Field Demonstration of the Horizontal Treatment Well (HRX Well®) for Passive In Situ Remediation

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Abstract

The horizontal reactive media treatment well (HRX Well®) uses directionally drilled horizontal wells filled with a treatment media to induce flow-focusing behavior created by the well-to-aquifer permeability contrast to passively capture proportionally large volumes of groundwater. Groundwater is treated in situ as it flows through the HRX Well and downgradient portions of the aquifer are cleaned via elution as these zones are flushed with clean water discharging from the HRX Well. The HRX Well concept is particularly well suited for sites where long-term mass discharge control is a primary performance objective. This concept is appropriate for recalcitrant and difficult-to-treat constituents, including chlorinated solvents, per- and polyfluoroalkyl substances (PFAS), 1,4-dioxane, and metals. A full-scale HRX Well was installed and operated to treat trichloroethene (TCE) with zero valent iron (ZVI). The model-predicted enhanced flow through the HRX Well (compared to the flow in and equivalent cross-sectional area orthogonal to flow in the natural formation before HRX Well installation) and treatment zone width was consistent with flows and widths estimated independently by point velocity probe (PVP) testing, HRX Well tracer testing, and observed treatment in downgradient monitoring wells. The actual average capture zone width was estimated to be between 45 and 69 feet. Total TCE mass discharge reduction was maintained through the duration of the performance monitoring period and exceeded 99.99% (%). Decreases in TCE concentrations were observed at all four downgradient monitoring wells within the treatment zone (ranging from 50 to 74% at day 436), and the first arrival of treated water was consistent with model predictions. The field demonstration confirmed the HRX Well technology is best suited for long-term mass discharge control, can be installed under active infrastructure, requires limited ongoing operation and maintenance, and has low life cycle energy and water requirements.

Introduction

Contaminant mass flux and discharge represent appropriate measures of plume dynamics and risk to receptors; therefore, remedial technologies focusing on long-term mass flux/discharge reduction are increasingly favored, especially for persistent contaminants like chlorinated solvents, metals, and per- and polyfluoroalkyl substances (PFAS) and at low-permeability sites where implementation of injection-based in situ treatment is more challenging. Furthermore, there is an increasing need for, and interest in, remedial technologies that minimize long-term energy and water consumption, require a limited surface footprint, and minimize the overall impact on site operations. The horizontal reactive media treatment well (also known as a Horizontal Treatment Well or HRX Well®) is a new in situ remediation concept that is particularly well suited for sites where passive long-term mass discharge reduction control is a primary performance objective (Divine et al. 2018a, 2018b).

The HRX Well consists of one or more large-diameter horizontal wells that are oriented roughly parallel to groundwater flow and contain an appropriate treatment media. Under passive operation, groundwater flow focusing occurs as a result of the high in-well hydraulic conductivity of the engineered treatment media relative to the aquifer hydraulic conductivity. Captured groundwater is treated in the subsurface within the well as it flows through the treatment media. Water that has passed through the treatment media then exits the downgradient screen. Locations further downgradient in the aquifer (i.e., downgradient monitoring wells) begin to clean up through flushing and elution over a period of time after treated water first arrives. According to the HRX Well concept (Figure 1), impacted groundwater (red shading) is drawn into the well due to flow focusing,
is treated in the well, and clean groundwater (blue shading) exits the downgradient portion of the well. For some applications, the flow through the HRX Well and size of the capture zone can be increased with the addition of a pump placed in the upgradient screen that directs groundwater through a packer into the treatment media (Divine et al. 2013). In this configuration, no groundwater is brought to the surface for treatment. Many different types of treatment media are already available (some potential media types include zero valent iron [ZVI], activated carbon, ion exchange resins, zeolites, slow-release oxidant materials, apatite, mulch, and chitin). Therefore, this approach could address a wide range of contaminants, including difficult-to-treat contaminants like chlorinated solvents, metals, and PFAS.

As presented in Divine et al. (2018a), the passive flow rate through an HRX Well ($Q_{HRX}$), including the treatment media, can be described by application of Darcy’s Law:

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

(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 inside the well. The vertically averaged steady-state capture and treatment zone width ($\bar{w}$) for an individual well can then be simplistically approximated by:

$$\bar{w} = \frac{K_{HRX} \cdot \pi r_{HRX}^2 \cdot i_{HRX}}{K_A \cdot b_A \cdot i_A}$$

or equivalently,

$$\bar{w} = \frac{Q_{HRX}}{K_A \cdot b_A \cdot i_A}$$

(2)

