/l	< 10 U	**0.90 J**	**0.51 J**	**0.52 J**	**1.1**	< 10 U	< 5.0 U	< 10 U
Hexachloro-1,3-butadiene	87-68-3	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Isopropylbenzene	98-82-8	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
m&p-Xylenes	ARC-mpXyl	ug/l	**2.6 J**	**2.7**	< 10 U	**0.93 J**	**0.61 J**	< 20 U	< 10 U	< 20 U
Methyl N-Butyl Ketone (2-Hexanone)	591-78-6	ug/l	< 100 U	< 10 U	< 50 U	< 10 U	< 10 U	< 100 U	< 50 U	< 100 U
Methyl-tert-butylether	1634-04-4	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Naphthalene	91-20-3	ug/l	< 20 U	**0.50 J**	< 10 U	< 2.0 U	< 2.0 U	< 20 U	< 10 U	< 20 U
n-Butylbenzene	104-51-8	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
n-Propylbenzene	103-65-1	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
o,p-Xylene	136777-61-2	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
o-Xylene	95-47-6	ug/l	**1.0 J**	**1.1**	< 5.0 U	**0.37 J**	**0.24 J**	< 10 U	< 5.0 U	< 10 U
sec-Butylbenzene	135-98-8	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Styrene (Monomer)	100-42-5	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
tert-Amyl methyl ether	994-05-8	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
tert-Butyl alcohol	75-65-0	ug/l	< 100 U	< 10 U	**31 J**	**24**	**35**	< 100 U	< 50 U	**750**
tert-Butylbenzene	98-06-6	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Tetrachloroethene	127-18-4	ug/l	**7.0 J**	**13**	**8.4**	**14**	**14**	**3.2 J**	**4.7 J**	**4.3 J**
Toluene	108-88-3	ug/l	< 10 U	**0.19 J**	< 5.0 U	**0.11 J**	**0.11 J**	< 10 U	< 5.0 U	< 10 U
trans-1,2-Dichloroethene	156-60-5	ug/l	**2.7 J**	**6.8**	**6.7**	**8.6**	**11**	**3.9 J**	**5.0 J**	**4.9 J**
trans-1,3-Dichloropropene	10061-02-6	ug/l	< 10 U	< 1.0 U	< 5.0 U	< 1.0 U	< 1.0 U	< 10 U	< 5.0 U	< 10 U
Trichloroethene	79-01-6	ug/l	**10000**	**10000**	**11000**	**15000**	**9500**	**45000**	**46000 D**	**36000**
Vinyl acetate	108-05-4	ug/l	< 20 U	< 2.0 U	< 10 U	< 2.0 U	< 2.0 U	< 20 U	< 10 U	< 20 U
Vinyl chloride	75-01-4	ug/l	< 5.0 U	< 0.50 U	< 2.5 U	< 0.50 U	< 0.50 U	< 5.0 U	**1.5 J**	**1.7 J**

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		Sample Location	**3-MW-35D**	**3-MW-35D**	**3-MW-35D**	**3-MW-35D**	**3-MW-35D**	**3-MW-35D**	**3-MW-47**	**3-MW-47**
		Sample ID	**SS003-3-MW-35D(4Q18)**	**SS003-3-MW-35D(1Q19)**	**SS003-3-MW-35D(2Q19)**	**SS003-3-MW-35D(3Q19)**	**SS003-3-MW-35D(4Q19)**	**SS003-DUP1(4Q19)**	**SS003-3-MW-47-100217**	**SS003-3-MW-47(4Q18)**
		Sample Date	**11/7/2018**	**1/21/2019**	**4/8/2019**	**7/18/2019**	**10/11/2019**	**10/11/2019**	**10/2/2017**	**11/7/2018**
Parameter	**CAS**	**Units**								
1,1,1,2-Tetrachloroethane	630-20-6	ug/l	< 2.5 U	< 0.50 U	< 2.5 U	< 0.50 U	< 2.5 U	< 2.5 U	< 0.50 U	< 2.5 U
1,1,1-Trichloroethane	71-55-6	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,1,2,2-Tetrachloroethane	79-34-5	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**23 J**	**20**
1,1,2-trichloro-1,2,2-trifluoroethane	76-13-1	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,1,2-Trichloroethane	79-00-5	ug/l	**4.1 J**	**3.3**	**3.7 J**	**3.0**	**4.1 J**	**3.7 J**	**1.0**	< 5.0 U
1,1-Dichloroethane	75-34-3	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,1-Dichloroethene	75-35-4	ug/l	**2.4 J**	**2.1**	**2.8 J**	**2.6**	**2.6 J**	**1.0 J**	**0.34 J**	< 5.0 U
1,1-Dichloropropene	563-58-6	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,2,3-Trichlorobenzene	87-61-6	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,2,3-Trichloropropane	96-18-4	ug/l	< 10 U	< 2.0 U	< 10 U	< 2.0 U	< 10 U	< 10 U	< 2.0 U	< 10 U
1,2,4-Trichlorobenzene	120-82-1	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,2,4-Trimethylbenzene	95-63-6	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 UJ	**0.73 J**
1,2-Dibromo-3-chloropropane	96-12-8	ug/l	< 10 U	< 2.0 U	< 10 U	< 2.0 U	< 10 U	< 10 U	< 2.0 U	< 10 U
1,2-Dibromoethane	106-93-4	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,2-Dichlorobenzene	95-50-1	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,2-Dichloroethane	107-06-2	ug/l	< 2.5 U	**0.13 J**	< 2.5 U	< 0.50 U	< 2.5 U	< 2.5 U	< 0.50 U	< 2.5 U
1,2-Dichloropropane	78-87-5	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,3,5-Trimethylbenzene	108-67-8	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**0.29 J**	< 5.0 U
1,3-Dichlorobenzene	541-73-1	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,3-Dichloropropane	142-28-9	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
1,4-Dichlorobenzene	106-46-7	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
2,2-Dichloropropane	594-20-7	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
2-Butanone (MEK)	78-93-3	ug/l	< 50 U	< 10 U	< 50 U	< 10 U	< 50 U	< 50 U	**8.8 J**	< 50 U
2-Chloroethyl vinyl ether	110-75-8	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
2-Chlorotoluene	95-49-8	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
4-Chlorotoluene	106-43-4	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
4-Methyl-2-Pentanone	108-10-1	ug/l	< 50 U	< 10 U	< 50 U	< 10 U	< 50 U	< 50 U	< 10 U	< 50 U
Acetone	67-64-1	ug/l	**34 J**	< 10 U	< 50 U	< 10 UB	< 50 U	< 50 U	**220**	**140**
Benzene	71-43-2	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**1.9**	**2.0 J**
Bromobenzene	108-86-1	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Bromochloromethane	74-97-5	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**1.3**	**1.9 J**
Bromodichloromethane	75-27-4	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Bromoform	75-25-2	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Bromomethane	74-83-9	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**0.77 J**	< 5.0 U
Carbon Disulfide	75-15-0	ug/l	**2.3 J**	**0.78 J**	< 5.0 U	**0.24 J**	**0.62 J**	< 5.0 U	< 1.0 U	**4.9 J**
Carbon Tetrachloride	56-23-5	ug/l	< 5.0 U	**0.14 J**	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
CFC-11	75-69-4	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U

		Sample Location	**3-MW-35D**	**3-MW-35D**	**3-MW-35D**	**3-MW-35D**	**3-MW-35D**	**3-MW-35D**	**3-MW-47**	**3-MW-47**
		Sample ID	**SS003-3-MW-35D(4Q18)**	**SS003-3-MW-35D(1Q19)**	**SS003-3-MW-35D(2Q19)**	**SS003-3-MW-35D(3Q19)**	**SS003-3-MW-35D(4Q19)**	**SS003-DUP1(4Q19)**	**SS003-3-MW-47-100217**	**SS003-3-MW-47(4Q18)**
		Sample Date	**11/7/2018**	**1/21/2019**	**4/8/2019**	**7/18/2019**	**10/11/2019**	**10/11/2019**	**10/2/2017**	**11/7/2018**
Parameter	**CAS**	**Units**								
CFC-12	75-71-8	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Chlorobenzene	108-90-7	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Chlorodibromomethane	124-48-1	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Chloroethane	75-00-3	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**0.47 J**	< 5.0 U
Chloroform	67-66-3	ug/l	**35**	**29**	**33**	**27**	**30**	**25**	**4.2**	**5.5**
Chloromethane	74-87-3	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**70**	**120**
cis-1,2-Dichloroethene	156-59-2	ug/l	**4300**	**1000**	**960**	**880**	**970**	**700**	**33 J**	**73**
cis-1,3-Dichloropropene	10061-01-5	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Cymene (p-Isopropyltoluene)	99-87-6	ug/l	**9.5**	**1.1**	< 5.0 U	**9.5**	**1.0 J**	< 5.0 U	**0.18 J**	< 5.0 U
Dichloromethane	75-09-2	ug/l	< 10 UB	< 2.0 UB	< 10 UB	**0.64 J**	< 10 UB	< 10 UB	**13**	**11**
Dichloromonofluoromethane	75-43-4	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
Di-isopropyl ether	108-20-3	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Ethyl tert-butyl ether	637-92-3	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Ethylbenzene	100-41-4	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**0.76 J**	< 5.0 U
Hexachloro-1,3-butadiene	87-68-3	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Isopropylbenzene	98-82-8	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**0.70 J**	**0.71 J**
m&p-Xylenes	ARC-mpXyl	ug/l	< 10 U	< 2.0 U	< 10 U	< 2.0 U	< 10 U	< 10 U	**0.69 J**	< 10 U
Methyl N-Butyl Ketone (2-Hexanone)	591-78-6	ug/l	< 50 U	< 10 U	< 50 U	< 10 U	< 50 U	< 50 U	< 10 U	< 50 U
Methyl-tert-butylether	1634-04-4	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Naphthalene	91-20-3	ug/l	< 10 U	< 2.0 U	< 10 U	< 2.0 U	< 10 U	< 10 U	**3.2**	**2.3 J**
n-Butylbenzene	104-51-8	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**0.45 J**	< 5.0 U
n-Propylbenzene	103-65-1	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**0.77 J**	< 5.0 U
o,p-Xylene	136777-61-2	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
o-Xylene	95-47-6	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**1.0**	**0.76 J**
sec-Butylbenzene	135-98-8	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	**0.56 J**	< 5.0 U
Styrene (Monomer)	100-42-5	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	NA R	< 5.0 U
tert-Amyl methyl ether	994-05-8	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
tert-Butyl alcohol	75-65-0	ug/l	< 50 U	**9.4 J**	< 50 U	**14**	< 50 U	< 50 U	**15**	< 50 U
tert-Butylbenzene	98-06-6	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Tetrachloroethene	127-18-4	ug/l	**3.4 J**	**5.0**	**2.9 J**	**3.9**	**4.6 J**	**2.1 J**	**13**	**12**
Toluene	108-88-3	ug/l	< 5.0 U	**0.29 J**	< 5.0 U	**0.27 J**	< 5.0 U	< 5.0 U	< 1.0 UB	< 5.0 U
trans-1,2-Dichloroethene	156-60-5	ug/l	**5.2**	**4.7**	**4.0 J**	**3.4**	**5.0**	**2.7 J**	**19**	**32**
trans-1,3-Dichloropropene	10061-02-6	ug/l	< 5.0 U	< 1.0 U	< 5.0 U	< 1.0 U	< 5.0 U	< 5.0 U	< 1.0 U	< 5.0 U
Trichloroethene	79-01-6	ug/l	**32000**	**39000**	**39000**	**27000**	**34000**	**24000**	**11000 D**	**8600**
Vinyl acetate	108-05-4	ug/l	< 10 U	< 2.0 U	< 10 U	< 2.0 U	< 10 U	< 10 U	< 2.0 U	< 10 U
Vinyl chloride	75-01-4	ug/l	< 2.5 U	**1.7**	**2.0 J**	**1.2**	**73 J**	**28 J**	< 0.50 U	< 2.5 U

		Sample Location	3-MW-47	3-MW-47	3-MW-47	3-MW-47	3-MW-47	3-MW-48	3-MW-48	3-MW-48
		Sample ID	SS003-DUP1(4Q18)	SS003-3-MW-47(1Q19)	SS003-3-MW-47(2Q19)	SS003-3-MW-47(3Q19)	SS003-3-MW-47(4Q19)	3-MW-48_20171130	SS003-3-MW-48(4Q18)	SS003-3-MW-48(1Q19)
		Sample Date	11/7/2018	1/21/2019	4/8/2019	7/16/2019	10/11/2019	11/30/2017	11/7/2018	1/23/2019
Parameter	CAS	Units								
1,1,1,2-Tetrachloroethane	630-20-6	ug/l	< 2.5 U	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U	< 5.0 U	< 0.50 U
1,1,1-Trichloroethane	71-55-6	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,1,2,2-Tetrachloroethane	79-34-5	ug/l	**21**	**23**	**17**	**28**	**22**	**19**	**23**	**24**
1,1,2-trichloro-1,2,2-trifluoroethane	76-13-1	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,1,2-Trichloroethane	79-00-5	ug/l	< 5.0 U	**1.6**	**0.92 J**	**1.4**	**1.3**	**2.8**	**1.7 J**	**2.3**
1,1-Dichloroethane	75-34-3	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,1-Dichloroethene	75-35-4	ug/l	< 5.0 U	**0.48 J**	**0.69 J**	**0.45 J**	**0.89 J**	< 1.0 U	< 10 U	**0.14 J**
1,1-Dichloropropene	563-58-6	ug/l	**0.60 J**	**0.25 J**	**0.22 J**	**0.69 J**	**2.5**	< 1.0 U	**1.5 J**	**8.5**
1,2,3-Trichlorobenzene	87-61-6	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,2,3-Trichloropropane	96-18-4	ug/l	< 10 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 20 U	< 2.0 U
1,2,4-Trichlorobenzene	120-82-1	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,2,4-Trimethylbenzene	95-63-6	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,2-Dibromo-3-chloropropane	96-12-8	ug/l	< 10 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 20 U	< 2.0 U
1,2-Dibromoethane	106-93-4	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,2-Dichlorobenzene	95-50-1	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,2-Dichloroethane	107-06-2	ug/l	< 2.5 U	**0.14 J**	< 0.50 U	**0.15 J**	< 0.50 U	**0.18 J**	< 5.0 U	**0.23 J**
1,2-Dichloropropane	78-87-5	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,3,5-Trimethylbenzene	108-67-8	ug/l	< 5.0 U	**0.23 J**	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,3-Dichlorobenzene	541-73-1	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,3-Dichloropropane	142-28-9	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
1,4-Dichlorobenzene	106-46-7	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
2,2-Dichloropropane	594-20-7	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
2-Butanone (MEK)	78-93-3	ug/l	< 50 U	**11**	**15**	**31**	**37**	**11**	< 100 U	**7.5 J**
2-Chloroethyl vinyl ether	110-75-8	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
2-Chlorotoluene	95-49-8	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
4-Chlorotoluene	106-43-4	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
4-Methyl-2-Pentanone	108-10-1	ug/l	< 50 U	< 10 U	**2.2 J**	< 10 U	< 10 U	< 10 U	< 100 U	< 10 U
Acetone	67-64-1	ug/l	**140**	**150**	**170**	**260**	**200**	**910 D**	< 100 U	< 10 U
Benzene	71-43-2	ug/l	**2.0 J**	**1.9**	**1.6**	**1.3**	**1.6**	**0.71 J**	< 10 U	**0.97 J**
Bromobenzene	108-86-1	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Bromochloromethane	74-97-5	ug/l	**1.7 J**	**1.6**	**1.1**	**1.8**	**1.1**	**1.7**	**1.5 J**	**1.0**
Bromodichloromethane	75-27-4	ug/l	< 5.0 U	**0.24 J**	**0.10 J**	**0.14 J**	**0.13 J**	**0.25 J**	< 10 U	< 1.0 U
Bromoform	75-25-2	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	**0.17 J**	< 10 U	< 1.0 U
Bromomethane	74-83-9	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	**0.28 J**	**0.32 J**	**0.32 J**	**11**	**3.3**
Carbon Disulfide	75-15-0	ug/l	**5.1**	**3.4**	**1.8**	**1.3**	**9.5**	**1.7**	**2.4 J**	**2.3**
Carbon Tetrachloride	56-23-5	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
CFC-11	75-69-4	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U

Appendix E - VOCs Groundwater Analytical Results
ESTCP Draft Final Report
Demonstration and Validation of the Horizontal Reactive Media Treatment Well
for Managing Contaminant Plumes in Complex Geologic Environments

