The Horizontal Reactive Treatment Well (HRX Well®): A New Remediation Technology for In Situ Contaminant Flux Control

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ABSTRACT
The Horizontal Reactive Treatment Well (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. The HRX Well utilizes horizontal wells oriented parallel to groundwater flow filled with a treatment media. The design leverages natural “flow-focusing” behavior induced by the engineered hydraulic conductivity contrast to passively capture and treat proportionally large volumes of groundwater within the well in situ. Clean groundwater then exits the horizontal well along its down-gradient sections. Many different types of treatment media are already available (e.g., zero valent iron [ZVI], activated carbon, biodegradable particulate organic matter (e.g., mulch), ion exchange resins, zeolite, apatite, chitin). Therefore, this concept could be used to address a wide range of contaminants, including difficult-to-treat contaminants including metals, chlorinated solvents, and per- and polyfluoroalkyl substances (PFASs). Field results demonstrate capture and treatment widths of up to tens of feet can be achieved for many aquifer settings, and that reductions in down-gradient concentrations and contaminant mass flux are nearly immediate. The specific performance results from the field site are consistent with model predictions. The HRX Well offers several technical and practical advantages over conventional permeable reactive barrier (PRB) treatment schemes, including highly efficient treatment media usage, the ability to use multiple media types in series (i.e., treatment trains), and easy/inexpensive media replacement. The HRX Well requires minimal aboveground footprint, can access deep zones, and contamination under surface infrastructure, and consumes no/minimal energy and water.

INTRODUCTION AND HRX WELL® CONCEPT

This paper discusses a new horizontal well application for in situ groundwater remediation and contaminant mass flux/discharge control. The primary benefit of horizontal wells is they can be readily installed and operated under buildings, roads, flight lines, and other surface infrastructure that may have been previously inaccessible via vertical boreholes. Additionally, advances in directional drilling methods have increased well design options while lowering overall installation costs[1]. The Horizontal Reactive Media Treatment well (HRX Well®) utilizes large-diameter horizontal wells for in situ treatment of metals, chlorinated solvents, per- and polyfluoroalkyl substances (PFAS), and other contaminants. The HRX Well concept is particularly well-suited for sites where long-term mass discharge control is a primary performance objective. Comparable remedial technologies include PRBs and groundwater pump and treat systems.

It is increasingly recognized that contaminant mass flux/discharge provides the most representative measure of plume dynamics and risk to receptors. Consequently, remedial technologies focusing on long-term mass flux/discharge reduction will be increasingly favored, and new strategies that can accurately measure changes in mass flux/discharge over time will be more frequently implemented. Flux-focused remediation and monitoring approaches are relevant for any type of contaminant source zone, but will be particularly important in the future for assessing the risk and benefits of mitigation activities for per- and polyfluoroalkyl substances (PFAS) discharging from fire training areas and other source area types.

The HRX Well uses directionally drilled horizontal wells installed in the direction of groundwater flow that are then filled with treatment media such as granular activated carbon (GAC) or zero valent iron (ZVI). The basic HRX Well concept requires no above-ground treatment, has limited ongoing maintenance, and does not require a surface footprint. For GAC, ZVI and other treatment media, the in situ units are designed for easy removal and regeneration or replacement when exhausted.

Contaminant mass discharge can be dramatically reduced, and 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. The HRX Well (Figure 1) is oriented in the general direction of groundwater flow and is filled with treatment media to treat captured groundwater within the well. Flow-focusing, resulting from a high in-well hydraulic conductivity relative to the aquifer hydraulic conductivity, passively directs a 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 medium, impacted groundwater is treated in-situ as it flows through the HRX Well, before discharging through the screen on the downgradient side of the well. For some applications, the flow through the HRX Well and size of the capture zone can be increased through pumping (i.e., active configuration), 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 1: Groundwater (indicated by blue flowlines) is focused and flows into the upgradient screen section of the HRX Well (grey cylinder) where it is treated as it passes through granular reactive media before exiting the downgradient screen section back into the aquifer. The color flood indicates contaminant concentrations, where hot colors represent high concentrations and cool colors indicate treated groundwater. Some flowlines are outside the treatment zone and do not enter the well; therefore, groundwater along these flow paths remains untreated.

Unlike many other in situ remediation technologies, 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 and allows many new types of treatment media to be considered, which potentially increases the list of contaminants that can be successfully treated (Table 1). Solid reagents can be advantageous because they generally exhibit relative rapid reactivity and are compatible with a wide range of groundwater chemistry conditions, and 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 (GAC), magnetite, zeolite, biodegradable particulate organic matter (e.g., mulch), apatite, limestone, magnesium, and iron sulfide. Magnesium hydroxide may be used to generate alkalinity to address acidic groundwater; conversely, reactive sulfide minerals (such as iron sulfide) may be used to generate acidity to treat alkaline groundwater. Multiple reactive media types can be combined or used in series to address complex mixtures or provide pretreatment. In most cases, exhausted reactive media can be subsequently removed and replaced or regenerated in-situ.

Table 1: Potential reactive media types and target groundwater contaminants for an HRX Well.