where $K_A$ is the average hydraulic conductivity of the targeted aquifer zone, $b_A$ is the targeted aquifer zone thickness, and $i_A$ is the regional aquifer hydraulic gradient (outside the influence of the HRX Well). In general $i_{HRX} < i_A$, however, as the length of the HRX Well and the screen sections increase, $i_{HRX}/i_A$ approaches unity and therefore for most field applications, $i_{HRX}$ can be practically assumed to be similar to the ambient aquifer hydraulic gradient, $i_A$ (Divine et al. 2011, 2018c; Nzeribe et al. 2020). The approximate average flow velocity $v_{HRX}$ and minimum average residence time $t_R$ of groundwater within the treatment media can be estimated by:

$$v_{HRX} = \frac{Q_{HRX}}{\phi_{HRX} \cdot \pi \cdot r_{HRX}}$$

(3)

$$t_R = \frac{l_{HRX}}{v_{HRX}}$$

(4)

where $\phi_{HRX}$ is the flowing effective porosity of the treatment 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 are appropriate when well screens are long and the well is 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. Additional detailed site-specific numerical modeling is necessary to more accurately understand the effects of site-specific complex aquifer geometry, anisotropy, and permeability distribution on treatment zone geometry.

Divine et al. (2018a) evaluate how the average capture zone and treatment widths are functions of the hydraulic conductivity contrast between the aquifer and treatment media, in addition to well diameter and impacted aquifer thickness. Specifically, they show that for sites with relatively thin impacted zones (20 feet or less) and moderate to low hydraulic conductivity (1 foot per day [feet/d] or less), treatment widths of tens of feet per HRX Well® are achievable. It is important to recognize that these results are based on passive operation, which relies on flow focusing due to the engineered permeability contrast. However, Divine et al. (2013) propose an alternative configuration where a pump is installed in the inlet screen section and the pumped water is pushed through a packer and the treatment media within the well, and then exits back into the aquifer via the outlet screen section. This effectively increases the value of the $Q_{HRX}$ term, which results in enhanced hydraulic capture and treatment width without bringing groundwater to the surface and may be particularly appropriate for higher permeability sites.

The HRX Well concept, laboratory- and pilot-scale physical testing, and detailed numerical modeling are presented elsewhere in the literature (Divine et al. 2011, 2013, 2018a, 2018b, 2018c; Nzeribe et al. 2020). This paper presents results of the first full-scale field demonstration of the HRX Well to passively treat chlorinated solvents (primarily trichloroethene [TCE]) via in situ chemical reduction with ZVI treatment media. For the application presented in this paper, the HRX Well was operated under a passive configuration; however, the active pumping configuration was also briefly tested. The overall goal of this effort was to field-validate the HRX Well technology, quantify technical performance and limitations, and provide a basis for wider application at other sites. Specifically, this demonstration was designed to assess the actual HRX Well hydraulic cap-
ture and treatment zone widths, residence times within the HRX Well, treatment media effectiveness, and contaminant mass discharge reductions achieved at a representative field site.

**Site Description**

The field demonstration was performed at Installation Restoration Program Site 003 (SS003) at Vandenberg Air Force Base (VAFB) in Central California. As a part of pre-design activities, both passive flux meters (Hatfield et al. 2004) and single well tracer tests (SWTTs, also known as point-dilution tests) were applied at several monitoring well locations to evaluate groundwater of flux and groundwater velocity. Additionally, multiple hydraulic profiling tool (HPT) borings were also installed along the planned alignment of the HRX Well. The results of these are investigation activities are presented in Divine et al. (2018c). Key specific conditions that made Site SS003 an ideal candidate for the HRX Well demonstration include:

- **The primary constituent of concern (TCE) is consistently present at high concentrations, generally ranging from 30,000 to 50,000 micrograms per liter (μg/L) near the former source area and at the upgradient location of the HRX Well.**
- **The target treatment zone (Principal Zone aquifer) is at a relatively shallow depth (20 feet) and thickness (ranging from approximately 7 to 12 feet, with average of approximately 8 feet), allowing for ease in installation of the HRX Well and easy identification of and performance monitoring for the target treatment zone.**
- **The lithologic materials observed within the Principal Zone aquifer consist of silts and silty sands, with moderate to low hydraulic conductivity values (average of approximately 0.35 feet/d), providing suitable hydraulic conductivity contrast (and therefore hydraulic performance of the HRX Well under a passive configuration) relative to the hydraulic conductivity of the in-well treatment media (ZVI).**
- **Site remedial objectives are consistent with use of this technology (i.e., targeted long-term reduction of mass discharge from a source or high-concentration area).**