		Sample Location	3-MW-47	3-MW-47	3-MW-47	3-MW-47	3-MW-47	3-MW-48	3-MW-48	3-MW-48
		Sample ID	**SS003-DUP1(4Q18)**	**SS003-3-MW-47(1Q19)**	**SS003-3-MW-47(2Q19)**	**SS003-3-MW-47(3Q19)**	**SS003-3-MW-47(4Q19)**	**3-MW-48_20171130**	**SS003-3-MW-48(4Q18)**	**SS003-3-MW-48(1Q19)**
		Sample Date	**11/7/2018**	**1/21/2019**	**4/8/2019**	**7/16/2019**	**10/11/2019**	**11/30/2017**	**11/7/2018**	**1/23/2019**
Parameter	**CAS**	**Units**								
CFC-12	75-71-8	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Chlorobenzene	108-90-7	ug/l	< 5.0 U	< 1.0 U	**0.10 J**	**0.16 J**	**0.12 J**	**0.18 J**	< 10 U	**0.22 J**
Chlorodibromomethane	124-48-1	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Chloroethane	75-00-3	ug/l	< 5.0 U	**0.68 J**	**0.48 J**	**0.80 J**	**0.67 J**	**1.1**	< 10 U	**1.9**
Chloroform	67-66-3	ug/l	**5.3**	**6.6**	**4.0**	**8.3**	**4.9**	**22**	**12**	**22**
Chloromethane	74-87-3	ug/l	**120**	**62**	**36**	**74**	**35**	**59**	**160**	**75**
cis-1,2-Dichloroethene	156-59-2	ug/l	**73**	**73**	**62**	**66**	**160**	**26**	**12**	**34**
cis-1,3-Dichloropropene	10061-01-5	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Cymene (p-Isopropyltoluene)	99-87-6	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Dichloromethane	75-09-2	ug/l	**11**	**12**	**7.2**	**14**	**7.7**	**21**	< 20 UB	**19**
Dichloromonofluoromethane	75-43-4	ug/l	NA	NA	NA	NA	NA	NA	NA	NA
Di-isopropyl ether	108-20-3	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Ethyl tert-butyl ether	637-92-3	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Ethylbenzene	100-41-4	ug/l	< 5.0 U	**0.42 J**	**0.38 J**	**0.23 J**	**0.41 J**	< 1.0 U	< 10 U	**1.9**
Hexachloro-1,3-butadiene	87-68-3	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Isopropylbenzene	98-82-8	ug/l	**0.65 J**	**0.85 J**	**0.85 J**	**0.32 J**	**0.82 J**	< 1.0 U	< 10 U	**0.11 J**
m&p-Xylenes	ARC-mpXyl	ug/l	< 10 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	NA	**2.2 J**	**0.47 J**
Methyl N-Butyl Ketone (2-Hexanone)	591-78-6	ug/l	< 50 U	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 100 U	< 10 U
Methyl-tert-butylether	1634-04-4	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Naphthalene	91-20-3	ug/l	**2.3 J**	**3.5**	**3.2**	**1.4 J**	**3.1**	< 2.0 U	< 20 U	< 2.0 U
n-Butylbenzene	104-51-8	ug/l	< 5.0 U	**0.70 J**	**0.55 J**	< 1.0 U	**0.38 J**	< 1.0 U	< 10 U	< 1.0 U
n-Propylbenzene	103-65-1	ug/l	< 5.0 U	**0.78 J**	**0.65 J**	**0.23 J**	**0.52 J**	< 1.0 U	< 10 U	**0.14 J**
o,p-Xylene	136777-61-2	ug/l	NA	NA	NA	NA	NA	< 2.0 U	NA	NA
o-Xylene	95-47-6	ug/l	**0.67 J**	**0.85 J**	**0.72 J**	**0.36 J**	**0.65 J**	< 1.0 U	< 10 U	**0.25 J**
sec-Butylbenzene	135-98-8	ug/l	< 5.0 U	**0.83 J**	**0.72 J**	**0.23 J**	**0.71 J**	< 1.0 U	< 10 U	**0.14 J**
Styrene (Monomer)	100-42-5	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 R	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
tert-Amyl methyl ether	994-05-8	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
tert-Butyl alcohol	75-65-0	ug/l	< 50 U	< 10 U	**10**	**16**	< 10 U	**2900 D**	< 100 U	< 10 U
tert-Butylbenzene	98-06-6	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Tetrachloroethene	127-18-4	ug/l	**11**	**16**	**10**	**11**	**11**	**14**	**6.9 J**	**17**
Toluene	108-88-3	ug/l	< 5.0 U	**0.10 J**	**0.11 J**	< 1.0 U	**0.14 J**	**0.22 J**	< 10 U	**0.17 J**
trans-1,2-Dichloroethene	156-60-5	ug/l	**30**	**38**	**37**	**20**	**39**	**4.2**	**1.8 J**	**5.9**
trans-1,3-Dichloropropene	10061-02-6	ug/l	< 5.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 10 U	< 1.0 U
Trichloroethene	79-01-6	ug/l	**8500**	**9100**	**7800**	**6000**	**4500**	**4200 D**	**4200**	**3800**
Vinyl acetate	108-05-4	ug/l	< 10 U	< 2.0 U	< 2.0 U	< 2.0 R	< 2.0 U	< 2.0 U	< 20 U	< 2.0 U
Vinyl chloride	75-01-4	ug/l	< 2.5 U	**0.28 J**	**0.34 J**	**0.26 J**	**9.6**	< 0.50 U	< 5.0 U	**0.17 J**

Appendix E - VOCs Groundwater Analytical Results
ESTCP Draft Final Report
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for Managing Contaminant Plumes in Complex Geologic Environments

		Sample Location	**3-MW-48**	**3-MW-48**	**3-MW-48**	**3-MW-48**	**HRX Inlet**	**HRX Inlet**	**HRX Inlet**
		Sample ID	**SS003-DUP3(1Q19)**	**SS003-3-MW-48(2Q19)**	**SS003-3-MW-48(3Q19)**	**SS003-3-MW-48(4Q19)**	**HRX BASELINE ENTRANCE**	**HRX ROUND2 ENTRANCE**	**HRX ROUND 3 ENTRANCE**
		Sample Date	**1/23/2019**	**4/8/2019**	**7/16/2019**	**10/11/2019**	**12/17/2018**	**2/27/2019**	**8/1/2019**
Parameter	**CAS**	**Units**							
1,1,1,2-Tetrachloroethane	630-20-6	ug/l	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U	< 0.50 U
1,1,1-Trichloroethane	71-55-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,1,2,2-Tetrachloroethane	79-34-5	ug/l	**27**	**19**	**20**	**8.4**	< 1.0 U	< 1.0 U	< 1.0 U
1,1,2-trichloro-1,2,2-trifluoroethane	76-13-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,1,2-Trichloroethane	79-00-5	ug/l	**2.8**	**2.8**	**3.1**	**3.0**	< 1.0 U	< 1.0 U	< 1.0 U
1,1-Dichloroethane	75-34-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,1-Dichloroethene	75-35-4	ug/l	**0.13 J**	**0.10 J**	**0.32 J**	**0.75 J**	**7.0**	**3.9**	**0.51 J**
1,1-Dichloropropene	563-58-6	ug/l	**8.7**	**4.1**	**3.5**	**2.9**	< 1.0 U	< 1.0 U	< 1.0 U
1,2,3-Trichlorobenzene	87-61-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,2,3-Trichloropropane	96-18-4	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U
1,2,4-Trichlorobenzene	120-82-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,2,4-Trimethylbenzene	95-63-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,2-Dibromo-3-chloropropane	96-12-8	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U
1,2-Dibromoethane	106-93-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,2-Dichlorobenzene	95-50-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,2-Dichloroethane	107-06-2	ug/l	**0.23 J**	**0.24 J**	**0.20 J**	< 0.50 U	**0.83**	**0.58**	**0.21 J**
1,2-Dichloropropane	78-87-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,3,5-Trimethylbenzene	108-67-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,3-Dichlorobenzene	541-73-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,3-Dichloropropane	142-28-9	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
1,4-Dichlorobenzene	106-46-7	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
2,2-Dichloropropane	594-20-7	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
2-Butanone (MEK)	78-93-3	ug/l	**7.1 J**	**23**	**40**	**32**	**200**	**210**	**52**
2-Chloroethyl vinyl ether	110-75-8	ug/l	NA	NA	NA	NA	NA	NA	NA
2-Chlorotoluene	95-49-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
4-Chlorotoluene	106-43-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
4-Methyl-2-Pentanone	108-10-1	ug/l	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U
Acetone	67-64-1	ug/l	< 10 U	**210**	**240**	**25**	**1000**	**650**	**160**
Benzene	71-43-2	ug/l	**0.97 J**	**1.0**	**0.92 J**	**1.0**	**0.16 J**	**0.22 J**	**0.16 J**
Bromobenzene	108-86-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Bromochloromethane	74-97-5	ug/l	**1.4**	**1.2**	**1.8**	**0.56 J**	< 1.0 U	< 1.0 U	< 1.0 U
Bromodichloromethane	75-27-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Bromoform	75-25-2	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Bromomethane	74-83-9	ug/l	**3.3**	**2.5**	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Carbon Disulfide	75-15-0	ug/l	**2.3**	**38**	**37**	**47**	< 1.0 U	< 1.0 U	< 1.0 U
Carbon Tetrachloride	56-23-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
CFC-11	75-69-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U

Appendix E - VOCs Groundwater Analytical Results
ESTCP Draft Final Report
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for Managing Contaminant Plumes in Complex Geologic Environments

		Sample Location	3-MW-48	3-MW-48	3-MW-48	3-MW-48	HRX Inlet	HRX Inlet	HRX Inlet
		Sample ID	SS003-DUP3(1Q19)	SS003-3-MW-48(2Q19)	SS003-3-MW-48(3Q19)	SS003-3-MW-48(4Q19)	HRX BASELINE ENTRANCE	HRX ROUND2 ENTRANCE	HRX ROUND 3 ENTRANCE
		Sample Date	1/23/2019	4/8/2019	7/16/2019	10/11/2019	12/17/2018	2/27/2019	8/1/2019
Parameter	**CAS**	**Units**							
CFC-12	75-71-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Chlorobenzene	108-90-7	ug/l	**0.25 J**	**0.25 J**	**0.26 J**	**0.20 J**	< 1.0 U	< 1.0 U	< 1.0 U
Chlorodibromomethane	124-48-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Chloroethane	75-00-3	ug/l	**2.0**	**1.7**	**2.2**	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Chloroform	67-66-3	ug/l	**25**	**24**	**19**	**11**	**0.74 J**	< 1.0 U	< 1.0 U
Chloromethane	74-87-3	ug/l	**90**	**70**	**73**	**11**	**0.21 J**	< 1.0 U	< 1.0 U
cis-1,2-Dichloroethene	156-59-2	ug/l	**33**	**160**	**56**	**360**	**4800**	**3500**	**94**
cis-1,3-Dichloropropene	10061-01-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Cymene (p-Isopropyltoluene)	99-87-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Dichloromethane	75-09-2	ug/l	**21**	**23**	**28**	**21**	**3.1**	**1.1 J**	**0.80 J**
Dichloromonofluoromethane	75-43-4	ug/l	NA	NA	NA	NA	NA	NA	NA
Di-isopropyl ether	108-20-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Ethyl tert-butyl ether	637-92-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Ethylbenzene	100-41-4	ug/l	**1.9**	**1.8**	**0.97 J**	**0.49 J**	**0.14 J**	**0.18 J**	< 1.0 U
Hexachloro-1,3-butadiene	87-68-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Isopropylbenzene	98-82-8	ug/l	**0.11 J**	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
m&p-Xylenes	ARC-mpXyl	ug/l	**0.45 J**	< 2.0 U	< 2.0 U	< 2.0 U	**0.42 J**	**0.54 J**	< 2.0 U
Methyl N-Butyl Ketone (2-Hexanone)	591-78-6	ug/l	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U	< 10 U
Methyl-tert-butylether	1634-04-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Naphthalene	91-20-3	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U
n-Butylbenzene	104-51-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
n-Propylbenzene	103-65-1	ug/l	**0.13 J**	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
o,p-Xylene	136777-61-2	ug/l	NA	NA	NA	NA	NA	NA	NA
o-Xylene	95-47-6	ug/l	**0.23 J**	< 1.0 U	< 1.0 U	< 1.0 U	**0.21 J**	**0.24 J**	< 1.0 U
sec-Butylbenzene	135-98-8	ug/l	**0.13 J**	**0.15 J**	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Styrene (Monomer)	100-42-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
tert-Amyl methyl ether	994-05-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
tert-Butyl alcohol	75-65-0	ug/l	< 10 U	**35**	**47**	**65**	**5.8 J**	**8.0 J**	**8.4 J**
tert-Butylbenzene	98-06-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Tetrachloroethene	127-18-4	ug/l	**18**	**17**	**18**	**11**	< 1.0 U	< 1.0 U	< 1.0 U
Toluene	108-88-3	ug/l	**0.17 J**	**0.12 J**	< 1.0 U	< 1.0 U	**0.67 J**	**0.49 J**	**0.22 J**
trans-1,2-Dichloroethene	156-60-5	ug/l	**5.6**	**5.1**	**2.9**	**11**	**1.0**	**0.76 J**	**1.0**
trans-1,3-Dichloropropene	10061-02-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U	< 1.0 U
Trichloroethene	79-01-6	ug/l	**3800**	**2600**	**2200**	**2100**	**310**	**5.1**	**13**
Vinyl acetate	108-05-4	ug/l	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U	< 2.0 U
Vinyl chloride	75-01-4	ug/l	**0.17 J**	**0.56**	**0.56**	**140**	**3.7**	**5.3**	**7200**

		Sample Location	**HRX Outlet**	**HRX Outlet**	**HRX Outlet**
		Sample ID	**HRX BASELINE EXIT**	**HRX ROUND2 EXIT**	**HRX ROUND 3 EXIT**
		Sample Date	**12/17/2018**	**2/27/2019**	**8/1/2019**
Parameter	**CAS**	**Units**			
1,1,1,2-Tetrachloroethane	630-20-6	ug/l	< 0.50 U	< 0.50 U	< 0.50 U
1,1,1-Trichloroethane	71-55-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,1,2,2-Tetrachloroethane	79-34-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,1,2-trichloro-1,2,2-trifluoroethane	76-13-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,1,2-Trichloroethane	79-00-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,1-Dichloroethane	75-34-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,1-Dichloroethene	75-35-4	ug/l	**0.32 J**	**0.13 J**	< 1.0 U
1,1-Dichloropropene	563-58-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,2,3-Trichlorobenzene	87-61-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,2,3-Trichloropropane	96-18-4	ug/l	< 2.0 U	< 2.0 U	< 2.0 U
1,2,4-Trichlorobenzene	120-82-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,2,4-Trimethylbenzene	95-63-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,2-Dibromo-3-chloropropane	96-12-8	ug/l	< 2.0 U	< 2.0 U	< 2.0 U
1,2-Dibromoethane	106-93-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,2-Dichlorobenzene	95-50-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,2-Dichloroethane	107-06-2	ug/l	**0.37 J**	**0.15 J**	< 0.50 U
1,2-Dichloropropane	78-87-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,3,5-Trimethylbenzene	108-67-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,3-Dichlorobenzene	541-73-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,3-Dichloropropane	142-28-9	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
1,4-Dichlorobenzene	106-46-7	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
2,2-Dichloropropane	594-20-7	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
2-Butanone (MEK)	78-93-3	ug/l	**1100**	**60**	**19**
2-Chloroethyl vinyl ether	110-75-8	ug/l	NA	NA	NA
2-Chlorotoluene	95-49-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
4-Chlorotoluene	106-43-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
4-Methyl-2-Pentanone	108-10-1	ug/l	< 10 U	< 10 U	< 10 U
Acetone	67-64-1	ug/l	**2300**	**56**	**78**
Benzene	71-43-2	ug/l	**0.41 J**	**0.26 J**	**0.39 J**
Bromobenzene	108-86-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Bromochloromethane	74-97-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Bromodichloromethane	75-27-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Bromoform	75-25-2	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Bromomethane	74-83-9	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Carbon Disulfide	75-15-0	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Carbon Tetrachloride	56-23-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
CFC-11	75-69-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U

