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APPLICATION OF HORIZONTAL WELLS TO ENHANCE SITE REMEDIATION

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AS	air sparging
bgs	beneath ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
COC	contaminant of concern
COD	chemical oxidant demand
Cr^{6+}	hexavalent chromium
CT	carbon tetrachloride
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DoD	Department of Defense
DTD	Directed Technologies Drilling
DTI	Directed Technologies Incorporated
EISB	enhanced in situ bioremediation
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
gpm	gallon per minute
GWQS	Groundwater Quality Standard
HDPE	high density polyethylene
HRX well™	horizontal reactive treatment media well
IDW	investigation derived waste
ISCO	in situ chemical oxidation
ISCR	in situ chemical reduction
lb_f	pounds of force
LNAPL	light non-aqueous phase liquid
NAPL	non-aqueous phase liquid
NASNI	Naval Air Station North Island
NAVFAC	Naval Facilities Engineering Command
NJDEP	New Jersey Department of Environmental Protection
ORP	oxidation reduction potential
PCE	tetrachloroethylene
PRB	permeable reactive barrier
psi	pounds per square inch

PVC	polyvinyl chloride
RAO	remedial action objective
ROD	Record of Decision
ROI	radius of influence
SCFM	standard cubic ft per minute
SVE	soil vapor extraction
SWMU	Solid Waste Management Unit
TCE	trichloroethylene
TCRA	time-critical removal action
TDS	total dissolved solids
TOC	total organic carbon
TPH	total petroleum hydrocarbon
VOC	volatile organic compound

1.0 INTRODUCTION

Horizontal wells have become a cost-effective and practical tool to facilitate the remediation of contaminants of concern (COCs) at challenging sites where vertical wells alone may not be able to achieve project objectives. Horizontal wells have been used in conjunction with a wide range of proven technologies including, but not limited to, in situ chemical oxidation (ISCO), in situ chemical reduction (ISCR), enhanced in situ bioremediation (EISB), soil vapor extraction (SVE), air sparging (AS), and multi-phase extraction. Recent advances in design and emplacement technologies have reduced the up-front cost and time to install horizontal wells, making them a viable option for more sites.

COMMON SCENARIOS FOR HORIZONTAL WELL USE

- Presence of aboveground infrastructure (e.g., buildings) that precludes installation of vertical wells
- Treatment of contaminants under busy roads and airport runways which prevent vertical wells from being sampled in a safe manner without interrupting existing operations
- Installation of permeable reactive barriers (PRBs)
- Treatment of thin contaminant plumes

Horizontal wells are typically more expensive to install than vertical wells. However, they offer an alternative when site-specific factors limit the technical practicability of installing and operating vertical wells. Horizontal wells may be preferred if there is limited access to the property to conduct monitoring and/or to ensure appropriate well spacing for amendment distribution. This could include sites where access from the surface is constrained because the plume has migrated off-site and/or aboveground structures are present such as buildings, busy roads, runways, or railways. Thin contaminant plumes also may be good candidates for treatment using horizontal wells since they can achieve greater contact between the well screen and the contaminated zone compared to vertical wells.

The Department of Defense (DoD) has applied horizontal wells at a wide range of sites across the United States. Figure 1 shows a selection of DoD facilities where horizontal wells have been installed to facilitate site remediation based on a review of abstracts published since 2002.

Figure 1. DoD Facilities at which Horizontal Wells Have Been Installed

2.0 IMPORTANT FACTORS TO CONSIDER FOR HORIZONTAL WELL INSTALLATION AND OPERATION

2.1 WHAT IS THE ANTICIPATED USE FOR THE WELL?

Horizontal wells can be used in conjunction with a wide range of remediation technologies. Initially, they were predominately used to introduce air or remove vapors as part of AS and SVE systems across large treatment areas. However, with the advancement of technologies that rely on the introduction of amendments such as ISCO and EISB, horizontal wells have been used in conjunction with these technologies to deliver amendments and facilitate their distribution in the aquifer. Single or vertically stacked horizontal wells can be used for installation of PRBs or amendment enhanced bio-barriers to prevent plume migration. Horizontal wells also can be an effective method to control vapor intrusion into buildings since they can be installed and screened beneath the building along one or more locations across its length and be connected to an SVE system to generate a region of low pressure beneath the building and recover vapors. Although horizontal wells can facilitate remediation using a wide range of technologies, in most cases, due to their high installation cost, the decision to use horizontal wells is based on access restrictions that prevent installation of multiple vertical wells.