**Final Design and Field Installation**

**Design Model and Final HRX Well Design**

To assist the HRX Well design phase and to provide a basis for performance expectations for the field demonstration, a three-dimensional calibrated groundwater flow and transport model (using MODFLOW; McDonald and Harbaugh 1988) was developed based on site-specific data. MODPATH (Pollock 2016) and MT3DMS (Zheng 1990) were used to predict groundwater flow paths near the HRX Well and to simulate the migration to and subsequent treatment of TCE by the HRX Well. The model domain extents were designed to reflect all relevant hydraulic features within the surrounding area and were located a sufficient distance away to reduce the potential for boundary effects. The model grid was refined to 4- by 4-inch grid node spacing near the HRX Well to capture details of the flow patterns where flow paths converged or diverged. The grid was coarsened to 5-foot spacings between nodes at locations removed from the HRX Well where flow paths were parallel or subparallel to the regional flow direction. The model was vertically discretized into 11 model layers with a 4-inch layer thickness around the HRX Well (layers 4, 5, and 6), and gradually increased layer thicknesses, up to 1.5 feet, at the top of the model (layers 1, 2, and 3) and 1-foot maximum layer thickness at the bottom of the model (layers 7 to 10). A variable thickness was assigned to layer 11 to represent the varying bottom elevation of the aquifer based on HPT and soil boring logs. Overall, the finite-difference grid included approximately 2 million grid nodes. Four hydraulic conductivity zones were used to represent the two identified hydraulically distinct regions in the Principal Zone aquifer, the treatment media, and the empty casing. The HRX Well was simulated using a high hydraulic conductivity zone and the impermeable casing was simulated as a no-flow zone (further details on the model structure and approach are provided in Divine et al. 2018a, 2018b). Various well design scenarios were simulated during the design process to evaluate sensitivity and optimize the well configuration. The final design model predicted a capture zone width of approximately 50 feet and a residence time within the ZVI of approximately 8 days. Further model design details and simulations from the original model are presented in Divine et al. (2018b, 2018c).

Because the application of ZVI to mediate the abiotic transformation of chlorinated solvents is well-established (Gillham and O’Hannesin 1994; Arnold and Roberts 2000; Henderson and Desmond 2007; Scherer et al. 2007; Fu et al. 2014; Wilkin et al. 2019), ZVI was selected as the treatment media. Previous project treatability studies that measured TCE decay rates ranging from approximately 9 to 13 per day (d⁻¹) for an 85% (% ZVI) and 15% sand mixture (Divine et al. 2018b). Therefore, a conservative TCE decay rate estimated of 1.8/d (half life of 0.39 days) for the 35% iron and 65% sand mixture used for the field demonstration. This suggests approximately 4 days of contact with the ZVI, is required for TCE to degrade from 50,000 μg/L to less than 50 μg/L. The results of previously conducted column tests using site water (Divine et al. 2018c) indicates the reactivity and permeability of the iron should remain constant for more than 1000 pore volumes. Based on simple stoichiometry calculations, the ZVI is expected to have a service life of at least 15 years and may the 30-year design life of the HRX Well.

A schematic cross-section diagram (Figure 2) shows the elements of the HRX Well and site hydrostratigraphy (the final HRX Well configuration is very similar to the planned design described in Divine et al. 2018c). 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 feet below typical historical average levels. The entry screen on the upgradient side is curved and extends above the water table to maintain the capture width in the presence of a seasonally variable water table elevation (i.e., 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. The final well was completed with 12-inch diameter casing and the treatment media was installed in 10-inch (nominal) diameter cartridges. The measured hydraulic conductivity of the ZVI/sand treatment media \( K_{ZVI} \) was 195 feet/d and the effective \( K_{HRX} \) was conservatively estimated at 320 feet/d by the commonly used method for estimating the effective hydraulic conductivity for heterogeneous systems with flow perpendicular to layers (McDonald and Harbaugh 1988):

\[
K_{HRX} = \left( \frac{x_{ZVI}}{K_{ZVI}} \right) + \left( \frac{x_o}{K_o} \right)
\]

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 hydraulic conductivity of the open section (estimated at approximately 2000 feet/d). Construction details for the HRX Well are summarized in Table S1 in the Supporting Information.

**Treatment and Monitoring Cartridges**

To maintain consistency and quality control over the volume and placement of ZVI media within the well, a cartridge system was developed to contain the treatment media. The treatment 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. The HRX Well was designed with seven treatment cartridges in the central cased horizontal section of the well, between the inlet and outlet screens. Prior to treatment media placement within the cartridges, specified volumes of sand and ZVI were measured into a portable cement mixer. The evenly distributed mixture was then shoveled into a cartridge body, elevated at one end to prevent the treatment media from settling in a fashion that would leave an open channel in the cartridge where preferential flow could occur. Final measurements of the treatment media column length, volume, and porosity were verified prior to capping the cartridge for transport to the site. 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 point velocity probes (PVPs) (Devlin et al. 2009) to measure groundwater velocity through the HRX Well. Cartridges were 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 (Figure 3, see also Divine et al. 2018c). Domestic and international patents are pending on the cartridge design.

**Performance Assessment**

Installation of the HRX Well was completed in August 2018; the performance monitoring and data interpretation methods used to assess performance are described below.