		Sample Location	**HRX Outlet**	**HRX Outlet**	**HRX Outlet**
		Sample ID	**HRX BASELINE EXIT**	**HRX ROUND2 EXIT**	**HRX ROUND 3 EXIT**
		Sample Date	**12/17/2018**	**2/27/2019**	**8/1/2019**
Parameter	**CAS**	**Units**			
CFC-12	75-71-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Chlorobenzene	108-90-7	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Chlorodibromomethane	124-48-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Chloroethane	75-00-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Chloroform	67-66-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Chloromethane	74-87-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
cis-1,2-Dichloroethene	156-59-2	ug/l	**110**	**97**	**6.8**
cis-1,3-Dichloropropene	10061-01-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Cymene (p-Isopropyltoluene)	99-87-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Dichloromethane	75-09-2	ug/l	**0.36 J**	< 2.0 U	< 2.0 U
Dichloromonofluoromethane	75-43-4	ug/l	NA	NA	NA
Di-isopropyl ether	108-20-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Ethyl tert-butyl ether	637-92-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Ethylbenzene	100-41-4	ug/l	**0.22 J**	**0.13 J**	< 1.0 U
Hexachloro-1,3-butadiene	87-68-3	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Isopropylbenzene	98-82-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
m&p-Xylenes	ARC-mpXyl	ug/l	**0.63 J**	**0.34 J**	< 2.0 U
Methyl N-Butyl Ketone (2-Hexanone)	591-78-6	ug/l	< 10 U	< 10 U	< 10 U
Methyl-tert-butylether	1634-04-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Naphthalene	91-20-3	ug/l	< 2.0 U	< 2.0 U	< 2.0 U
n-Butylbenzene	104-51-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
n-Propylbenzene	103-65-1	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
o,p-Xylene	136777-61-2	ug/l	NA	NA	NA
o-Xylene	95-47-6	ug/l	**0.29 J**	**0.16 J**	**0.11 J**
sec-Butylbenzene	135-98-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Styrene (Monomer)	100-42-5	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
tert-Amyl methyl ether	994-05-8	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
tert-Butyl alcohol	75-65-0	ug/l	**4.1 J**	**5.6 J**	**14**
tert-Butylbenzene	98-06-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Tetrachloroethene	127-18-4	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Toluene	108-88-3	ug/l	**0.77 J**	**0.59 J**	**0.43 J**
trans-1,2-Dichloroethene	156-60-5	ug/l	**0.52 J**	**0.19 J**	**0.19 J**
trans-1,3-Dichloropropene	10061-02-6	ug/l	< 1.0 U	< 1.0 U	< 1.0 U
Trichloroethene	79-01-6	ug/l	< 1.0 U	**0.21 J**	**7.6**
Vinyl acetate	108-05-4	ug/l	< 2.0 U	< 2.0 U	< 2.0 U
Vinyl chloride	75-01-4	ug/l	**0.80**	**0.65**	**430**

Appendix F

TOC Groundwater Analytical Results

Appendix F - TOC Groundwater Analytical Results
ESTCP Draft Final Report
Demonstration and Validation of the Horizontal Reactive Media Treatment Well
for Managing Contaminant Plumes in Complex Geologic Environments

Sample Location		3-MW-13	3-MW-14	3-MW-35D	3-MW-47	3-MW-47	3-MW-48	HRX Inlet	HRX Inlet	HRX Outlet	HRX Outlet
Sample Number		SS003-3-MW-13(4Q18)	SS003-3-MW-14(4Q18)	SS003-3-MW-35D(4Q18)	SS003-3-MW-47(4Q18)	SS003-DUP1(4Q18)	SS003-3-MW-48(4Q18)	HRX ROUND2 ENTRANCE	HRX ROUND 3 ENTRANCE	HRX ROUND2 EXIT	HRX ROUND 3 EXIT
Sample Date		11/7/2018	11/7/2018	11/7/2018	11/7/2018	11/7/2018	11/7/2018	2/27/2019	8/1/2019	2/27/2019	8/1/2019
Parameter	Units										
Total Organic Carbon	ug/l	6930000	4900000 J	49700	569000	453000	6770000	339000	89300	22300	77200

Appendix G

Mann-Kendall and Sen’s Slope Trend Tests

Well Location	Well ID	Constituent	Start Date	End Date	Minimum Concentration	Maximum Concentration	Concentration Most Recently Measured	Number of Data Points in Analysis	% Data Above Laboratory Reporting Limit	S-Statistic	p-value	Trend Direction	Significance of Trend (90% Confidence)	Sen's Slope (µmol or µg per liter per day)		
														90% LCL	Mean	90% UCL
Upgradient	3-MW-35D	Total Molar Concentration	11/7/2018	10/11/2019	214 µmol/L	307 µmol/L	270 µmol/L	5	100	-4	0.242	Potentially Decreasing	Not Significant	--	--	--
		PCE			2.9 J µg/L	5 µg/L	4.6 J µg/L	5	100	2	0.408	No Trend	Not Significant	--	--	--
		TCE			27,000 µg/L	39,000 µg/L	34,000 µg/L	5	100	-1	0.5	No trend	Not Significant	--	--	--
		cDCE			880 µg/L	4,300 µg/L	970 µg/L	5	100	-6	0.117	Potentially Decreasing	Not Significant	--	--	--
		VC			1.2 µg/L	73 J µg/L	73 J µg/L	5	80	6	0.117	Potentially Increasing	Not Significant	--	--	--
Downgradient	3-MW-13	Total Molar Concentration	7/10/2018	10/11/2019	30.5 µmol/L	61.4 µmol/L	30.5 µmol/L	6	100	-9	0.068	Decreasing	Significant	-0.134	-0.051	-0.008
		PCE			0.66 J µg/L	22 µg/L	6.1 µg/L	6	100	-3	0.36	No trend	Not Significant	--	--	--
		TCE			190 µg/L	6,900 µg/L	1,800 µg/L	6	100	-5	0.235	Potentially Decreasing	Not Significant	--	--	--
		cDCE			620 µg/L	4,800 µg/L	720 µg/L	6	100	-1	0.5	No trend	Not Significant	--	--	--
		VC			0.45 J µg/L	590 µg/L	590 µg/L	6	83	11	0.028	Increasing	Significant	--	--	--
	3-MW-14	Total Molar Concentration	11/7/2018	10/11/2019	72.9 µmol/L	114 µmol/L	72.9 µmol/L	5	100	2	0.408	No trend	Not Significant	--	--	--
		PCE			7 J µg/L	14 µg/L	14 µg/L	5	100	7	0.08	Increasing	Significant	--	--	--
		TCE			9,500 µg/L	15,000 µg/L	9,500 µg/L	5	100	1	0.5	No trend	Not Significant	--	--	--
		cDCE			16 µg/L	47 µg/L	47 µg/L	5	100	7	0.08	Increasing	Significant	--	--	--
		VC			<0.5 U µg/L	<5.0 U µg/L	<0.5 U µg/L	5	0	NA	NA	NA	NA	--	--	--
	3-MW-47	Total Molar Concentration	11/7/2018	10/11/2019	36.1 µmol/L	70.1 µmol/L	36.1 µmol/L	5	100	-8	0.042	Decreasing	Significant	-0.136	-0.124	-0.065
		PCE			10 µg/L	16 µg/L	11 µg/L	5	100	-3	0.325	No trend	Not Significant	--	--	--
		TCE			4,500 µg/L	9,100 µg/L	4,500 µg/L	5	100	-8	0.042	Decreasing	Significant	-17.9	-17.1	-8.54
		cDCE			62 µg/L	160 µg/L	160 µg/L	5	100	1	0.5	No trend	Not Significant	--	--	--
		VC			0.26 J µg/L	9.6 µg/L	9.6 µg/L	5	80	6	0.117	Potentially Increasing	Not Significant	--	--	--
	3-MW-48	Total Molar Concentration	11/7/2018	10/11/2019	17.4 µmol/L	32.1 µmol/L	21.9 µmol/L	5	100	-6	0.117	Potentially Decreasing	Not Significant	--	--	--
		PCE			6.9 J µg/L	18 µg/L	11 µg/L	5	100	3	0.325	No trend	Not Significant	--	--	--
		TCE			2,100 µg/L	4,200 µg/L	2,100 µg/L	5	100	-10	0.008	Decreasing	Significant	-12.5	-6.36	-3.56
		cDCE			12 µg/L	360 µg/L	360 µg/L	5	100	8	0.042	Increasing	Significant	--	--	--
		VC			0.17 J µg/L	140 µg/L	140 µg/L	5	80	9	0.025	Increasing	Significant	--	--	--

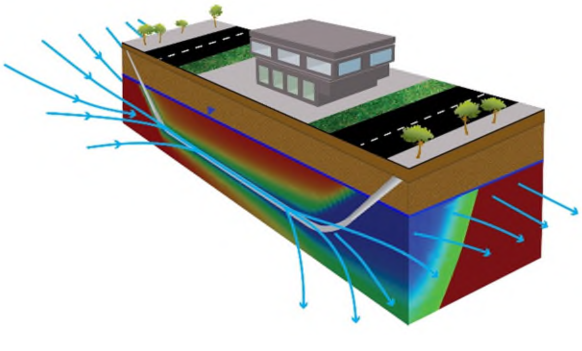
Notes:
TCE = trichloroethene
cDCE = cis-1,2-dichloroethene
VC = vinyl chloride
µmol/L = micromoles per liter
µg/L = micrograms per liter
% = percent
LCL = lower confidence limit
UCL = upper confidence limit
-- = Sen's Slope estimates not applicable (trend is not statistically significantly decreasing)
NA = trend analysis not applicable for non-detect constituent

Appendix H

Design, Cost, and Sustainability Tool and Analysis Memo

HRX WELL DESIGN, COST, AND SUSTAINABILITY TOOL AND ANALYSIS

DEMONSTRATION AND VALIDATION OF THE HORIZONTAL REACTIVE MEDIA TREATMENT WELL (HRX Well®) FOR MANAGING CONTAMINANT PLUMES IN COMPLEX GEOLOGIC ENVIRONMENTS



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February 2020

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1 INTRODUCTION

The HRX Well® design tool was developed to provide preliminary site design estimates to practitioners considering implementation of the HRX Well. Many HRX Well configurations are possible, but the applicability of any design is subject to site-specific factors. The tool allows the user to optimize the design based on user-provided values and using the equations described in Divine et al. (2018). Supplemental literature values can also be used as inputs to support high-level estimations. The tool predicts well length, capture width, and the number of wells required to meet target treatment goals. In addition, the associated costs and sustainability implications are calculated, which can further inform design selection. For many sites, a site-specific numerical flow and transport model may be useful for final design, as well as predicting and assessing HRX Well performance.

The tool can be used for a holistic evaluation of known or estimated site parameters and the resulting HRX Well configuration. Additional iterations using the tool can be completed to improve the design. A Tool Overview tab provides background, assumptions, and instructions. The User Input tab allows values to be entered or selected, depending on the parameter. Initial results are calculated in a locked HRX Well calculations tab, the Cartridge Calculations tab, the Cost tab, and the Sustainability tab, and the results are given in the Summary tab. The user can enter a pump rate or select mix-in media values to further specify capture width. The adjusted capture width and associated results will also be displayed under the Summary tab. The primary tool outputs are the required number of wells, well diameter, cartridges, well length, and the retention time required. The tool incorporates several user-specified inputs to minimize cost and maximize effective treatment. In addition, both cost analysis and sustainability analysis are included.

The design tool includes cost and sustainability assessments based on the materials used and drilling time. Data were obtained from several sources and references and web links are provided in the Lookup Tables and Assumed Values tabs in the design tool. These references can easily be updated with specific values by replacing the data in the cell, though the value should be converted to units shown.

Costs for mobilization, directional drilling, well assembly, development, sealing, cartridges, casing, and well ends and vaults were provided by Michael Lubrecht at Directed Technologies Drilling-Ellingson. These costs were determined for the Vandenberg Air Force Base installation and the resulting costs in the tool for a specific site should be taken as estimates. A formal quote should be obtained from the drilling company. An option to use polyvinyl chloride (PVC) casing was included on the User Inputs tab and the associated costs were determined from online suppliers: Flex Pipe, PVC Pipe Supply Store, and PVC Fittings Online. Reactive media costs were similarly determined from available costs at home water treatment supply stores, chemical supply companies, cost reports for treatment systems, and miscellaneous online retailers. These costs therefore represent estimates and the user should obtain quotes from reputable suppliers specific to their sites. The option is provided to add known cost data for media and this option is recommended.

Sustainability data were also obtained from multiple sources. A literature search demonstrated that the metrics intended to be included in the tool were not all available from the same reference for the same material. For example, granular activated carbon CO_2 equivalent emissions may be available from one reference, but not PM_{10} emissions. Furthermore, the literature reference may not have provided enough information to ensure each metric was comparable for the given material. Therefore, the SiteWise program (version 3.2) was used (where cited) in the tool as a baseline and was supported by additional references. All references and links are in the Lookup Tables tab. The results from the sustainability tab provide a general sustainability assessment and are useful to compare between design iterations. The results should not be taken as a complete lifecycle inventory analysis such as those obtained from a software such as GaBi.

Table 1. Cost References Used in the Design Tool

Item	Reference
Mobilization costs Directional drilling HRX Well assembly and installation HRX Well development HRX Well sealing Cartridge construction + supplies 12 in St. steel well screen 12 in carbon steel casing HRX Well ends, vaults	Michael Lubrecht (DTD-Ellingson), 2019, personal communication.
Activated carbon	Water softener parts (webpage): https://www.softenerparts.com/Carbon
Zeolite	EnviroSupply (webpage) https://envirosupply.net/products/zeolite
Persulfate	Rosansky and Dindal. (2010). Cost and Performance Report for Persulfate Treatability Studies.
Zero valent iron	Connelly Iron Products. (2018). Product Quote.

Table 2. Sustainability References Used in the Design Tool

Material	Reference
Baseline references	NAVFAC, 2016. SiteWise™ Tool - V3.1. Developed by the Department of the Navy, Army Corps of Engineers, & Battelle Link: https://www.navfac.navy.mil/navfac_worldwide/specialty_centers/exwc/products_and_services/ev/erb/gsr.html#tools
Bentonite	Hammond and Jones. (2008). Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers. 161:2, 87-98. https://researchportal.bath.ac.uk/en/publications/embodied-energy-and-carbon-in-construction-materials

Material	Reference
Portland cement	Song, D., Yang, J., Chen, B., Hayat, T., Alsaedi, A. (2016). Life-cycle environmental impact analysis of a typical cement production chain. Applied Energy, 164:15, 916:923. https://www.sciencedirect.com/science/article/pii/S0306261915010715
PVC	Baitz, M., Kreibig, J., Byrne, E., Makishi, C., Kupfer, T., Frees, N., Bey, N., Hansen, M.S., Hansen, A., Bosch, T., Borghi, V., Watson, J.., Miranda., M. (2015). Lifecycle Assessment of PVC and of principle competing materials. European Commission. https://ec.europa.eu/environment/waste/studies/pdf/pvc-final_report_lca.pdf
Stainless steel	Finkbeiner, M., Dowdell, D., Inaba, A., Young, S. (2011). Methodology Report: Lifecycle inventory for steel products. World Steel Association. https://www.worldsteel.org/en/dam/jcr:6a222ba2-e35a-4126-83ab-5ae5a79e6e46/LCA+Methodology+Report.pdf
Activated carbon	Bayer, P., Heuer, E., Karl, U., Finkel, M. (2005). Economic and ecological comparisons of granular activated carbon (GAC) adsorber refill strategies. Water Research. 39, 1719-1728. https://www.ncbi.nlm.nih.gov/pubmed/15899270
Diesel	Office of Transportation and Air Quality. (2016). Nonroad Compression-Ignition Engines: Exhaust Emission Standards. United States EPA. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100OA05.pdf

2 USER INSTRUCTIONS

The following can be used to guide the user through the design tool. The instructions do not include an overview of groundwater hydrology concepts as the tool is intended for use by experienced remediation professionals.

Step One: Review Tool Guidance

The first tab in the design tool (Tool Overview) provides an introduction, necessary definitions and assumptions, and instructions which are also provided below:

HRX Well Design Tool Overview and Instructions

The HRX Well tool has been produced to assist in system design. The tool uses values from literature and user inputs to estimate number and size of wells and the associated costs for site-specific conditions. The current and future design tool versions will be available at:

https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-201631

Notes and Assumptions

1. Treatment media treatability testing is not required to make use of the tool; however, it may be advantageous or necessary for some applications. Attempts have been made to provide useful and valid literature-based treatment media values, but they should only be taken as general information. These generalizations apply to hydraulic conductivity, reaction rate, and cost.

2. Method used to determine reference values available in the tool:

- **A.** Determine contaminant categories and general media categories.
- **B**. Pick a representative contaminant for the contaminant category.
- **C.** Literature search for hydraulic conductivity for each media.
- **D.** Literature search for direct values or information to calculate reaction rate with media for representative contaminant.

3. Key input values: Site hydraulic conductivity, aquifer thickness, treatment media hydraulic conductivity, reaction/adsorption rate constant, and treatment goals and the contaminants included.

4. Key output values: Number of HRX Wells, HRX Well dimensions, pumping rate if required.

The tool has been designed to allow the user to enter and or select specific known values which are used to calculate the key output values as well as other information. These values are reported in the Summary tab.

Active pump rate: This value should be determined from pumping tests and supplied by the user.

5. For users interested in further refining values to meet project requirements, a pump rate can be added or a mix-in media (explained below).

6. Cost data include values for HRX Well materials and installation provided for 10-inch diameter HRX Wells. In the case where a smaller or larger diameter is used the costs should be considered general and not be interpreted as the final project cost. Please see Assumed Values tab for more information.