Target Groundwater Contaminant	Reactive Media
Chromium, arsenic, other metals, chlorinated solvents (CVOCs), nitrate, perchlorate, energetics,	Zero valent iron (ZVI) Bimetallics (e.g., ZVI + Pd, Pt, or Ni)
Low pH, acid rock drainage	Limestone, lime, magnesium oxide
Cr, high pH	Iron sulfide
Ammonium, radionuclides, PFAS	Zeolites
Radium	Barium sulfate (barite)
CVOCs, PFAS, hydrocarbons, halomethanes	Granulated Activated Carbon (GAC), Organosilicates (e.g., Osorb®)
CVOCs, 1,4-dioxane, hydrocarbons, polyaromatic hydrocarbons (PAHs), phenolic compounds (e.g., pentachlorophenol; PCP), energetics	Sustained Release Oxidants (e.g., RemOxSR+ISCO)
CVOCs, nitrate, perchlorate	Biodegradable particulate organic carbon (e.g., mulch)
Brines, PFAS	Ion exchange resins

FIELD RESULTS

The HRX Well technology was initially tested and verified through extensive numerical and physical modeling (i.e., laboratory tank testing) completed as part of Strategic Environmental Research and Development Program Project ER-2423. The concept was then first field validated at Vandenberg Space Force Base (formerly Vandenberg Air Force Base) in California as part of Environmental Security Technology Certification Program (ESTCP) Project ER 201631 (https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-201631/ER-201631). 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 lithologic materials observed within the Principal Zone aquifer consist of silts and silty sands, with moderate to low hydraulic conductivity values, 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).

To assist the HRX Well design parameter 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 in the HRX Well. The results of the design model are provided in Figure 3 and indicated the capture and flushing zone widths would be approximately 16 m (52 ft) under passive configuration

Figure 3: Groundwater (indicated by blue flowlines) is focused and flows into the upgradient screen section of the HRX Well (grey cylinder) where it is treated as it passes through granular reactive media before exiting the downgradient screen section back into the aquifer. The color flood indicates contaminant concentrations, where hot colors represent high concentrations and cool colors indicate treated groundwater. Some flowlines are outside the treatment zone and do not enter the well; therefore, groundwater along these flow paths remains untreated.

ZVI was selected as the treatment media based on treatability studies that indicated the expected TCE decay rate would be approximately 1.8 day^{-1} (half life of 0.39 days). The results of previously conducted column tests using the site-specific groundwater (Divine et al., 2018c) indicate that the reactivity and permeability of the iron should remain constant for more than 1,000 pore volumes. Based on simple stoichiometry calculations, the ZVI is expected to have a service life of at least 15 years and may last through the 30-year design life of the HRX Well. The as-built well was completed with 30-cm diameter casing and the treatment media was installed in 25-cm diameter cartridges. The effective hydraulic conductivity of the HRX Well was estimated to be approximately 100 m/day.

TCE concentrations near the upgradient HRX Well screen ranged from approximately 30,000 to 40,000 microgram per liter (ug/L) throughout the monitoring period and TCE concentrations at the HRX Well outlet never exceeded 7.6 ug/L, representing greater than 99.99% reduction (Figure 3). By day 436, all four performance monitoring wells (all within the anticipated treatment zone) show reductions in TCE from 28 to 99%, which are consistent with the predicted mechanism of clean water flushing out of downgradient HRX screen. In general, changes in TCE concentrations are consistent with an elution-based process. Once treated water discharging from the HRX Well arrives at a monitoring well, TCE concentrations begin to decline; this behavior is particularly evident at MW-48 where TCE remained relatively stable through day 100 and then started to decline as soon as treated water began arriving. 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.

Figure 3: TCE 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 were used for Day = 0).

In summary, field results from the VSFB project validated the HRX Well as an in situ remediation approach with an average mass discharge reduction of approximately 1.8 g/day for over 1,200 days. HRX Well systems have been installed at additional sites to treat chlorinated solvents and PFAS, demonstrating successful installation under active infrastructure and in a range of hydrogeologic conditions. Further information on this demonstration are available elsewhere[2,3,4].

SUMMARY AND CONCLUSIONS

The HRX Well concept is a promising new approach that offers the following distinguishing elements compared to other technologies:

- Leverages site hydrogeology and induces flow-focusing behavior for passive in-situ treatment in a focused zone;
- HRX well's performance can be improved by operating the Well under active configuration (i.e., pumping/injecting), and can be upscaled (multiple HRX Wells in space) to address more extensive contaminated area.
- Intends to quickly reduce contaminant mass flux and control migration;
- Compatible with a wide range of reactive media and, therefore, may address many contaminants categories;
- Requires limited above-ground footprint, no active groundwater management or above-ground treatment systems, and minimal ongoing maintenance; and,
- May be more appropriate for some lower-permeability aquifer settings compared to other conventional methods.

The successful field implementations validate 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 are effective 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 1,000 times or greater). The active HRX Well configuration, where flow through the HRX Well and size of the capture zone are increased through pumping, will likely offer more favorable performance and cost effectiveness for sites with higher hydraulic conductivity (e.g., greater than approximately 5 ft/day) 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.

REFERENCES

[1] Koenigsberg SS, Piatt ER, Robinson LI. 2018. New perspectives in the use of horizontal wells for assessment and remediation. Remediation, 28:45–50. https://doi.org/10.1002/rem.21575.

[2] 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

[3] 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.

[4] Divine, et al., 2020. Field Demonstration of the Horizontal Reactive Media Treatment Well (HRX Well®) for Passive In-Situ Remediation. GWMR, 40(3): 42-554, https://doi.org/10.1111/gwmr.12407.