**Modeling**

To evaluate hydraulic capture and treatment media residence time, and the overall performance assessment of the HRX Well, the model was updated to incorporate the most recent site data and more accurately reflect the specifications of the HRX Well (Figure 4). The simulated effects of the
HRX Well can be seen by the equipotential contour lines that bend near the inlet and outlet screens of the HRX Well, and the zone of hydraulic capture and flushing (i.e., treatment) is defined by the path lines that converge into the HRX Well. The simulated capture width under the passive configuration was 52 feet and the average groundwater residence time within the ZVI cartridges was approximately 9 days.

**HRX Well Tracer Testing**

A tracer test was initiated 140 days following installation of the HRX Well using a distilled water tracer as an additional method to measure velocity and flow through the HRX Well. A total injection volume of 40 gal of distilled water tracer was injected into the HRX Well inlet over 25 h, which is equivalent to an injection rate of 5.1 cubic feet per day (feet$^3$/d). Tracer breakthrough was monitored by measuring the change in electrical resistivity in the water leaving the well using the PVPs installed at the downgradient monitoring cartridge. As described in detail in Devlin et al. (2009), a PVP measures the resistance to the flow of electricity through groundwater between two electrodes by measuring the voltage drop between two wires at a fixed current in a half bridge circuit, according to Ohm’s Law (current equals voltage divided by resistance). The PVP measures a voltage, which is directly related to the resistivity of the water, and inversely related to the electrical conductivity of the water. As the pulse of distilled water moves past the PVP detectors, the resistance increases (and the electrical conductivity decreases), and the voltage measured by the PVP increases. The changes in resistance are measured with a half-bridge circuit that scales the resistance measurements between 0 and 1, and therefore can be considered a normalized, or relative resistance. Leads from the detectors on the PVPs were connected to a Campbell Scientific CR1000 datalogger equipped with a half bridge circuit.

Relative resistivity was found to be relatively stable until approximately 80 days, when relative resistivity became highly variable with an overall increase noted over an approximately 5-day period. The electrical conductivity then returned to baseline conditions (the unintended periods of missing data were the result of failed battery power and programming errors) (Figure 5). A simple one-dimensional analytical transport model (Ogata and Banks 1961), modified for a step tracer application using the principle of
superposition was fit to the data (shown as the black line on Figure 5). The fitted average velocity across the entire HRX Well was 1.6 feet/d, with a fitted dispersivity of 0.4 feet. Based on final dimensions of the HRX Well, this equates to average velocity values in the treatment media cartridges (diameter = 9.4 inches, porosity = 0.38) and open section (diameter = 12 inches, porosity = 1.00) of approximately 7.3 and 0.74 feet/d, respectively, and an average flow rate of 1.3 feet$^3$/d. Using the aquifer hydraulic gradients measured at the beginning and end of the test, and by rearranging Equation 2, the estimated average HRX Well capture/treatment width during the testing period was approximately 45 feet, which compares well with the model prediction (52 feet). Overall, the tracer breakthrough and duration were consistent with both the model predictions and the flow velocities in treatment media measured by PVP testing.

**PVP Testing**

To directly measure flow velocity within the HRX Well treatment media, custom-designed PVPs (based on the design described Devlin et al. 2009) were installed in sand-filled cartridges on the inlet and outlet sides of the treatment media to measure seepage velocities inside the well (see Figure 6). Tests were completed by injecting 0.5 to 5 mL of distilled water tracer into the injection lines, recording the time of the start of injection, and the duration of the injection phase. Typically, at least 30 min 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 min was generally found to be sufficient, depending on actual velocities on the testing day) to measure the breakthrough curve of the tracer (defined by the measured change in relative resistivity) at the PVP detectors. The breakthrough curves were imported into the Excel software VelProbePE (Schilig 2012) and fit with a solution to the advection-dispersion equation to obtain the estimate of $v_{HRX}$ (Figure 6). A photograph of the tracer injection line, data logger, battery, and HRX Well outlet wellhead completion is provided as Figure S1 in the Supporting Information.

Based on the results the first set of PVP tests (not reported here), it was determined that maintenance was needed to fix seals around the monitoring cartridges. Unfortunately, the PVP installed near the inlet was damaged during this maintenance activity and was out of service after the first set of tests. However, subsequent tests completed at the outlet PVP were predominantly successful. The average estimated flow velocities for the three testing events were 9.6, 4.2, and 13 feet/d (overall average = 8.9 feet/d); these velocity values bracket the model prediction of 7.6 feet/d. Based on the casing diameter (9.4 inches) and treatment media porosity (estimated at 0.38), the estimated HRX Well flows correlated to these results were approximately 1.7, 0.9, and 2.4 feet$^3$/d respectively (overall average = 1.7 feet$^3$/d). HRX Well flows will vary as regional aquifer flows and gradients vary. However, because the hydraulic gradients of the aquifer and HRX Well are functionally related, the capture/treatment width of the HRX Well is expected to be generally insensitive to changes in the aquifer flow rates and

Figure 5. HRX Well tracer test breakthrough curve. Measured tracer data are shown in blue, and the fitted transport model is shown in black. $\Delta$ Resistivity = change in relative resistivity.