7. Treatment and cartridge length. Treatment length is defined as the length of media, per cartridge diameter, available for treatment. Cartridge length is the length of the cartridge containing media as well as empty fittings on either end. The cartridge length is equal to the media length plus 25% of the media length to account for space for fittings.

General Instructions

1. White cells are for calculations and are locked. Cells highlighted in **green** are for value selection from a list. In some cases, parameter value selection is not required if values are entered in adjacent cells. In these cases, one set of cells must remain blank. For example, under User Inputs tab, there is an option (in **orange**) to enter contaminant and media values and below that in green to select media values from the literature. Calculations in other tabs using these values require one set of cells (orange or green) to be blank. Blank cells

highlighted in **blue** indicate the rows requiring information to calculate capture width, and nothing else.

2. Under the User Inputs tab note that a simple calculator is available to convert hydraulic conductivity from ft/d to cm/s and concentration from molar units to ug/L in O and P rows 5-9. Additional conversion factors are available immediately below:

A. Enter site name, location, and the contaminant(s) present. The information is transferred to the Summary tab for organizational purposes.

B. Enter Contaminant information and treatment goals. If more than one contaminant is present:

Enter individual contaminant name, initial concentration, target concentration or percent reduction, and rate constant for one contaminant at a time.

→ Record the treatment length (M49, User Inputs) for each contaminant.

→ Use the information associated with the longest calculated treatment length to determine HRX Well length in later steps. Note: If two contaminants are highly dissimilar and or require different media the above steps may not be appropriate.

C. Enter site hydraulic conductivity, site and well hydraulic gradient, and aquifer thickness. Note that the tool uses hydraulic conductivity in cm/s. Transmissivity is calculated automatically based on input values.

D. Enter treatment media information in row 32 (row 31 notes each component required) *or:*

E. Select treatment media information in row 35. A small selection of values from the literature are provided and categorized by contaminant class. Values may not be representative for your site. The values are also available in the Lookup Tables tab and can be manually entered in row 32 in other combinations.

F. If media capacity information is available enter it in M37. Capacity is not a required input but will update both cost and sustainability data.

→ If capacity is not available and K_d is, enter the K_d value which will be used with initial concentration to approximate capacity.

G. In M41 select “Active” for sites where K_{media} is greater than 5 ft/d. Otherwise, select “Passive”.

→ If “Active” was selected, enter a pump rate in M42. The pump rate will override the media conductivity values entered and be used in the capture width calculation.

H. Select HRX Well diameter from the drop-down menu in M48. Note that the tool will assume the cartridge diameter is 2 inches less than the HRX Well diameter.

I. Select carbon steel or PVC well casing from M55. The selection will be used to determine the casing cost.

J. Enter known or estimated cost per kilogram of treatment media used.

3. View results of 1. in the Summary tab in H3-28.

A. Review capture width, number of HRX Wells, and the HRX Well retention time versus the retention time required based on the contaminant information entered.

B. If capture width is not satisfactory consider:

→Increasing HRX Well diameter

→Adding a pump rate in User Inputs M42

→Selecting a mix-in media and entering the percent of media to use

→Determining if there is flexibility in treatment goals or treatment media (hydraulic conductivity) used

4. Change flexible parameters from Step 2 and or add a small pump or mix-in media in the User Inputs tab.

5. View results from using mix-in media or adding a pump in the Summary tab

A. Repeat the above steps to continue refining the design.

Step 2: Gather Input Information

The tool requires a series of values to be supplied and or selected by the user. **Table 3** gives the required values and can be used to organize information prior to using the tool. **Table 4** provides the selection values where these are required. Estimated values may be used in the design tool but values from site investigations and treatability testing are ideal for high level estimation.

Table 3. Required Information for the Design Tool

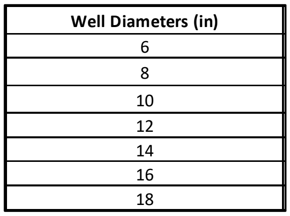
General Site Info	
Site Name	
Site Location	
Known contaminant:	
Contaminant information	
Target treatment width (feet [ft])	
Target treatment depth (ft)	
Initial contaminant concentration (micrograms per liter [µg/L])	
Enter treatment media porosity n	
Treatment goals	
Percent reduction (%)	
or	
Concentration (µg/L)	
Enter $k_{contaminant}$ (min^{-1})	
Contaminant half-life (days)	

Site information	
Enter site hydraulic conductivity K (centimeters per second [cm/s]; feet per day [ft/d])	
Enter site hydraulic gradient i	
Enter aquifer thickness b_a (ft)	
Enter site transmissivity T (square centimeters per second [cm^2/s]; square feet per day [ft^2/d])	
HRX Well hydraulic gradient	
Enter or select contaminant and media values	
Enter contaminant name	
Enter media type	
Enter media hydraulic conductivity (cm/s)	
Select	See Tables 4A-B
Select Media	See Tables 4A-B
Media hydraulic conductivity (cm/s)	
HRX Well parameters	
Select HRX Well diameter (inches [in])	
If the site will require pumps enter the rate (gallons per minute [gpm])	
Drill time (hours)	
Miscellaneous	
Enter cost per kilograms (kg) of media	

Table 4A and B. Summary of Available Selections for Table 3

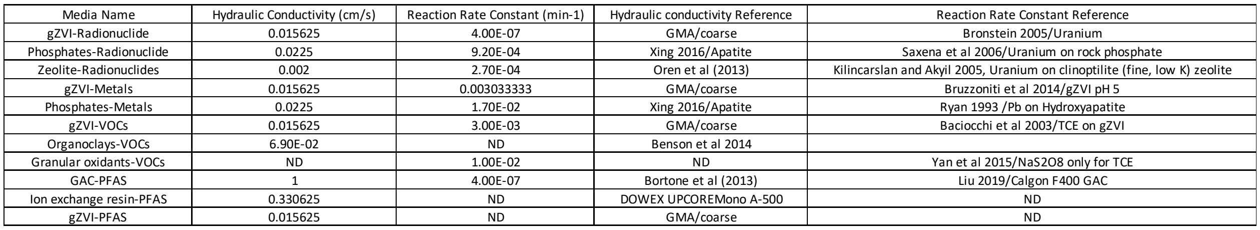
(These values can also be found under Lookup Tables and Assumed Values tabs in the design tool.)

A



Well Diameters (in)
6
8
10
12
14
16
18

B



Media Name	Hydraulic Conductivity (cm/s)	Reaction Rate Constant (min-1)	Hydraulic conductivity Reference	Reaction Rate Constant Reference
gZVI-Radionuclide	0.015625	4.00E-07	GMA/coarse	Bronstein 2005/Uranium
Phosphates-Radionuclide	0.0225	9.20E-04	Xing 2016/Apatite	Saxena et al 2006/Uranium on rock phosphate
Zeolite-Radionuclides	0.002	2.70E-04	Oren et al (2013)	Kilincarslan and Akyil 2005, Uranium on clinoptilite (fine, low K) zeolite
gZVI-Metals	0.015625	0.003033333	GMA/coarse	Bruzzoniti et al 2014/gZVI pH 5
Phosphates-Metals	0.0225	1.70E-02	Xing 2016/Apatite	Ryan 1993 /Pb on Hydroxyapatite
gZVI-VOCs	0.015625	3.00E-03	GMA/coarse	Baciocchi et al 2003/TCE on gZVI
Organoclays-VOCs	6.90E-02	ND	Benson et al 2014	
Granular oxidants-VOCs	ND	1.00E-02	ND	Yan et al 2015/NaS2O8 only for TCE
GAC-PFAS	1	4.00E-07	Bortone et al (2013)	Liu 2019/Calgon F400 GAC
Ion exchange resin-PFAS	0.330625	ND	DOWEX UPCOREMono A-500	ND
gZVI-PFAS	0.015625	ND	GMA/coarse	ND

Step 3: Enter Values in Design Tool

Preliminary calculations only require **Table 3** to be completed (found under the User Inputs tab). The preliminary output values can be found in the top table (Summary tab) shown in **Table 5**.

Table 5. Values Included in a Summary of Initial Outputs

Outputs from User Input tab	Result
HRX Well average capture width (ft)	
Number of HRX Wells	
HRX Well HRT (days)	
Contaminant HRT required (days)	
HRX Well length (ft)	
Site is active or passive	
Active pumping rate (gpm)	
Cartridge length (ft)	
Number of cartridges	
Total capital cost per HRX Well (USD)	
Initial cost of reaction media (USD)	
Annual media changeout cost (USD)	
Consumables total (kg CO_2 e)	
Consumables total (g NOx)	

Outputs from User Input tab	Result
Consumables total (g SOx)	
Consumables total (g PM10)	
Consumables total (MJ)	
Consumables total (MWH)	
Annual media changeouts (kg CO_2 e)	
Drilling total (kg CO_2 e)	
Drilling total (g NOx)	
Drilling total (g SOx)	
Drilling total (g PM10)	
Drilling total (MJ)	
Drilling total (MWH)	
Drilling for changeouts kg CO_2 e)	

These values are calculated under the HRX Well Calculations tab, the Cartridge Calculations tab, the Sustainability tab, and the Cost tab. Additional values calculated can be viewed under the respective tabs but the tabs are locked to prevent alterations to the equations used.

Step 4: Optimization of Inputs

The optimization step is optional and was configured to increase capture width and reduce the number of HRX Wells. The subsequent outcomes include reducing costs and increasing installation efficiency. It is assumed that many site characteristics (i.e. aquifer thickness and hydraulic conductivity) cannot be altered for the sake of optimization. Therefore, a simplified table is provided in **Table 6**.

Table 6. Parameters That Can Be Adjusted to Increase Capture Width

Design Optimization	Value
Enter or select treatment media	Select from Tables 4A-B
Enter media hydraulic conductivity (cm/s)[A]	
Enter reaction rate constant[A]	
Select mix-in media	
Enter mix-in media percent	
Update HRX Well diameter	
Enter a pump rate in M44	

[A] Enter if not selected along with contaminant and treatment media

The same values given in **Table 4A-B** can be selected here. There are two options to improve capture width or increase retention time. First, by adjusting hydraulic conductivity with a non-reactive mix-in media (described below) the capture width can be adjusted. Second, by entering a pump rate in M44 under the User Inputs tab.

Selections of mix-in media (e.g., coarse grained silica sand) are provided to adjust hydraulic conductivity (**Table 7**). Mix-in media was included in the design tool in order to optimize hydraulic conductivity (and related parameters) in the cartridges. The non-reactive mix-in media are useful when hydraulic conductivity is too high or too low for the treatment media. In these scenarios, the retention time determined from reaction rate constants may not be achieved. Changing the hydraulic conductivity in the cartridge is one method of specifying the cartridge retention time.

Table 7. Mix-in Media Available for In-Well Hydraulic Conductivity Adjustments

Mix-in media	Hydraulic conducitivity (cm/s)	Porosity
Gravel	3.00E+00	0.2
Coarse sand	6.00E-01	0.25
Fine sand	2.00E-06	0.3

The results of the optimization are given in **Table 8** (Summary tab).

Table 8. Summary of Optimization Activities

Updated Results Using Mix-in Media or a Pump Outputs from User Inputs tab	Result
HRX Well average capture width (ft)	
Number of HRX Wells	
HRX Well HRT (days)	
HRX Well length (ft)	
Active pumping (gpm)	
Cartridge length (ft)	
Number of cartridges	
Total capital cost (USD)	
Total cost of reaction media (USD)	
Consumables total (kg CO_2 e)	
Consumables total (g NOx)	
Consumables total (g SOx)	
Consumables total (g PM10)	
Consumables total (MJ)	
Consumables total (MWH)	
Drilling total (kg CO_2 e)	
Drilling total (g NOx)	
Drilling total (g SOx)	
Drilling total (g PM10)	

Updated Results Using Mix-in Media or a Pump Outputs from User Inputs tab	Result
Drilling total (MJ)	
Drilling total (MWH)	
Cartridge length (ft)	**Number for HRX Well length**
5	
10	

Step Six: Assessment of Results

Results of the tool should be reviewed and the practicality of recommendations considered. Use of the tool does not guarantee successful installation, complete project costs, or desired treatment outcomes. Thorough site investigations and treatability testing are typically necessary to have successful remediation outcomes. It is important to note that the tool currently does not have restrictions on most values, therefore common sense should be used when reviewing the summary. For example, if the number of HRX Wells exceeds site or budget capacity, additional design iterations should be completed to reduce the number of HRX Wells. If multiple HRX Wells will be applied at the site, the configuration is shown in **Figure 1**. HRX Wells be oriented parallel to the direction of groundwater flow but site-specific orientations may be required.

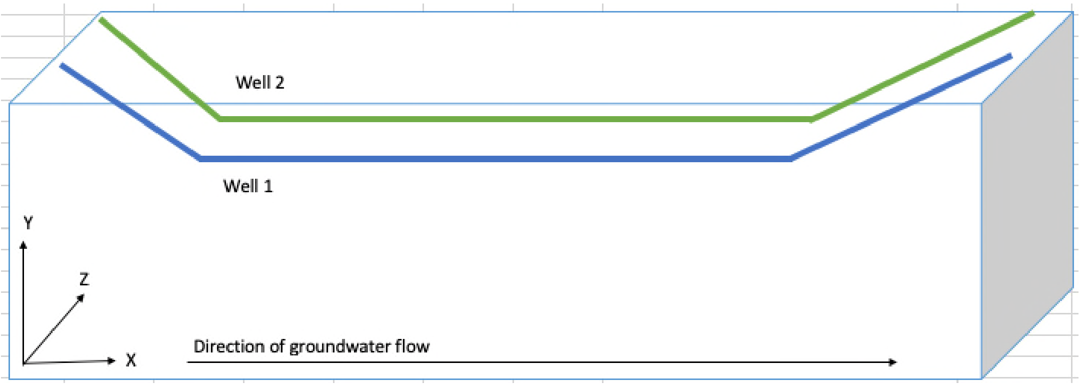


Figure 1. Orientation of Multiple HRX Wells Relative to Direction of Groundwater Flow

3 DESIGN TOOL APPLICATION EXAMPLES

The HRX Well design tool was demonstrated for four Department of Defense (DoD) sites: Vandenberg Air Force Base (VAFB) Site 3 where the field demonstration was completed and three additional DoD sites where HRX Wells are being considered (referred to here as DoD-A, DoD-B, and DoD-C). Known and estimated values were used in the tool for the latter three sites and additional iterations were completed to achieve reasonable capture widths. The following variables shown in each table are defined:

K_{rxn} -Pseudo first-order rate constant

K_A -Aquifer hydraulic conductivity

K_W -Media hydraulic conductivity

n -Media porosity

b_A -Aquifer thickness

i_A -Aquifer hydraulic gradient

i_W -Well hydraulic gradient

The tool was first demonstrated using the same inputs described in the previous modeling component for VAFB. **Table 9** provides the inputs and results for the design.

Table 9. HRX Well Design Tool for the VAFB Site

Site Name: Vandenburg						
Input Parameter	Value	Units		Output Parameter	Value	Units
Target treatment width	150	ft		Treatment width	44	ft
Target treatment depth	20	ft		Number of wells	4	
k_{rxn}	0.001	min^{-1}		Well length total	425	ft
Required retention time	5	days		Treatment length	64	ft
Actual retention time	12.7	days		Cost	272736	$
Treatment magnitude	3.2	OoM				
K_A	0.35	ft/d				
K_W	196	ft/d				
n	0.3					
b_A	7	ft				
i_A	0.007					
i_W	0.007					
Well diameter	12	in				
Cartridge diameter	10	in				
Active or passive	passive					
Active rate	NA	gpm				

The results in **Table 9** show that a 12-inch diameter well with media hydraulic conductivity of 196 ft/d will exhibit a capture and treatment zone width of 44 ft. The capital cost to build and install the well was $275,742. These costs do not include the consulting or oversight-related costs. Installing three wells to cover the target 150 ft plume costs $872,226 which is less than capital costs associated with several other comparable remedial technologies. It is important to note that while the well diameter is 12 inches, the cartridge diameter is approximately 2 inches less. The cartridges contain the media and therefore the flow-focusing is in response to the media and associated diameter of the cartridges.

Table 10. Vandenburg Results from the Design Tool for a 10-inch Well

Site Name: Vandenburg						
Input Parameter	Value	Units		Output Parameter	Value	Units
Target treatment width	150	ft		Treatment width	27	ft
Target treatment depth	20	ft		Number of wells	6	
k_{rxn}	0.0001	min^{-1}		Well length total	425	ft
Required retention time	5	days		Treatment length	64	ft
Actual retention time	12	days		Cost	272168	$
Treatment magnitude	3.2	OoM				
K_A	0.35	ft/d				
K_W	196	ft/d				
n	0.3					
b_A	7	ft				
i_A	0.007					
i_W	0.007					
Well diameter	10	in				
Cartridge diameter	8	in				
Active or passive	passive					
Active rate	NA	gpm				

Table 10 shows the results for a 10-inch diameter well. Here the treatment width has decreased to 27 ft as a result of decreased well diameter. In addition, as the aquifer thickness parameter increases the capture will decrease. For example, at a target depth of 8 ft a 12-inch well diameter (10-inch cartridge diameter) captures 38 ft, and a 10 inch well diameter (8-in cartridge diameter) capture 24 ft. The full output from the design tool for a 10-inch well at VAFB is included as **Attachment G-1**.