Figure 6. Left: Redesigned PVP. Center: Conceptual schematic of PVP installed in monitoring cartridge. Right example PVP data (blue series) and fitted model (red lines).
hydraulic gradient. Using the aquifer hydraulic gradients measured at testing times and by rearranging Equation 2, the capture and treatment widths of the HRX Well calculated from the PVP tests data are approximately 66, 39, and 103 feet (overall average = 69 feet), respectively, which bracket and are similar to the model prediction (52 feet). In general, compared to other testing methods, PVP data measured instantaneous flow rates through the HRX Well and therefore may identify possible short-term variations in flow that represent maximum and minimum stresses on the treatment media.

Single-Well Tracer Tests

As part of preinstallation data collection activities, SWTTs and passive flux meters were used to measure flux at wells 3-MW-13, 3-MW-35D, and 3-MW-48. These tests were performed using a distilled water tracer which exhibited a specific conductivity contrast with groundwater that was used as the tracer signal. The tracer solution was mixed to achieve a homogeneous well water column and the observed tracer washout data were used to estimate well water flux with an analytical model (Drost et al. 1968; Hall 1993). Because the HRX Well focuses groundwater, groundwater flux increases in the immediate vicinity of the inlet and outlet screens. To confirm and measure this phenomenon, SWTTs were repeated at the same three wells approximately 350 days after the HRW Well was installed.

Results of the SWTTs completed pre- and postinstallation of the HRX Well are summarized in Table 1. The results suggest that a slight increase in tracer washout rate is detectable at all three wells as a result of increases in local groundwater flux. As expected, the observed magnitude of the increase in the flux of groundwater brought about by the HRX Well is approximately an inverse function of the distance between the monitoring well and the inlet or outlet screens of the HRX Well. The 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 increases in flux values are subtle and likely near or within the uncertainty range of the SWTT method, the results are consistent with the expectation that the HRX Well enhances groundwater flux in the immediate vicinity of the inlet and outlet screens.

Groundwater Elevations and Flow Field

Groundwater elevations were measured and contoured before and periodically after the HRX Well was installed and are presented on Figure 7. The water level elevation for 3-MW-47 was consistently approximately 1 foot lower than all other nearby wells and a review of the boring and well construction logs suggest that the Principal Zone aquifer is less defined at this location; therefore, data from this well were not used to interpret groundwater elevation contours. Consistent with the model, the local hydraulic gradient

| Well       | Linear Distance from HRX Well Inlet or Outlet (Feet) | Pre-HRX Well SWTT-Measured Flux (Feet/D) | Post-HRX Well SWTT-Measured Flux (Feet/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%                      |

Figure 7. Groundwater elevations and interpreted equipotential contours flow field at the HRX Well Outlet. Values are feet above mean sea level. Note: The distance between wells 3-MW-14 and 3-MW-48 is 45 feet.
increased near the HRX Well outlet after installation as indicated by an increase in water elevation differences between wells 3-MW-13 and 3-MW-14. Also, although the interpreted equipotential contours and flow field are qualitative and not highly constrained due to the limited number of wells, they are consistent with enhanced groundwater flow discharging from the HRX Well outlet.

**Groundwater Concentrations**

TCE concentrations near the upgradient HRX Well screen ranged from approximately 30,000 to 40,000 μg/L throughout the monitoring period and TCE concentrations at the HRX Well outlet (measured in samples collected with a peristaltic pump) never exceeded 7.6 μg/L, representing greater than 99.99% reduction (Figure 8 and Table SI2 of the Supporting Information). By day 436, all four performance monitoring wells (all within the anticipated treatment zone) show reductions in TCE that are consistent with flushing with treated water and range from 50 to 74%. In general, changes in TCE concentrations are consistent with an elution-based process. Once treated water discharging from the HRX Well arrives at a well, concentrations begin to decline; this behavior is particularly evident at MW-48 where TCE remained relatively stable through day 100 and then began to decline as treated water began arriving at that location. The rate of decline and time to achieve cleanup goals at these wells will be controlled by several processes, including mixing, desorption, and back diffusion from lower permeability zones. Contaminant concentrations will continue to be monitored on a semi-annual frequency to assess long-term performance.

At some sample locations, a temporary increase in cis-1,2-dichloroethene (cis-1,2-DCE) and vinyl chloride was also observed, including a notable increase in vinyl chloride at the HRX Well outlet at 365 days. This is likely a result of enhanced biologically mediated reductive dechlorination induced by the presence of unrecovered fermentable biopolymer- (i.e., guar) based drilling fluid. Although total organic carbon (TOC) was not analyzed as frequently as contaminants, this hypothesis is supported by elevated TOC measured at the HRX Well inlet and outlet at 92 days (22.3 and 339 milligrams per liter [mg/L]) and 365 days (89.3 and 77.2 mg/L, respectively). It is expected that TOC concentrations will decline over time and this parameter will continue to be measured semiannually.

Changes in TCE and cis-1,2-DCE concentrations through time in downgradient wells (3-MW-47, 3-MW-48, 3-MW-

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**Figure 8.** Contaminant concentrations through time. The blue shading downgradient of the HRX Well indicates the anticipated approximate treatment zone location. For all graphs, green series represents TCE, blue series represent cis-1,2-DCE, and orange series represents vinyl chloride. The posted green value represents the decrease in TCE from baseline. All y-axes are concentration (μg/L) and all x-axis are elapsed time (days).
13, and 3-MW-14) indicate that the first breakthrough of treated water ranges from approximately 50 to 200 days at these wells. Table 2 compares these breakthrough times to model-predicted travel times from the HRX Well outlet to these wells for effective (or mobile) porosity values of 1, 5, and 10% (retardation was assumed to be negligible). The model-simulated breakthrough times for effective porosity values of 1 to 5% are generally consistent with the range of observed breakthrough times for most wells.

There was a significant decrease in TCE concentration between 3-MW-35D and the HRX Well inlet (in fact, TCE was measured at a maximum concentration 210 μg/L at the HRX Well inlet) and increases in cis-1,2-DCE and vinyl chloride concentrations measured at the HRX Well inlet (up to 4800 and 7200 μg/L, respectively) during the performance monitoring period. This is shown in Figure 8 and all concentration data are presented in Table S12 in the Supporting Information. This is likely the result of enhanced biotransformation promoted by unrecovered biodegradable biopolymer drilling fluid. Using average total molar concentrations of chlorinated ethenes and 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 outlet was abiotic, an estimated 76% of the total treatment during the performance period (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 through time. For downgradient wells, elution is the primary mechanism causing concentration reductions at wells; however, the effects of biotic processes are indicated by the presence of daughter products. Comparing average molar concentrations of cis-1,2-DCE and vinyl chloride to the average decrease in molar concentrations of TCE, biotic processes are estimated to account for 10% of the average TCE reductions observed at the four performance monitoring wells. It is anticipated that the relative contribution of biodegradation will decrease through time as the degradable carbon is fully consumed and aquifer conditions return to more aerobic conditions.

Active Configuration Testing

Although not originally planned for the demonstration, the HRX Well was temporarily modified to an active (i.e., pumping) configuration. The inlet monitoring cartridge with the PVP was temporarily removed and a packer was installed approximately 214 feet down the HRX Well, immediately past the inlet screen, but before the treatment media cartridges. Approximately 160 feet of intake poly tubing, secured 54 feet above the packer (to prevent well screen dewatering), was placed down the inlet side of the HRX Well and connected in line to a high-capacity peristaltic pump and flow totalizer. The discharge line from the flow totalizer was then placed back into the HRX Well with approximately 220 feet of polyvinyl chloride pipe, which was secured to the packer.

The pump was operated for approximately 20 h, pumping a total of 35.5 feet³ (of which, 30 to 32 feet³ was estimated to be from wellbore storage). Drawdown data obtained from pressure transducers installed in wells near the upgradient and downgradient screens were used to further calibrate the model. 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 feet³/d, 1.5 to 2 times the flow rate through the HRX Well under passive operation. Accordingly, simulations suggest that continual operation of the HRX Well under an active configuration at the maximum aquifer yield would increase the steady-state capture and treatment zone width to more than 100 feet.

Discussion

HRX Well Hydraulics and Treatment Zone Width

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 (Figure 7). Figure 9 compares the average flow through the HRX Well and capture zone width calculated by:

- Equation 2 using the average \( i_s \), the effective \( K_{HRX} \) value, the average aquifer hydraulic conductivity, the average aquifer thickness, and the HRX Well cartridge inner diameter (9.4 inches).
- The calibrated steady-state numerical flow model.
- The flow velocity measured by the HRX Well tracer test, the assumed porosity for the treatment media, and the HRX Well cartridge inner diameter the average aquifer hydraulic conductivity, the average aquifer thickness, and the aquifer hydraulic gradient over the testing period.