Three additional DoD sites were recently identified for pilot installations of the HRX Well. The first, named DoD-A, had an aquifer depth of 30 ft, aquifer conductivity of 0.74 ft/d and well media conductivity initially assumed as 57 ft/d. The combination of these factors suggested a small pump would be needed in situ to sufficiently increase flow rate and capture zone size. Therefore a 5 gpm (962 ft^3/day) was initially prescribed as shown in **Table 11**. It should be noted that this flow rate is an unreasonably high value for the site's aquifer transmissivity (K_A x b_A = 22 ft^2/day); however, this value was initially used to demonstrate the optimization processes.

Table 11. DoD-A Input Values for the Design Tool and Resulting Outputs

Site Name: DoD-A						
Input Parameter	Value	Units		Output Parameter	Value	Units
Target treatment width	45	ft		Treatment width	4336	ft
Target treatment depth	90	ft		Number of wells	1	
k_{rxn}	0.0009	min^{-1}		Well length total	2073	ft
Required retention time	3	days		Treatment length	459	ft
Actual retention time	8	days		Cost	1135404	$
Treatment magnitude	1.8	OoM				
K_A	0.74	ft/d				
K_W	57	ft/d				
n	0.25					
b_A	30	ft				
i_A	0.01					
i_W	0.01					
Well diameter	6	in				
Cartridge diameter	4	in				
Active or passive	Active					
Active rate	5	gpm				

At 5 gpm for the given site and according to Equation 1, the resulting effective well hydraulic conductivity (calculated by manipulation of the equation below) is 1.1E6 ft/d resulting in a calculated capture width of 4,336 ft, which is clearly unreasonably high.

$$Q = K_{media} * \pi * r^2 i_W$$

Equation 1. Flow rate due to media hydraulic conductivity and cartridge diameter.

Several iterations were then completed using the design tool to decrease the pump rate while monitoring capture width. The results of a pump rate of 0.05 gpm (9.6 ft^3/day), which is certainly sustainable for these aquifer conditions, are given in **Table 12**. The full output from the design tool for site DoD-A is included as **Attachment G-2**.

Table 12. Optimized Input and Output of DoD-A

Site Name: DoD-A					
Input Parameter	Value	Units	Output Parameter	Value	Units
Target treatment width	45	ft	Treatment width	43.2	ft
Target treatment depth	90	ft	Number of wells	1	
k_{rxn}	0.0009	min^{-1}	Well length total	981	ft
Required retention time	3	days	Treatment length	5	ft

Site Name: DoD-A					
Actual retention time	8	days	Cost	469493	$
Treatment magnitude	1.8	OoM			
K_A	0.74	ft/d			
K_W	57	ft/d			
n	0.25				
b_A	30	ft			
i_A	0.01				
i_W	0.01				
Well diameter	6	in			
Cartridge diameter	4	in			
Active or passive	Active				
Active rate	0.05	gpm			

The results in **Table 12** show that the capture width was reduced to 43.2 ft with a low and reasonable pumping rate; if the sustainable pumping rate can be increased. Alternatively, changes in input values would affect capture width, but may not be viable depending upon user requirements.

The second DoD site was called DoD-B and was contaminated with PFOS and PFOA. The site initially was presumed to not require an in situ pump and the associated results are shown in **Table 13**. The full output from the design tool for site DoD-B is included as **Attachment G-3**.

Table 13. Initial Input and Output values for DoD-B

Site Name: DoD-B					
Input Parameter	Value	Units	Output Parameter	Value	Units
Target treatment width	45	ft	Treatment width	0.56	ft
Target treatment depth	45	ft	Number of wells	90	
k_{rxn}	0.05	min^{-1}	Well length total	581	ft
Required retention time	0.1	days	Treatment length	42	ft
Actual retention time	0.2	days	Cost	317528	$
Treatment magnitude	3.1	OoM			
K_A	14.5	ft/d			
K_W	935	ft/d			
n	0.2				
b_A	10	ft			
i_A	0.037				
i_W	0.037				
Well diameter	6	in			
Cartridge diameter	4	in			
Active or passive	Passive				
Active rate	0	gpm			

Table 13 shows that, because of the relatively high aquifer hydraulic conductivity and thicker aquifer, the calculated capture width is very small, effectively the well diameter of 0.6 foot. If increases in well diameter were possible, then **Table 14** shows the result of doubling the well diameter.

Table 14. DoD-B Results When the Diameter was Increased to 12 Inches

Site Name: DoD-B					
Input Parameter	Value	Units	Output Parameter	Value	Units
Target treatment width	45	ft	Treatment width	4	ft
Target treatment depth	45	ft	Number of wells	14	
k_{rxn}	0.05	min^{-1}	Well length total	581	ft
Required retention time	0.1	days	Treatment length	42	ft
Actual retention time	0.2	days	Cost	308775	$
Treatment magnitude	3.1	OoM			
K_A	14.5	ft/d			
K_W	935	ft/d			

Site Name: DoD-B					
n	0.2				
b_A	10	ft			
i_A	0.037				
i_W	0.037				
Well diameter	12	in			
Cartridge diameter	10	in			
Active or passive	Passive				
Active rate	0	gpm			

The increased diameter increased capture width to 4 ft. Though the result is an improvement, it is not sufficient to achieve the target treatment width of 45 ft. Finally, the site was then changed to active and several pump rate values entered to achieve a reasonable capture width as shown in **Table 15**.

Table 15. DoD-B Updated Results from Adding a Small Pump

Site Name: DoD-B					
Input Parameter	Value	Units	Output Parameter	Value	Units
Target treatment width	45	ft	Treatment width	36	ft
Target treatment depth	45	ft	Number of wells	1	
k_{rxn}	0.05	min^{-1}	Well length total	486	ft
Required retention time	0.1	days	Treatment length	3	ft
Actual retention time	0.2	days	Cost	323550	$
Treatment magnitude	3.1	OoM			
K_A	14.5	ft/d			
K_W	935	ft/d			
n	0.2				
b_A	10	ft			
i_A	0.037				
i_W	0.037				
Well diameter	6	in			
Cartridge diameter	4	in			
Active or passive	Active*				
Active rate	1	gpm			

*Used pump rate to get reasonable capture and then the value to determine equivalent k_W.

The resulting capture width was 36 ft when the pump rate was exactly 1.0 gpm (192 ft^3/day), which is likely a reasonable sustainable yield for the transmissivity of this aquifer (K_A x b_A = 145 ft^2/day). As with DoD-A, the rate could be further optimized to increase capture, or other parameters altered if possible.

A third DoD site was identified where the primary contaminants of concern were 1,4 dioxane and trichloroethene (TCE). The site information is detailed in **Table 16**. The full output from the design tool for site DoD-B is included as **Attachment G-4**.

Table 16. DoD-C Updated Results from Adding a Small Pump

Site Name: DoD-B					
Input Parameter	Value	Units	Output Parameter	Value	Units
Target treatment width	185	ft	Treatment width	79	ft
Target treatment depth	10	ft	Number of wells	1*	
k_{rxn}	0.003	min^{-1}	Well length total	423	ft
Required retention time	0.9	days	Treatment length	106	ft
Actual retention time	2.4	days	Cost	293,232	$
Treatment magnitude	1.8	OoM			
K_A	0.142	ft/d			
K_W	283	ft/d			
n	0.35				
b_A	5	ft			
i_A	0.055				
i_W	0.055				
Well diameter	8	in			
Cartridge diameter	6	in			
Active or passive	Passive				
Active rate	NA	gpm			

*In order to address the target plume width of 185 ft, three wells would be required. The site is intended as a pilot installation and therefore only one well will be installed.

The capture width for DoD-C was determined to be 79 ft based on initial input values. There was enough hydraulic conductivity contrast such that neither a pump nor mix-in media was required to achieve reasonable capture.

4 SUSTAINABILITY ASSESSMENT OF THE HRX WELL

The tool was used to complete a sustainability analysis for the demonstration project at VAFB. To maximize benefits of a remediation system the associated environmental impacts from materials, installation, and use should be minimized. The SiteWise program (Battelle, U.S. Army Corps of Engineers) was used to assess three remediation systems designed to accomplish similar treatment goals. The goal of the assessment was to provide sufficient data to compare the HRX Well to other commonly used remediation systems, in terms of lifecycle impacts. The system boundary was around direct inputs including materials, energy sources, and equipment use. Equipment manufacture and transport was not included, however, personnel transport during installation, and materials transport to the site was included. Direct system installation was included but not construction of buildings, roads, or other infrastructure. Each remediation alternative (**Table 17**) was divided into three phases. Phase 1- materials manufacture, Phase 2- system installation, and Phase 3- system operation. Operation was considered either active or passive. where passive impacts were media replacements. The data for each phase of each alternative was entered into the SiteWise input sheet one at a time so impacts could be clearly assessed separately. The results of each analysis are given in **Figures 2** through **4** which depict greenhouse gas (GHG) emissions, energy use, and NOx, SOx, and PM_{10} emissions.

Table 17 includes the values and assumptions for each alternative. Alternative 1 was the HRX Well, Alternative 2 a groundwater extraction and treatment system (GETS), and Alternative 3 a permeable reactive barrier all intended to target a TCE plume. It is important to note that each alternative does necessarily appear equivalent in terms of total materials mass or method of operation.

Table 17A – D. Inputs used in SiteWise for Three Remediation Alternatives Considered in Three Phases

Table 14A				
System/Phase	**Assumption**	**Input**	**Value**	**Units**
Site	Contaminant: Trichloroethylene	Plume dimensions	(l) 500 (w) 150 (d) 25	ft
Travel	7 personnel	Air travel total	24328	miles
	7 personnel	Car travel total- 25 mpg car	207	miles
Travel/HRX	Equipment- shared long-road	Total materials weight	24	tons
Travel/GETS	Equipment- shared long-road	Total materials weight	28	tons
Travel/PRB	Equipment- shared long-road	Total materials weight	1267	tons
	Max 40 tons of materials per truck	31 trips	40	tons/trip

Table 17B				
System/Phase	**Assumption**	**Input**	**Value**	**Units**
HRX/Phase 1	3 wells	Diameter	1	ft
	Well casing:	Sc 40 PVC Casing	265	ft
	Well screen	Sc 40 St. steel screen	165	ft
	13 5ft cartridges, Sch 40 SS	Diameter	1	ft
	75% reactive media	ZVI (per well)	630	kg
	5% casing grout	Bentonite (per well)	94	kg
	95% casing grout	Typical cement (per well)	179	kg
HRX/Phase 2	Drilling operations from Lubrecht 2012	0.086 hrs/ft	37	hours
	Excavator	Soil removed per well	6.6	yd^3
	Water-development	12 gallons/ft well; total for 3 wells	721	gallons
HRX/Phase 3	1 media replacement at 15 years	630 kg per well	1890	kg

Table 17C				
System/Phase	**Assumption**	**Input**	**Value**	**Units**
GETS/Phase 1	10 vertical wells	Diameter	0.5	ft
	Well casing:	Sc 40 PVC (total ft)	120	ft
	Well screen	Sc 40 st steel (total ft)	100	ft
	Grout 5%	Bentonite (total mass)	500	kg
	Grout 95%	Typical cement (total mass)	5210	kg
	Virgin GAC, 2 replacements/year	Total mass per replacement	3325	lbs

Table 17C				
System/Phase	**Assumption**	**Input**	**Value**	**Units**
GETS/Phase 2	Drill rig	0.086 hrs/ft (total for 10 wells)	10.32	hours
	Excavator	Cubic yards soil removed	122	yd^3
	Water-development	Gallons used per well (and assumed 50% recovered to WWTP)	721	gallons
GETS/Phase 3	10 extraction pumps	2 hp each (05 gpm each) (total hp given). Assume 24 hrs operation/day.	20	hp
	1 compressor	2 hp compressor. Assume 24 hrs operation/day.	2	hp
	1 system pump	4 hp pump. Assume 24 hrs operation/day.	4	hp
	GAC Replacement (annual)	Total mass	3325	lbs

Table 17D				
System/Phase	**Assumption**	**Input**	**Value**	**Units**
PRB/Phase 1	25% treatment media	ZVI (total)	214096	kg
	Sand (35%)	Total mass	398254	kg
	Portland cement (3%)	Total mass	18143	kg
PRB/Phase 2	Trencher 16-25 hp and 300 linear ft/day (CHM Report)	Operating time (25*150)	75	hours
	Excavator removed soil	Cubic yards removed	450	yd^3
PRB/Phase 3	1 media replacement at 15 years	Total ZVI	214096	kg

Table 17D				
System/Phase	**Assumption**	**Input**	**Value**	**Units**
	1 sand (35%) replacement at 15 years	Total mass	398254	kg
	1 Portland cement (3%) replacement at 15 years	Total mass	18143	kg

4.1 Emissions Impacts

Table 14 demonstrates that impacts of each system will vary. For example, the mass of materials transported and used in each system was much greater for the PRB than GETS or the HRX Well. The resulting GHG emissions from all phases are shown in **Figure 2**. Clearly, operation of the GETS system (GETS-3), shown as annual operation, had the greatest impact overall due to continuous operation of extraction and system pumps, in addition to a blower. Further comparison shows that in the travel phase PRB-related transport was greater than the HRX Well or GETS because of the much larger mass of ZVI used. However, in comparison to GETS operation, the PRB media is only replaced once during the system lifetime making PRB-3 much lower than GETS-3. PRB media manufacture similarly was greater than the other alternatives. GHG emissions were higher for HRX-1 than GETS-1 though the impacts are clearly offset by the GHG emissions avoided by use of passive water capture and treatment. HRX-3 has a slight impact as a result of media replacements while PRB-3 is higher due to the replacement halfway through its lifecycle.

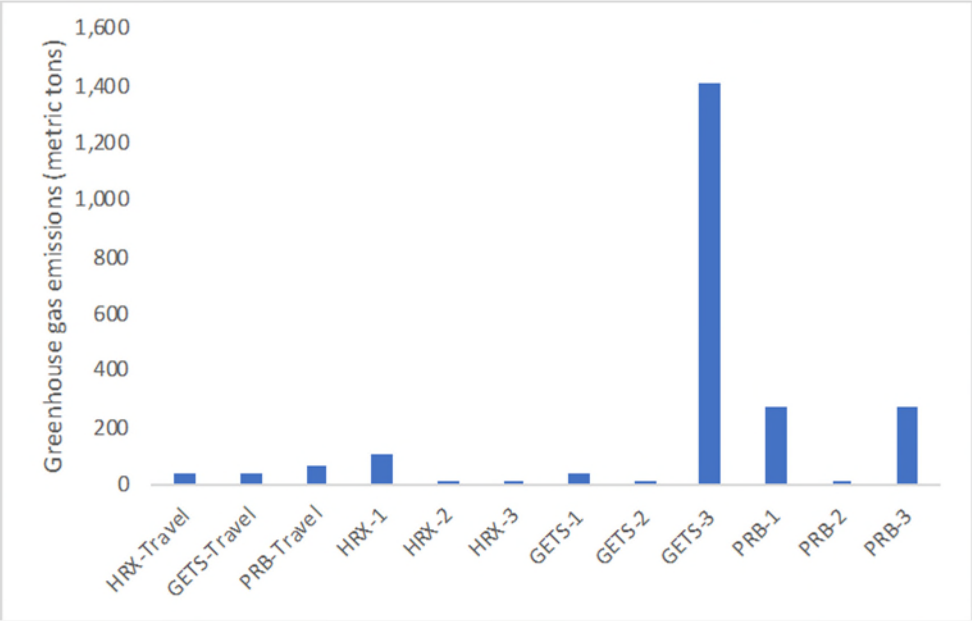


Figure 2. Greenhouse Gas Emissions Resulting from Three Lifecycle Phases (Manufacture, Installation, Operation) for Three Remediation Alternatives

Materials manufacturing resulted in more emissions to air in the order of PRB>HRX Well>GETS. The same order was observed for Phase 2 except that only NOx is visible in **Figure 3** as it is the primary impact of installation and related to the equipment type used. In Phase 3, again, the HRX Well had substantially lower impacts than the other two alternatives, and the impacts were lower than HRX Well in Phase 1. In Phase 1 the well materials were also manufactured increasing emissions. Due to specific methods of operation the NOx, SOx, and PM_{10} emissions vary from GETS to the PRB. For example, because GETS requires electricity for operation, and in turn fossil fuel combustion to produce the electricity, NOx emissions were greater. However, more SOx and PM_{10} were produced during PRB media replacement as a result of ZVI processing.