### Table 2

| Monitoring Well | Observed Breakthrough Time (Days) | Model-Predicted Breakthrough Time (Days) |
|-----------------|----------------------------------|-----------------------------------------|
|                 | Observed TCE Decline             | Observed Cis-1,2-DCE Increase            | 10% Effective Porosity | 5% Effective Porosity | 1% Effective Porosity |
| 3-MW-47         | <92                              | <92                                     | 167                  | 83                   | 17                    |
| 3-MW-13         | <50                              | 92-176                                  | 267                  | 133                  | 27                    |
| 3-MW-14         | <92                              | —                                       | 1000                 | 500                  | 100                   |
| 3-MW-48         | 92157                            | 157-250                                 | 1100                 | 550                  | 110                   |

Notes: < = less than; — = Not observed.
The flow velocities measured by the PVP tests, the assumed porosity for the treatment media, the HRX Well cartridge inner diameter, the average aquifer hydraulic conductivity, the average aquifer thickness, and the aquifer hydraulic gradients at the times of the tests.

Multiple methods clearly confirm significantly enhanced flow through the HRX Well. There is high confidence that the actual average flow during the performance period was between 1.3 and 1.6 feet/d (approximately 0.02 feet/d would be expected if no flow focusing was occurring). Likewise, multiple measurements confirm that the average HRX Well capture zone is between 45 and 69 feet, which is consistent with predictions from the simple Equation 2 (55 feet) and the numerical flow model (52 feet). The similarity between the results of Equation 2 and the numerical flow model supports the usefulness of Equation 2 and the practical similarity of \( i_s \) and \( i_{\text{num}} \) when the HRX Well and simulated screen lengths are long (the numerical model predicts \( i_{\text{num}}/i_s \) of approximately 0.8 based on the calculated heads in the middle of the HRX Well inlet and outlet screens and various aquifer locations near the HRX Well). Overall, the results summarized in Figure 9 confirm the significant flow-focusing behavior of the HRX Well concept for these settings and the reliability of models for estimating the magnitude of this effect.

It is worth noting that Hosseini et al. (2018) discuss results of tank tests where they evaluated the hydraulic and treatment performance of several configurations (including scenarios with the well oriented parallel to flow) of non-pumping reactive wells filled with ZVI to treat nitrate in situ. Although somewhat similar to the HRX Well, their horizontally oriented wells did not have long screens, but rather were solid tubes only open to the aquifer on the ends. Their analysis indicated that the relative capture zone size of horizontally oriented wells was limited, even notably smaller, than vertically oriented wells. However, the much smaller open areas of their design that are hydraulically connected to the aquifer are a critical difference compared to the HRX Well concept, which uses long inlet and outlet screens. In effect, the small effective area open to the aquifer (i.e., effective screen area) of their wells greatly limits flow into the well and, therefore, the capture zone size. This comparison highlights the importance of using long screens to maximize capture and this parameter should be optimized during the design through iterative modeling.

**Mass Discharge Reduction and Treatment Media Performance and Contaminant**

Contaminant mass discharge reduction was estimated by multiplying the difference in TCE between well 3-MW-35D (representing the groundwater 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. 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 a greater than 99.99% reduction in contaminant mass discharge across a transect defined by the capture width.

In general, available data do not indicate any decline in treatment media performance (reactivity or hydraulic conductivity) during the performance period. Based on an average flow velocity in the treatment media of 7 to 8 feet/d, the estimated treatment media residence time is 8 to 9 days. Effective decay rates were calculated for TCE, cis-1,2-DCE, and vinyl chloride for dates where HRX Well inlet concentrations were approximately 100 μg/L or greater.

The estimated first-order TCE transformation rate (0.9 d\(^{-1}\)) is approximately half the design value estimated from the treatability testing (1.8 d\(^{-1}\)), but greater than the estimated minimum rate (0.7 d\(^{-1}\)) needed to treat TCE from 33,000 μg/L to less than 50 μg/L, and greater than the estimated minimum rate (0.2 d\(^{-1}\)) needed to treat TCE from 310 μg/L (highest observed HRX Well inlet concentration) to less than 50 μg/L. Estimated transformation rates for cis-1,2-DCE (approximately 0.4 d\(^{-1}\)) and vinyl chloride (0.3 d\(^{-1}\)) are 50 to 66% lower than for TCE, which is commonly observed for ZVI (Tratnyek et al. 1997; Wilkin et al. 2019). It is not clear why the apparent field TCE transformation rates are lower than expected; however, the effects of high TOC levels (and associated low redox conditions) were not evaluated in the treatability testing and may be influential. Others have shown that natural organic matter (e.g., humic acid) present at similar levels (200 mg/L) decreased reactivity and TCE transformation rates of two nanoscale ZVI materials by 60% and 78%, respectively (Han et al. 2019). However, He et
al. (2020) note that the effect of organic carbon on hydrogen evolution and ZVI selectivity and reactivity by ZVI has not been widely studied. However, if the current elevated TOC levels are the primary cause of the lower-than-anticipated ZVI transformation rates, ZVI reactivity would be expected to increase as TOC levels continue to decline over time.

Lessons Learned, Risks, and Implementation Challenges

Overall, the HRX Well achieved the demonstration objectives; however, as with any new technology implemented for the first time, items were identified that can be considered for future HRX Well designs and installations. One of the most important lessons learned was the value of iterative modeling to optimize the final design. For example, for this site, wells screen lengths shorter than about 50 feet resulted in significantly lower flow and capture zone width. Similarly, increasing the well diameter and treatment media hydraulic conductivity increased the predicted flow-focusing behavior and, therefore, the total treatment zone size. Lengthening the well segment containing the treatment media increased \( t_R \) and, therefore, treatment effectiveness and longevity. Conversely, decreasing the treatment media hydraulic conductivity reduced flow velocity in the well, increasing residence times, but also reduced the flow-focusing behavior and total treatment zone size. The relative sensitivity of these various factors depends highly upon site conditions and therefore the use of site-specific numerical flow models for field designs is strongly recommended.

This work also emphasized the importance of treatment media selection. Using treatment media with the highest reactivity will reduce the required residence times and selecting treatment media with high treatment capacity will increase the overall longevity of the HRX Well and minimize cartridge replacement frequency. However, in some cases, more reactive treatment media may have a smaller average grain size and hydraulic conductivity, and this potential trade-off must be carefully considered. Furthermore, residual carbon-based biopolymer drilling fluid may remain after well development and its potential influence on treatment media performance (e.g., treatment rates, efficiency, capacity) should be considered during treatability testing.

The most important technical risk with an HRX Well is inadequate treatment media contact time and/or the potential for short circuiting within the well, which could result in the migration of untreated or partially treated groundwater to downgradient areas. These risks are primarily managed through effective cartridge design, use of engineering safety factors, and performance monitoring. Additionally, grout is placed in the annulus between the HRX Well casing and the borehole wall to prevent short circuiting outside the HRX Well. Aquifer heterogeneity and anisotropy will complicate the hydraulic behavior and potentially reduce the predictability and capture efficiency of the HRX Well. This risk can be managed through the development of robust and dynamic conceptual models and model sensitivity testing during the design process. Fouling of the inlet and outlet screens or treatment media will reduce flow through the HRX Well and capture zone size. Long-term changes in performance due to loss of treatment media reactivity or hydraulic conductivity can be evaluated through performance monitoring.

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 built prototypes for this demonstration included the treatment 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 for similar site settings are generally understood and can likely be mitigated or avoided with simple design changes. Potential implementation challenges are associated with the directional drilling methods used to install HRX Wells; however, they are not specific to HRX Wells. Examples include the potential for inadvertent drilling fluid returns to the ground surface along preferential pathways and electromagnetic interference with borehole navigation. Horizontal well guidance documents (Directed Technologies Drilling Incorporated [DTD] 2004; USEPA 2017) further discuss the advantages and disadvantages of directional drilling. 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 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).

Conclusions and Recommendations

This field implementation validates the overall performance and implementability of the concept and demonstrates that HRX Wells can be installed under active infrastructure, require limited ongoing operation and maintenance, and have low ongoing energy and water requirements. Appropriately constructed models can reliably predict the hydraulic behavior and capture zone size and should be used for HRX Well design optimization and performance assessment. The passive HRX Well configuration will be most efficient when there is a sufficiently high contrast in hydraulic conductivity between the aquifer and the treatment media (generally 1000 times or greater). The active HRX Well configuration will likely offer more favorable performance and cost effectiveness for sites with higher hydraulic conductivity (e.g., greater than approximately 5 feet/d) and/or target aquifer thicknesses greater than approximately 20 feet. This study also underscores the importance of treatability testing for selecting treatment media that exhibits high permeability and high reaction rates to maximize capture efficiency and ensure treatment goals are achieved within the hydraulic retention time. Based on the results of this study, it is recommended that HRX Wells be further considered for broader use, especially at sites with recalcitrant and other difficult to treat contaminants (e.g., PFAS, 1,4-dioxane, metals) where long-term mass discharge control is a critical priority.
Acknowledgments

This work was completed through significant contributions by many individuals and organizations. Specific acknowledgment and appreciation are extended to Hoa Voscott, Kelli Parsons, Matt Spurlin, Kelly Houston, Nageshwar Kunte Pandurangarao, Billy Hodge, James Ditto, Don Eley, and Connelly GPM, Inc. Funding and support for this work was provided through the U.S. Department of Defense’s Environmental Security Technology Certification Program (ESTCP; project ER-201631). The insights and comments provided by Michael Gefell, John Wilson, and an anonymous reviewer are greatly appreciated and resulted in a significantly improved manuscript. Arcadis is the patent assignee for the HRX Well®.

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