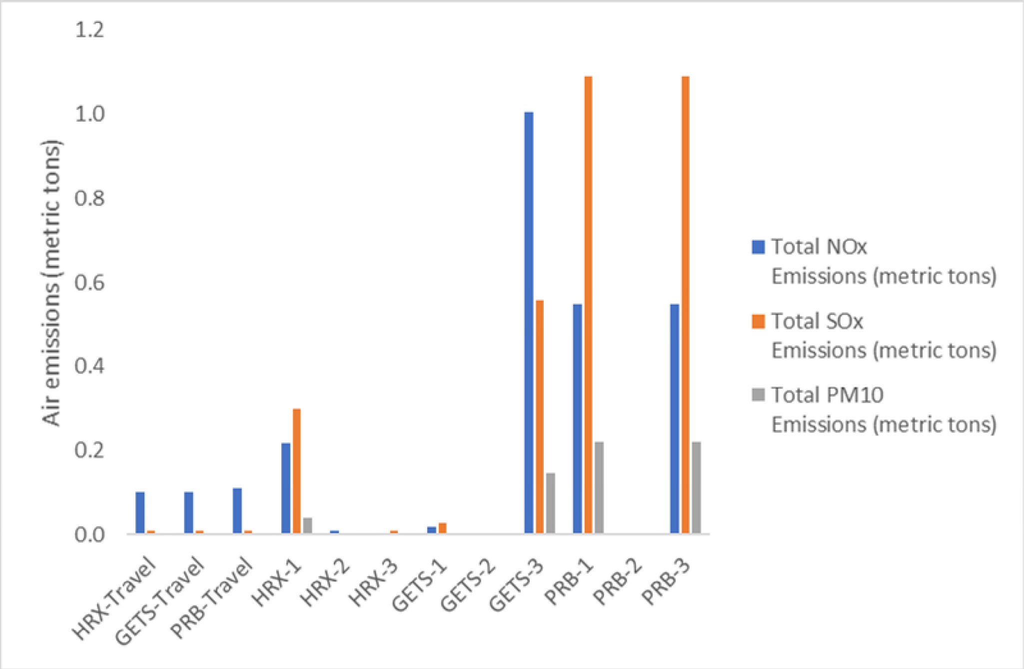


Figure 3. NOx, SOx, and PM_{10} Emissions Resulting from the Lifecycles of Three Remediation Alternatives Considered for Remediation of a TCE Plume

The HRX Well did not have uniformly lower impacts. Comparison of total lifecycle impacts, as a sum of impacts in each phase, showed that the HRX Well has the lowest impact overall. The difference is particularly evident in Phase 3 where impacts in Phase 1 and Phase 2 are not carried through operations. By passively treating contaminants the same remediation goal can be achieved with reduced impacts. As a result, the remediation outcome is improved when emissions impacts are avoided.

4.2 Energy Impacts

Energy use (in millions of BTUs) was also characterized and is shown in **Figure 4.** Travel impacts were relatively similar as for GHG gas emissions. The order of energy use for materials manufacture was in the same order as travel, which was also implied in **Table 14** by the materials used. Despite the use of heavy equipment to install all three alternatives the Phase 2 energy use was uniformly low compared to all other phases. In Phase 3 the HRX Well clearly outperformed both GETS and the PRB due to passive operation and comparatively less reactive media used, respectively. GETS operation was assumed to be continuous and the PRB media mass used (214096 kg ZVI) was much greater than that in the three HRX Wells (1890 kg). While the PRB passively intercepts contaminant plumes the mass of reactive media required has a much more significant impact.

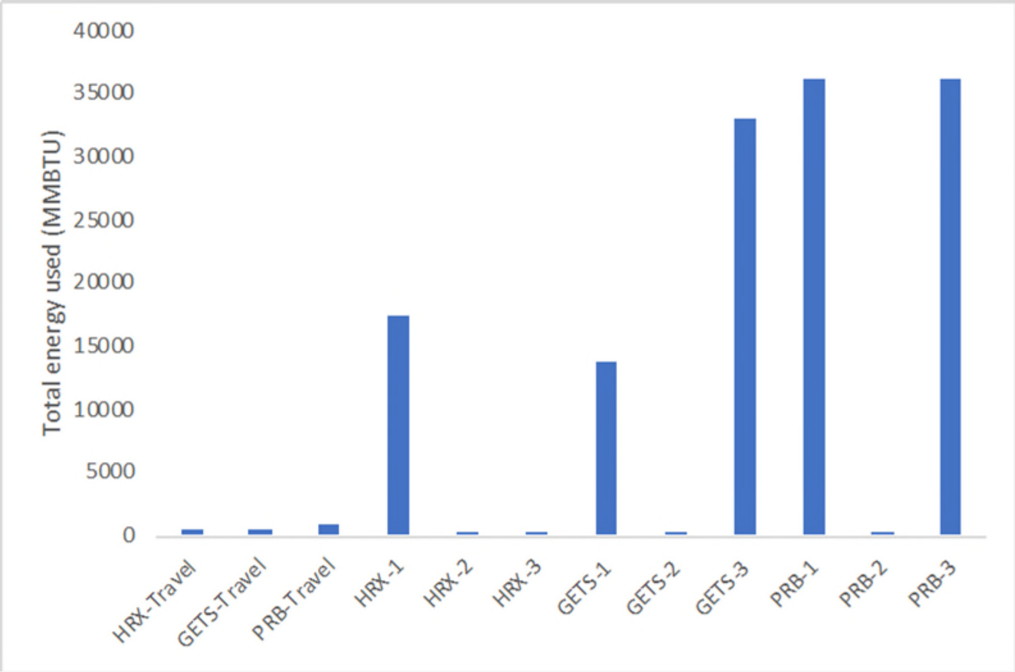


Figure 4. Total Energy Used in Millions of BTUs for Three Remediation Alternatives by Lifecycle Phase

4.3 Resource Impacts

Based on the inputs from each table and the resulting emissions data, the natural resource impacts from the HRX Well are minimized in comparison to GETS or PRB. The HRX Well is capable of meeting remediation goals while minimizing natural resource consumption. For example, the efficient use of ZVI by the HRX Well where the mass of ZVI used in the system lifecycle is a fraction of that used by the PRB. The HRX Well is also passive and therefore does not require extraction of fossil fuels, water, or other recurring materials (other than a single media replacement after 15 years) to meet remediation goals.

4.4 On-Site Safety

The lifecycle phases of the HRX Well were not found to present unusual risks to workers. In some cases, risks were minimized compared to the alternatives. The HRX Well is an in situ system and thus does not require contaminants to be removed from the aquifer thereby reducing worker exposure. Installation activities were closely monitored, and worker safety was prioritized. The HRX Well operates in situ and passively which also does not introduce risk from operation and maintenance activities. In comparison to the alternatives the HRX Well does not pose exceptional risks or risks out of proportion with the sustainability benefits.

5 REFERENCES

Divine, C.E., Wright, J., Wang, J., McDonough, J., Kladias, M., Crimi, M., Nzeribe, B.N., Devlin, J.F., Lubrecht, M., Ombalski, D., Hodge, W., Voscott, H., Gerber, K. 2018. The Horizontal Reactive Media Treatment Well (HRX Well®) for Passive In Situ Remediation: Design, Implementation, and Sustainability. Remediation Journal 28 (4), 5-16.

Attachment H-1

VAFB

Cell Key	Enter value	Select value	Calculated value	Required value to get capture width

Contaminant information

Enter:

1. Plume dimensions- Note that these are target treatment dimensions which may not be equal to the total plume. Plume length is not used in calculations. Instead, treatment length is calculated below using user-provided rate constants or those from the lookup tables.
2. Contaminant concentration- see below
3. Media porosity-This value should typically fall between 0.2 and 0.5
4. Treatment goals as percent reduction or a final concentration, including specific regulatory limits.

If treatability testing was not completed enter estimated values.

If more than one contaminant is present and part of the HRX Well(R) treatment plan do the following:

1. Enter one contaminant initial concentration and treatment goal. This can be in random order or address a primary contaminant of concern first. Note that known rate constants are entered in P32 or selected with media options in P35.
2. Take note of the resulting treatment and well lengths.
3. If two or more contaminants are present and part of the treatment plan repeat steps 1 and 2.
4. From the resulting well lengths use the longest treatment length to ensure the longest retention time required is achieved.

NOTE 1: Treatment lengths for two more more contaminants that are chemically dissimilar and or present in different concentrations should not be assumed correct without laboratoy verification from batch or column tests of the site groundwater containing the contaminants of concern.

NOTE 2: Use psuedo first-order rate constant for adsorptive media.

Site information

Enter values from site investigations and treatability testing. If information is not available use best estimates.

The HRX Well® hydraulic gradient should be assumed approximately equal to the aquifer hydraulic gradient. Item **F** on the adjacent diamgram show

Treatment media information

Enter data from treatability testing in M32, N32, and O32 will auto-fill.

If treatability testing was not completed select reference values from M35 and N35 (O35 will autofill).

Enter media density from known values or from Q2:Q13 in the Lookup Tables tab

Enter a media capacity value in M39. If the value is not known enter the partitioning coefficient and the capacity will be estimated using the concentration data provided above.

Enter media partition coefficient (measured or from literature) and the changeout freqeuncy will be calculated assuming changeout occurs at 70% of media capacity.

Active and passive sites

Active sites are those with hydraulic conductivity greater than 5 ft/d

Passive sites have hydrulic conductivity less than 5 ft/d

If site is active enter the gpm value from pumping tests.

Cell H8 under the Summary tab will display if the site is active or passive.

If sufficient capture is not achieved with the reactive media alone, a pump rate can be entered to increase capture width.

NOTE; That increasing flow rate into the well will cause well length to increase if reaction rates remain the same.

Explanation of mix-in media

Mix-in media was included in the design tool in order to optimize hydraulic conductivity (and related parameters) in the cartridges. These media are not reactive but it should be noted that using too much will reduce the total available surface area of treatment media. The mix-in media are useful when hydraulic conductivity is too high or too low for the treatment media. In these scenarios the retention time determined from reaction rate constants may not be achieved. Changing the hydraulic conductivity in the cartridge is one method of specifying the cartridge retention time.

Note that the weighted media hydraulic conductivity is an *estimate* only. For a thorough analysis refer to HydrogeoSieveXL2 (http://people.ku.edu/~jfdevlin/Software.html)

Well parameters

Select HRX Well® diameter.

The remaining values are automatically calculated in a separate tab and returned here.

A reference diagram is provided to the right- match letters next to input cells to diagram.

The cartridge diameter is assumed to be 2 inches less than the HRX Well® diameter.

Enter well hydraulic gradient. The value should be approximately equal to the aquifer hydraulic gradient.

	Tool input description	Value
	General Site Info	
	Site Name	VAFB
	Site Location	CA
	Known contaminant:	TCE
	Contaminant information	
🟦	Target treatment width (ft)	150
🟦	Target treatment depth (ft)	20
	Initial contaminant concentration (ug/L)	75000

Treatment goals	**Value**
Percent reduction (%)	
or	
Concentration (ug/L)	50

	Aquifer Properties		Value (secondary units)
🟦	Enter site hydraulic conductivity *K* (cm/s; ft/d)	1.23E-04	0.350
🟦	Enter site hydraulic gradient i	0.007	
🟦	Enter aquifer thickness b_a (ft)	7	
	Enter site transmissivity *T* (cm^2/s; ft^2/d)	0.026	2.450

Enter or select contaminant and media values

	Contaminant	Media	Media hydraulic conducitvity (cm/s)	Media hydraulic conducitvity (ft/day)	Enter $k_{contaminant}$ (min^{-1})	Calculated half-life (days)
🟦	TCE	ZVI	0.069	196	9.00E-04	0.5

	Contaminant	Select	Media hydraulic conductivity (cm/s)	Media hydraulic conducitvity (ft/day)	$k_{contaminant}$ (min^{-1})
🟦	Select	Select	#N/A	#N/A	#N/A

Enter treatment media porosity *n*	0.3
Enter media density value (kg/m^3)	2100
Media capacity (mg/kg)	
Media K_d (L/kg)	
Enter cost per kg of treatment media	$1.64

Select "Active" if the site will use a pump	Passive
If active, enter gpm value	

Select mix-in media	Mix-in media K (cm/s)
Gravel	3.00E+00

Enter % of mix in media	Percent reaction media (%)
0.00%	100.00%

Weighted K_{media} (ft/d)	196

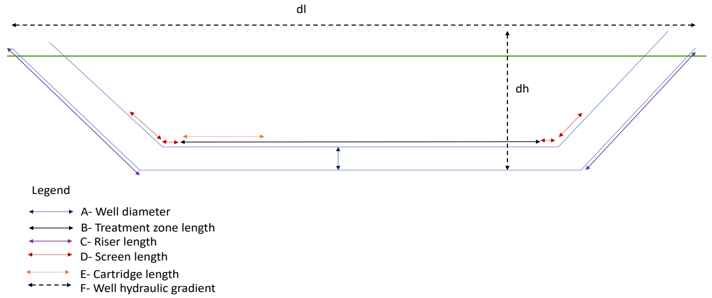
	Well parameters	
🟦	**A** Select HRX Well® diameter (in)	10
	B Minimum treatment zone length (ft)	64
	C Riser length (ft)	200
	D Total screen length (ft)	160
	Total HRX Well® length (ft)	425
	E Number of 10 ft cartridges	8
	Drill time (Hrs)	37
	Select well casing material	Carbon steel
🟦	**F** HRX Well® hydraulic gradient	0.007

Unit Conversions

Enter hydraulic conductivity in ft/d to get value in cm/s	
Hydraulic conductivity in cm/s	0
If concentration is in molar units enter value	
Enter contaminant molecular weight	
Concentration in ug/L	0

Other helpful conversion factors

	86400 seconds
1 foot	30.48 cm
1 gpm	192.5 ft^3/d
1 gallon	3.785 L
PPT	ng/L
PPB	ug/L
PPM	mg/L



General Site Info	Value
Site Name	VAFB
Site Location	CA
Known contaminant type 1:	TCE
Known contaminant concentration (ug/L)	75000
Treatment goals	
Percent reduction (%)	0.000
or	
Concentration (ug/L)	50
Tool setup	
Select contaminant category	TCE
Compatible media	ZVI
Media hydraulic conductivity (ft/d)	196
Media reactivity (min^{-1})	9.00E-04

Data Summary

The first block (Outputs from User Inputs gab) summarzies the well design based on the inputs in that tab. If the results shown are not practical input values can be adjusted where reasonable (i.e. aquifer hydraulic conductivity cannot practically be altered).

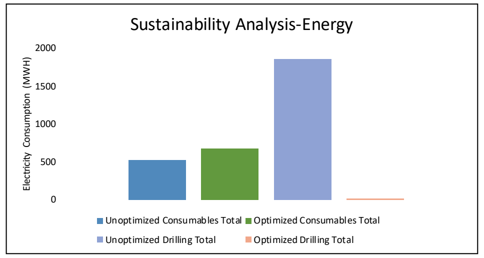
The second block will display updated values if mix-in media or a pump is added.

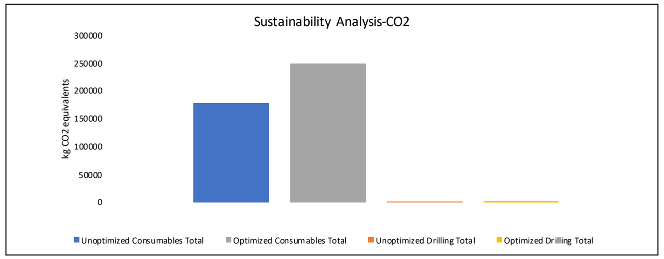
Outputs from User Input tab	Result
Well average capture width (ft)	28
Number of wells	6
Well HRT (days)	14.1
Contaminant HRT required (days)	5.6
Well length (ft)	425
Site is active or passive	Passive
Active pumping rate (gpm)	0.000
Cartridge length (ft)	10
Number of cartridges	5
Total capital cost **per well** (USD)	$272,168
Initial cost of reaction media (USD)	$4,784
Media changeout frequency (years)	0
Annual media changeout cost (USD)	30,000
Consumables total (kg CO_2 e)	177853
Consumables total (g NOx)	282663
Consumables total (g SOx)	392332
Consumables total (g PM10)	50743
Consumables total (MJ)	1863822
Consumables total (MWH)	518
Annual media changeouts (kg CO_2 e)	0
Drilling total (kg CO_2 e)	1914
Drilling total (g NOx)	22
Drilling total (g SOx)	2157
Drilling total (g PM10)	19861
Drilling total (MJ)	2480
Drilling total (MWH)	1852
Drilling for changeouts kg CO_2 e)	0

Results from mix-in media or added pump	Result
Well average capture width (ft)	28
Number of wells	6
Well HRT (days)	6
Well length (ft)	292
Active pumping (gpm)	0.000
Cartridge length (ft)	10
Number of 10 ft cartridges	3
Total capital cost (USD)	$183,397
Total cost of reaction media (USD)	$0
Consumables total (kg CO_2 e)	250528
Consumables total (g NOx)	428634
Consumables total (g SOx)	582123
Consumables total (g PM10)	73933
Consumables total (MJ)	2423356
Consumables total (MWH)	673
Drilling total (kg CO_2 e)	22
Drilling total (g NOx)	0
Drilling total (g SOx)	24
Drilling total (g PM10)	224
Drilling total (MJ)	28
Drilling total (MWH)	21

Cartridge length (ft)	Number for initial well length
5	13
10	6

Cartridge length (ft)	Number for well length
5	5
10	3





Interpreting Sustainability Results

Example sustainability data and external comparisons are given in the table below to give context to sustainability data outputs.
The site had target plume width of 150 ft and target depth of 20 ft. The well was *450* ft long and the

Impact category for consumables	Associated CO_2 eq emissions (kg)	Associated NO_X Emissions (g)
Consumables emissions	496151	786333
Equivalent to driving n passenger cars per year	105	49730
Drilling emissions	5303	60
Equivalent to driving n passenger cars per year	1.1	3.8

Attachment H-2

Site A

Cell Key	Enter value	Select value	Calculated value	Required value to get capture width

Contaminant information

Enter:

1. Plume dimensions- Note that these are target treatment dimensions which may not be equal to the total plume. Plume length is not used in calculations. Instead, treatment length is calculated below using user-provided rate constants or those from the lookup tables.
2. Contaminant concentration- see below
3. Media porosity-This value should typically fall between 0.2 and 0.5
4. Treatment goals as percent reduction or a final concentration, including specific regulatory limits.

If treatability testing was not completed enter estimated values.

If more than one contaminant is present and part of the HRX Well(R) treatment plan do the following:

1. Enter one contaminant initial concentration and treatment goal. This can be in random order or address a primary contaminant of concern first. Note that known rate constants are entered in P32 or selected with media options in P35.
2. Take note of the resulting treatment and well lengths.
3. If two or more contaminants are present and part of the treatment plan repeat steps 1 and 2.
4. From the resulting well lengths use the longest treatment length to ensure the longest retention time required is achieved.

NOTE 1: Treatment lengths for two more more contaminants that are chemically dissimilar and or present in different concentrations should not be assumed correct without laboratoy verification from batch or column tests of the site groundwater containing the contaminants of concern.

NOTE 2: Use psuedo first-order rate constant for adsorptive media.

Site information

Enter values from site investigations and treatability testing. If information is not available use best estimates.

The HRX Well® hydraulic gradient should be assumed approximately equal to the aquifer hydraulic gradient. Item **F** on the adjacent diamgram show

Treatment media information

Enter data from treatability testing in M32, N32, and O32 will auto-fill.
If treatability testing was not completed select reference values from M35 and N35 (O35 will autofill).
Enter media density from known values or from Q2:Q13 in the Lookup Tables tab
Enter a media capacity value in M39. If the value is not known enter the partitioning coefficient and the capacity will be estimated using the concentration data provided above.
Enter media partition coefficient (measured or from literature) and the changeout freqeuncy will be calculated assuming changeout occurs at 70% of media capacity.

Active and passive sites

Active sites are those with hydraulic conductivity greater than 5 ft/d
Passive sites have hydrulic conductivity less than 5 ft/d
If site is active enter the gpm value from pumping tests.
Cell H8 under the Summary tab will display if the site is active or passive.
If sufficient capture is not achieved with the reactive media alone, a pump rate can be entered to increase capture width.
NOTE; That increasing flow rate into the well will cause well length to increase if reaction rates remain the same.

Explanation of mix-in media

Mix-in media was included in the design tool in order to optimize hydraulic conductivity (and related parameters) in the cartridges. These media are not reactive but it should be noted that using too much will reduce the total available surface area of treatment media. The mix-in media are useful when hydraulic conductivity is too high or too low for the treatment media. In these scenarios the retention time determined from reaction rate constants may not be achieved. Changing the hydraulic conductivity in the cartridge is one method of specifying the cartridge retention time.
Note that the weighted media hydraulic conductivity is an *estimate* only. For a thorough analysis refer to HydrogeoSieveXL2 (http://people.ku.edu/~jfdevlin/Software.html)

Well parameters

Select HRX Well® diameter.
The remaining values are automatically calculated in a separate tab and returned here.
A reference diagram is provided to the right- match letters next to input cells to diagram.
The cartridge diameter is assumed to be 2 inches less than the HRX Well® diameter.
Enter well hydraulic gradient. The value should be approximately equal to the aquifer hydraulic gradient.

	Tool input description	Value
	General Site Info	
	Site Name	DoD-A
	Site Location	
	Known contaminant:	TCE, PCE

	Contaminant information	
🟦	Target treatment width (ft)	45
🟦	Target treatment depth (ft)	90
	Initial contaminant concentration (ug/L)	320

Treatment goals	Value
Percent reduction (%)	
or	
Concentration (ug/L)	5

	Aquifer Properties		Value (secondary units)
🟦	Enter site hydraulic conductivity *K* (cm/s; ft/d)	2.61E-04	0.740
🟦	Enter site hydraulic gradient i	0.01	
🟦	Enter aquifer thickness b_a (ft)	30	
	Enter site transmissivity *T* (cm^2/s; ft^2/d)	0.239	22.195

Enter or select contaminant and media values

	Contaminant	Media	Media hydraulic conductivity (cm/s)	Media hydraulic conducitvity (ft/day)
🟦	TCE, PCE	ZVI	0.02	57

	Contaminant	Select	Media hydraulic conductivity (cm/s)	Media hydraulic conducitvity (ft/day)
🟦	Select	Select	#N/A	#N/A

Enter treatment media porosity *n*	0.25
Enter media density value (kg/m^3)	2100
Media capacity (mg/kg)	
Media K_d (L/kg)	
Enter cost per kg of treatment media	$1.64

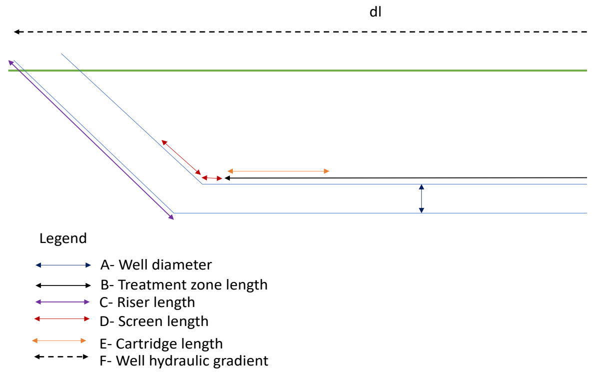
Select "Active" if the site will use a pump	Active
If active, enter gpm value	0.050

Select mix-in media	Mix-in media K (cm/s)
Gravel	3.00E+00

Enter % of mix in media	Percent reaction media (%)
0.00%	100.00%

Weighted K_{media} (ft/d)	11029

	Well parameters	
🟦	**A** Select HRX Well® diameter (in)	6
	B Minimum treatment zone length (ft)	1
	C Riser length (ft)	900
	D Total screen length (ft)	72
	Total HRX Well® length (ft)	973
	E Number of 10 ft cartridges	0
	Drill time (Hrs)	84
	Select well casing material	Carbon steel
🟦	**F** HRX Well® hydraulic gradient	0.01



Unit Conversions	
Enter hydraulic conductivity in ft/d to get value in cm/s	
Hydraulic conductivity in cm/s	
If concentration is in molar units enter value	
Enter contaminant molecular weight	
Concentration in ug/L	

Other helpful conversion factors	
1 foot	
1 gpm	
1 gallon	
PPT	
PPB	
PPM	

General Site Info	Value
Site Name	DoD-A
Site Location	0
Known contaminant type 1:	TCE, PCE
Known contaminant concentration (ug/L)	320
Treatment goals	
Percent reduction (%)	0.000
or	
Concentration (ug/L)	5
Tool setup	
Select contaminant category	TCE, PCE
Compatible media	ZVI
Media hydraulic conductivity (ft/d)	57
Media reactivity (min^{-1})	3.00E-03

Data Summary

The first block (Outputs from User Inputs gab) summarzies the well design based on the inputs in that tab. If the results shown are not practical input values can be adjusted where reasonable (i.e. aquifer hydraulic conductivity cannot practically be altered).

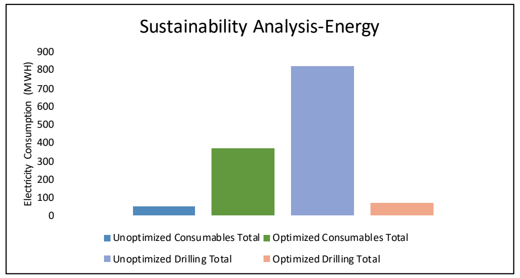
The second block will display updated values if mix-in media or a pump is added.

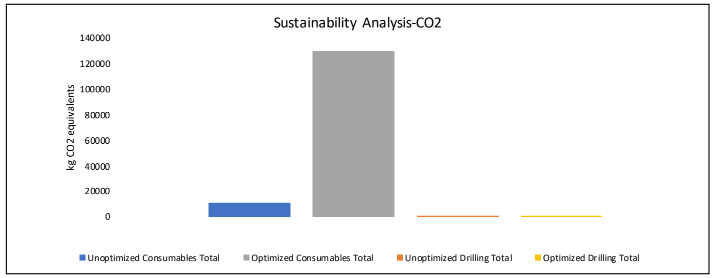
Outputs from User Input tab	Result
Well average capture width (ft)	43
Number of wells	1
Well HRT (days)	2.4
Contaminant HRT required (days)	1.0
Well length (ft)	973
Site is active or passive	Passive
Active pumping rate (gpm)	0.050
Cartridge length (ft)	10
Number of cartridges	19
Total capital cost **per well** (USD)	$469,493
Initial cost of reaction media (USD)	$26
Media changeout frequency (years)	0
Annual media changeout cost (USD)	30,000
Consumables total (kg CO_2 e)	10857
Consumables total (g NOx)	21230
Consumables total (g SOx)	31511
Consumables total (g PM10)	4292
Consumables total (MJ)	173178
Consumables total (MWH)	48
Annual media changeouts (kg CO_2 e)	0
Drilling total (kg CO_2 e)	846
Drilling total (g NOx)	10
Drilling total (g SOx)	954
Drilling total (g PM10)	8779
Drilling total (MJ)	1096
Drilling total (MWH)	818
Drilling for changeouts kg CO_2 e)	0

Results from mix-in media or added pump	Result
Well average capture width (ft)	43
Number of wells	1
Well HRT (days)	1
Well length (ft)	1949
Active pumping (gpm)	0.050
Cartridge length (ft)	10
Number of 10 ft cartridges	42
Total capital cost (USD)	$1,053,095
Total cost of reaction media (USD)	$0
Consumables total (kg CO_2 e)	129772
Consumables total (g NOx)	258648
Consumables total (g SOx)	351283
Consumables total (g PM10)	44618
Consumables total (MJ)	1342935
Consumables total (MWH)	373
Drilling total (kg CO_2 e)	69
Drilling total (g NOx)	1
Drilling total (g SOx)	77
Drilling total (g PM10)	713
Drilling total (MJ)	89
Drilling total (MWH)	66

Cartridge length (ft)	Number for initial well length
5	0
10	0

Cartridge length (ft)	Number for well length
5	85
10	42





Interpreting Sustainability Results

Example sustainability data and external comparisons are given in the table below to give context to sustainability data outputs.

The site had target plume width of 150 ft and target depth of 20 ft. The well was *450* ft long and the

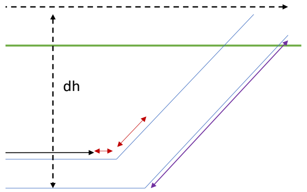
Impact category for consumables	Associated CO_2 eq emissions (kg)	Associated NO_X Emissions (g)
Consumables emissions	496151	786333
Equivalent to driving n passenger cars per year	105	49730
Drilling emissions	5303	60
Equivalent to driving n passenger cars per year	1.1	3.8

0
0

86400 seconds
30.48 cm
192.5 ft^3/d
3.785 L
ng/L
ug/L
mg/L

Enter $k_{contaminant}$ (min^{-1})	Calculated half-life (days)
3.00E-03	0.2

$k_{contaminant}$ (min^{-1})
#N/A



Attachment H-3

Site B

Cell Key	Enter value	Select value	Calculated value	Required value to get capture width

Contaminant information

Enter:

1. Plume dimensions- Note that these are target treatment dimensions which may not be equal to the total plume. Plume length is not used in calculations. Instead, treatment length is calculated below using user-provided rate constants or those from the lookup tables.
2. Contaminant concentration- see below
3. Media porosity-This value should typically fall between 0.2 and 0.5
4. Treatment goals as percent reduction or a final concentration, including specific regulatory limits.

<u>If treatability testing was not completed enter estimated values.</u>

If more than one contaminant is present and part of the HRX Well(R) treatment plan do the following:

1. Enter one contaminant initial concentration and treatment goal. This can be in random order or address a primary contaminant of concern first. Note that known rate constants are entered in P32 or selected with media options in P35.
2. Take note of the resulting treatment and well lengths.
3. If two or more contaminants are present and part of the treatment plan repeat steps 1 and 2.
4. From the resulting well lengths use the longest treatment length to ensure the longest retention time required is achieved.

NOTE 1: Treatment lengths for two more more contaminants that are chemically dissimilar and or present in different concentrations should not be assumed correct without laboratoy verification from batch or column tests of the site groundwater containing the contaminants of concern.

NOTE 2: Use psuedo first-order rate constant for adsorptive media.

Site information

Enter values from site investigations and treatability testing. If information is not available use best estimates.

Treatment media information

Enter data from treatability testing in M32, N32, and O32 will auto-fill.

If treatability testing was not completed select reference values from M35 and N35 (O35 will autofill).

Enter media density from known values or from Q2:Q13 in the Lookup Tables tab

Enter a media capacity value in M39. If the value is not known enter the partitioning coefficient and the capacity will be estimated using the concentration data provided above.

Enter media partition coefficient (measured or from literature) and the changeout freqeuncy will be calculated assuming changeout occurs at 70% of media capacity.

Active and passive sites

Active sites are those with hydraulic conductivity greater than 5 ft/d

Passive sites have hydrulic conductivity less than 5 ft/d

If site is active enter the gpm value from pumping tests.

Cell H8 under the Summary tab will display if the site is active or passive.

If sufficient capture is not achieved with the reactive media alone, a pump rate can be entered to increase capture width.

NOTE; That increasing flow rate into the well will cause well length to increase if reaction rates remain the same.

Explanation of mix-in media

Mix-in media was included in the design tool in order to optimize hydraulic conductivity (and related parameters) in the cartridges. These media are not reactive but it should be noted that using too much will reduce the total available surface area of treatment media. The mix-in media are useful when hydraulic conductivity is too high or too low for the treatment media. In these scenarios the retention time determined from reaction rate constants may not be achieved. Changing the hydraulic conductivity in the cartridge is one method of specifying the cartridge retention time.

Note that the weighted media hydraulic conductivity is an *estimate* only. For a thorough analysis refer to HydrogeoSieveXL2 (http://people.ku.edu/~jfdevlin/Software.html)

Well parameters

Select HRX Well® diameter.

The remaining values are automatically calculated in a separate tab and returned here.

A reference diagram is provided to the right- match letters next to input cells to diagram.

The cartridge diameter is assumed to be 2 inches less than the HRX Well® diameter.

Enter well hydraulic gradient. This value should be approximately equal to the aquifer hydraulic gradient.

	Tool input description	**Value**
	General Site Info	
	Site Name	DoD-B
	Site Location	
	Known contaminant:	PFOA, PFOS
	Contaminant information	
🟦	Target treatment width (ft)	45
🟦	Target treatment depth (ft)	45
	Initial contaminant concentration (ug/L)	80

Treatment goals	**Value**
Percent reduction (%)	
or	
Concentration (ug/L)	0.07

	Aquifer Properties		**Value (secondary units)**
🟦	Enter site hydraulic conductivity *K* (cm/s; ft/d)	5.11E-03	14.485
🟦	Enter site hydraulic gradient i	0.037	
🟦	Enter aquifer thickness b_a (ft)	10	
	Enter site transmissivity *T* (cm^2/s; ft^2/d)	1.558	144.850

Enter or select contaminant and media values

	Contaminant	Media	Media hydraulic conducitvity (cm/s)	Media hydraulic conducitvity (ft/day)	Enter $k_{contaminant}$ (min^{-1})	Calculated half-life (days)
🟦	PFOA, PFOS	GAC, ZVI	0.33	935	3.00E-03	0.2

	Contaminant	**Select**	**Media hydraulic conductivity (cm/s)**	Media hydraulic conducitvity (ft/day)	$k_{contaminant}$ (min^{-1})
🟦	Select	Select	#N/A	#N/A	#N/A

Enter treatment media porosity *n*	0.2
Enter media density value (kg/m^3)	2100
Media capacity (mg/kg)	
Media K_d (L/kg)	
Enter cost per kg of treatment media	$1.64

Select "Active" if the site will use a pump	Active
If active, enter gpm value	1.000

Select mix-in media	Mix-in media K (cm/s)
Gravel	3.00E+00

Enter % of mix in media	Percent reaction media (%)
0.00%	100.00%

Weighted K_{media} (ft/d)	59619

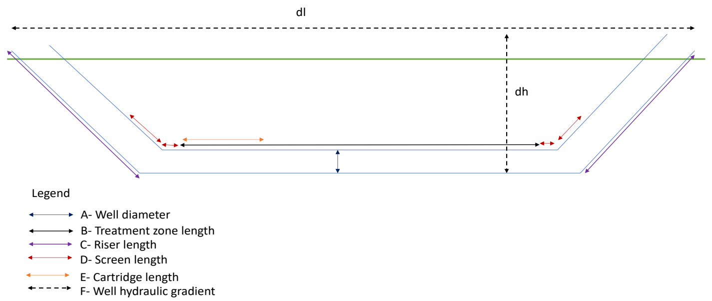
	Well parameters	
🟦	**A** Select HRX Well® diameter (in)	6
	B Minimum treatment zone length (ft)	47
	C Riser length (ft)	450
	D Total screen length (ft)	95
	Total HRX Well® length (ft)	592
	E Number of 10 ft cartridges	6
	Drill time (Hrs)	51
	Select well casing material	Carbon steel
🟦	**F** HRX Well® hydraulic gradient	0.037

Unit Conversions

Enter hydraulic conductivity in ft/d to get value in cm/s	
Hydraulic conductivity in cm/s	0
If concentration is in molar units enter value	
Enter contaminant molecular weight	
Concentration in ug/L	0

Other helpful conversion factors

	86400 seconds
1 foot	30.48 cm
1 gpm	192.5 ft^3/d
1 gallon	3.785 L
PPT	ng/L
PPB	ug/L
PPM	mg/L



General Site Info	Value
Site Name	DoD-A
Site Location	0
Known contaminant type 1:	TCE, PCE
Known contaminant concentration (ug/L)	320
Treatment goals	
Percent reduction (%)	0.000
or	
Concentration (ug/L)	5
Tool setup	
Select contaminant category	TCE, PCE
Compatible media	ZVI
Media hydraulic conductivity (ft/d)	57
Media reactivity (min^{-1})	3.00E-03

Data Summary

The first block (Outputs from User Inputs gab) summarzies the well design based on the inputs in that tab. If the results shown are not practical input values can be adjusted where reasonable (i.e. aquifer hydraulic conductivity cannot practically be altered).

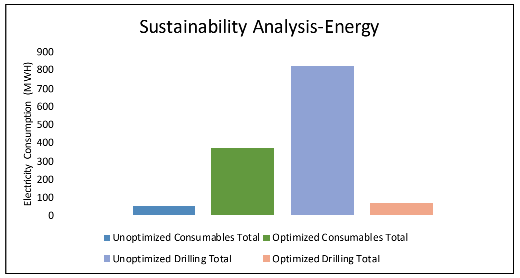
The second block will display updated values if mix-in media or a pump is added.

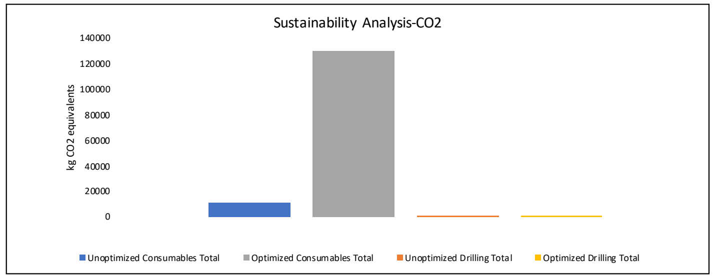
Outputs from User Input tab	Result
Well average capture width (ft)	43
Number of wells	1
Well HRT (days)	2.4
Contaminant HRT required (days)	1.0
Well length (ft)	973
Site is active or passive	Passive
Active pumping rate (gpm)	0.050
Cartridge length (ft)	10
Number of cartridges	19
Total capital cost **per well** (USD)	$469,493
Initial cost of reaction media (USD)	$26
Media changeout frequency (years)	0
Annual media changeout cost (USD)	30,000
Consumables total (kg CO_2 e)	10857
Consumables total (g NOx)	21230
Consumables total (g SOx)	31511
Consumables total (g PM10)	4292
Consumables total (MJ)	173178
Consumables total (MWH)	48
Annual media changeouts (kg CO_2 e)	0
Drilling total (kg CO_2 e)	846
Drilling total (g NOx)	10
Drilling total (g SOx)	954
Drilling total (g PM10)	8779
Drilling total (MJ)	1096
Drilling total (MWH)	818
Drilling for changeouts kg CO_2 e)	0

Results from mix-in media or added pump	Result
Well average capture width (ft)	43
Number of wells	1
Well HRT (days)	1
Well length (ft)	1949
Active pumping (gpm)	0.050
Cartridge length (ft)	10
Number of 10 ft cartridges	42
Total capital cost (USD)	$1,053,095
Total cost of reaction media (USD)	$0
Consumables total (kg CO_2 e)	129772
Consumables total (g NOx)	258648
Consumables total (g SOx)	351283
Consumables total (g PM10)	44618
Consumables total (MJ)	1342935
Consumables total (MWH)	373
Drilling total (kg CO_2 e)	69
Drilling total (g NOx)	1
Drilling total (g SOx)	77
Drilling total (g PM10)	713
Drilling total (MJ)	89
Drilling total (MWH)	66

Cartridge length (ft)	Number for initial well length
5	0
10	0

Cartridge length (ft)	Number for well length
5	85
10	42





Interpreting Sustainability Results

Example sustainability data and external comparisons are given in the table below to give context to sustainability data outputs.

The site had target plume width of 150 ft and target depth of 20 ft. The well was *450* ft long and the

Impact category for consumables	Associated CO_2 eq emissions (kg)	Associated NO_X Emissions (g)
Consumables emissions	496151	786333
Equivalent to driving n passenger cars per year	105	49730
Drilling emissions	5303	60
Equivalent to driving n passenger cars per year	1.1	3.8

Attachment H-4

Site C

Cell Key	Enter value	Select value	Calculated value	Required value to get capture width

Contaminant information

Enter:
1. Plume dimensions- Note that these are target treatment dimensions which may not be equal to the total plume. Plume length is not used in calculations. Instead, treatment length is calculated below using user-provided rate constants or those from the lookup tables.
2. Contaminant concentration- see below
3. Media porosity-This value should typically fall between 0.2 and 0.5
4. Treatment goals as percent reduction or a final concentration, including specific regulatory limits.

If treatability testing was not completed enter estimated values.

If more than one contaminant is present and part of the HRX Well(R) treatment plan do the following:
1. Enter one contaminant initial concentration and treatment goal. This can be in random order or address a primary contaminant of concern first. Note that known rate constants are entered in P32 or selected with media options in P35.
2. Take note of the resulting treatment and well lengths.
3. If two or more contaminants are present and part of the treatment plan repeat steps 1 and 2.
4. From the resulting well lengths use the longest treatment length to ensure the longest retention time required is achieved.

NOTE 1: Treatment lengths for two more more contaminants that are chemically dissimilar and or present in different concentrations should not be assumed correct without laboratoy verification from batch or column tests of the site groundwater containing the contaminants of concern.
NOTE 2: Use psuedo first-order rate constant for adsorptive media.

Site information

Enter values from site investigations and treatability testing. If information is not available use best estimates.

The HRX Well® hydraulic gradient should be assumed approximately equal to the aquifer hydraulic gradient. Item **F** on the adjacent diamgram show

Treatment media information

Enter data from treatability testing in M32, N32, and O32 will auto-fill.
If treatability testing was not completed select reference values from M35 and N35 (O35 will autofill).
Enter media density from known values or from Q2:Q13 in the Lookup Tables tab
Enter a media capacity value in M39. If the value is not known enter the partitioning coefficient and the capacity will be estimated using the concentration data provided above.
Enter media partition coefficient (measured or from literature) and the changeout freqeuncy will be calculated assuming changeout occurs at 70% of media capacity.

Active and passive sites

Active sites are those with hydraulic conductivity greater than 5 ft/d
Passive sites have hydrulic conductivity less than 5 ft/d
If site is active enter the gpm value from pumping tests.
Cell H8 under the Summary tab will display if the site is active or passive.
If sufficient capture is not achieved with the reactive media alone, a pump rate can be entered to increase capture width.
NOTE; That increasing flow rate into the well will cause well length to increase if reaction rates remain the same.

Explanation of mix-in media

Mix-in media was included in the design tool in order to optimize hydraulic conductivity (and related parameters) in the cartridges. These media are not reactive but it should be noted that using too much will reduce the total available surface area of treatment media. The mix-in media are useful when hydraulic conductivity is too high or too low for the treatment media. In these scenarios the retention time determined from reaction rate constants may not be achieved. Changing the hydraulic conductivity in the cartridge is one method of specifying the cartridge retention time.
Note that the weighted media hydraulic conductivity is an *estimate* only. For a thorough analysis refer to HydrogeoSieveXL2 (http://people.ku.edu/~jfdevlin/Software.html)

Well parameters

Select HRX Well® diameter.
The remaining values are automatically calculated in a separate tab and returned here.
A reference diagram is provided to the right- match letters next to input cells to diagram.
The cartridge diameter is assumed to be 2 inches less than the HRX Well® diameter.
Enter well hydraulic gradient. The value should be approximately equal to aquifer hydraulic gradient.

	Tool input description	**Value**
	General Site Info	
	Site Name	DoD-C
	Site Location	
	Known contaminant:	TCE, 1,4-dioxane
	Contaminant information	
🟦	Target treatment width (ft)	185
🟦	Target treatment depth (ft)	10
	Initial contaminant concentration (ug/L)	300

Treatment goals	**Value**
Percent reduction (%)	
or	
Concentration (ug/L)	5

	Aquifer Properties		**Value (secondary units)**
🟦	Enter site hydraulic conductivity *K* (cm/s; ft/d)	5.00E-05	0.142
🟦	Enter site hydraulic gradient i	0.055	
🟦	Enter aquifer thickness b_a (ft)	5	
	Enter site transmissivity *T* (cm^2/s; ft^2/d)	0.008	0.709

Enter or select contaminant and media values

	Contaminant	Media	Media hydraulic conducitvity (cm/s)	Media hydraulic conducitvity (ft/day)	Enter $k_{contaminant}$ (min^{-1})	Calculated half-life (days)
🟦	TCE, 1,4-dioxane	ZVI	0.1	283	3.00E-03	0.2

	Contaminant	**Select**	**Media hydraulic conductivity (cm/s)**	Media hydraulic conducitvity (ft/day)	$k_{contaminant}$ (min^{-1})
🟦	Select	Select	#N/A	#N/A	#N/A

Enter treatment media porosity *n*	0.35
Enter media density value (kg/m^3)	2100
Media capacity (mg/kg)	
Media K_d (L/kg)	
Enter cost per kg of treatment media	$1.64

Select "Active" if the site will use a pump	Passive
If active, enter gpm value	

Select mix-in media	Mix-in media K (cm/s)
Gravel	3.00E+00

Enter % of mix in media	Percent reaction media (%)
0.00%	100.00%

Weighted K_{media} (ft/d)	283

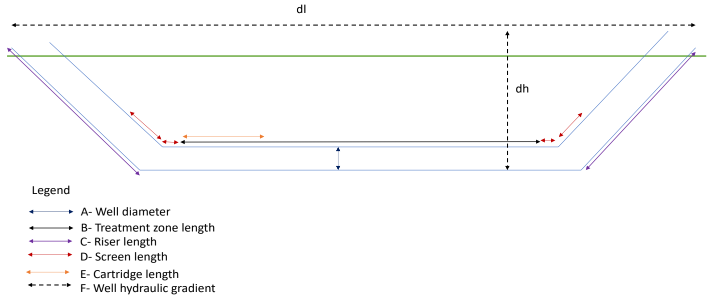
	Well parameters	
🟦	**A** Select HRX Well® diameter (in)	8
	B Minimum treatment zone length (ft)	106
	C Riser length (ft)	100
	D Total screen length (ft)	218
	Total HRX Well® length (ft)	423
	E Number of 10 ft cartridges	13
	Drill time (Hrs)	36
	Select well casing material	Carbon steel
🟦	**F** HRX Well® hydraulic gradient	0.055

Unit Conversions

Enter hydraulic conductivity in ft/d to get value in cm/s	
Hydraulic conductivity in cm/s	0
If concentration is in molar units enter value	
Enter contaminant molecular weight	
Concentration in ug/L	0

Other helpful conversion factors

	86400 seconds
1 foot	30.48 cm
1 gpm	192.5 ft^3/d
1 gallon	3.785 L
PPT	ng/L
PPB	ug/L
PPM	mg/L



General Site Info	Value
Site Name	DoD-C
Site Location	0
Known contaminant type 1:	TCE, 1,4-dioxane
Known contaminant concentration (ug/L)	300
Treatment goals	
Percent reduction (%)	0.000
or	
Concentration (ug/L)	5
Tool setup	
Select contaminant category	TCE, 1,4-dioxane
Compatible media	ZVI
Media hydraulic conductivity (ft/d)	283
Media reactivity (min^{-1})	3.00E-03

Data Summary

The first block (Outputs from User Inputs gab) summarzies the well design based on the inputs in that tab. If the results shown are not practical input values can be adjusted where reasonable (i.e. aquifer hydraulic conductivity cannot practically be altered).

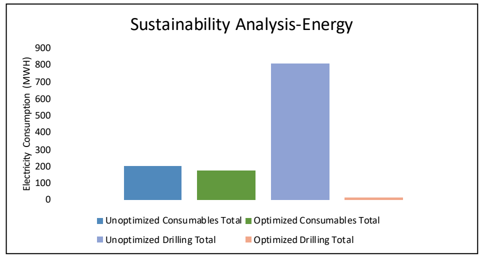
The second block will display updated values if mix-in media or a pump is added.

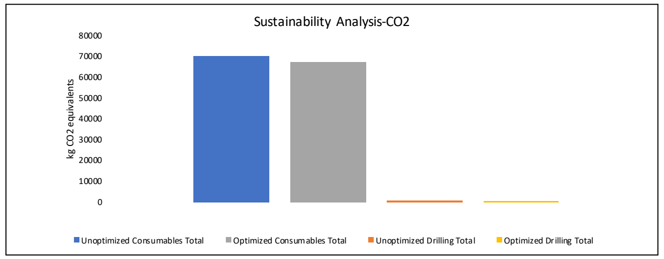
Outputs from User Input tab	Result
Well average capture width (ft)	79
Number of wells	3
Well HRT (days)	2.4
Contaminant HRT required (days)	0.9
Well length (ft)	423
Site is active or passive	Passive
Active pumping rate (gpm)	0.000
Cartridge length (ft)	10
Number of cartridges	6
Total capital cost **per well** (USD)	$293,232
Initial cost of reaction media (USD)	$4,412
Media changeout frequency (years)	0
Annual media changeout cost (USD)	30,000
Consumables total (kg CO_2 e)	70160
Consumables total (g NOx)	111035
Consumables total (g SOx)	152800
Consumables total (g PM10)	19623
Consumables total (MJ)	703437
Consumables total (MWH)	195
Annual media changeouts (kg CO_2 e)	0
Drilling total (kg CO_2 e)	835
Drilling total (g NOx)	9
Drilling total (g SOx)	941
Drilling total (g PM10)	8666
Drilling total (MJ)	1082
Drilling total (MWH)	808
Drilling for changeouts kg CO_2 e)	0

Results from mix-in media or added pump	Result
Well average capture width (ft)	79
Number of wells	3
Well HRT (days)	1
Well length (ft)	231
Active pumping (gpm)	0.000
Cartridge length (ft)	10
Number of 10 ft cartridges	4
Total capital cost (USD)	$173,533
Total cost of reaction media (USD)	$0
Consumables total (kg CO_2 e)	66946
Consumables total (g NOx)	104885
Consumables total (g SOx)	142439
Consumables total (g PM10)	18090
Consumables total (MJ)	624467
Consumables total (MWH)	173
Drilling total (kg CO_2 e)	15
Drilling total (g NOx)	0
Drilling total (g SOx)	17
Drilling total (g PM10)	161
Drilling total (MJ)	20
Drilling total (MWH)	15

Cartridge length (ft)	Number for initial well length
5	21
10	11

Cartridge length (ft)	Number for well length
5	8
10	4





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Equivalent to driving n passenger cars per year	1.1	3.8