As part of the design process, it is necessary to know how each well will be used to ensure that it is designed properly for its intended use. Like vertical wells, the design of the screen (length, interval, and slot size) is determined based on the well's intended application and other site-related factors. All materials must be compatible with the well, keeping in mind the potential for chemical interactions and ensuring that the well can withstand anticipated process temperatures, pressures, and flowrates.

A horizontal well should not be confused with a French drain. A French drain is generally used to address water drainage at a site, although it can be used to introduce amendment in certain circumstances. A French drain generally is constructed by installing a relatively shallow perforated or screened pipe beneath ground surface. Gravel or other coarse material is placed around the pipe to help convey groundwater into it. Applications of French drains for site remediation are not covered in this document.

The anticipated use of the well influences the design of the well and therefore has a direct impact on installation cost. Major cost drivers include well length, well depth, screen and casing diameter, geology, single- or double-ended well configuration, and screen open area design/percentage (Directed Technologies Drilling [DTD], 2020). Contamination depths exceeding about 130 to 160 feet result in much higher installation costs and therefore are an important consideration. In addition, site-specific factors including lithology (e.g., drilling into bedrock), site access and need to use specialized tracking systems (e.g., wireline) can impact cost (Directed Technologies Incorporated [DTI], 2020). As a result, costs to install horizontal wells vary significantly and have been reported to range from about $80/ft to over $500/ft (DTD, 2020).

2.2 HOW DOES SITE-SPECIFIC LITHOLOGY AND HYDROGEOLOGY AFFECT THE DESIGN, INSTALLATION AND OPERATION OF A HORIZONTAL WELL?

Lithology and hydrogeology have significant impacts on the design, installation, and operation of a horizontal well, and therefore, it is important to have a detailed understanding of the conceptual site model prior to installation. Site lithology must be well characterized since changes in lithology can affect the direction of the drill head and the tools to monitor it. Similarly, aquifer characteristics must be known to ensure the wells are designed to achieve adequate introduction and distribution or removal of fluids.

Horizontal wells have been installed in all types of geologic formations; however, they are commonly installed in materials such as clay, silt, and sand. They also can be installed in bedrock but require more advanced drilling systems and have a greater installation cost. Dual-rod systems can be used that reduce the need for mud motors in hard formations (DTD, 2004). In addition, innovations allowing operators to use and quickly interchange a variety of tools, such as roller cone bits and air hammers, have facilitated well installation in rock formations.

Special care must be taken if a horizontal well is installed across lithologies with varying hydraulic conductivities or permeabilities (e.g., sand followed by clay). It may be challenging to achieve uniform distribution across the length of the well. The design of the well screen slot size and method used to introduce into or extract fluids from the formation must be carefully designed to facilitate uniform introduction or removal of fluids across the length of the screen.

Lithology also can impact techniques that are used to develop horizontal wells after installation. For instance, over pressurization, which involves applying a large hydraulic pressure to force materials out of the slots, works well in sand and silts, but can be challenging if substantial clay is present, making it difficult to remove.

Groundwater level and associated seasonal fluctuations can impact the operation of a horizonal well. Because the well is installed over a narrow horizontal interval in the formation, it can be susceptible to changes in groundwater elevation. For instance, if a SVE well is installed in the vadose zone and the groundwater elevation increases above the bottom of the well during seasonal or other high water level conditions, water will be entrained in the well, possibly rendering it ineffective. Conversely, during a dry season or drought, a light non-aqueous phase liquid (LNAPL) recovery well may not be able to recover fluids if the water level drops below the elevation of the well.

2.3 HOW IS A HORIZONTAL WELL INSTALLED?

Installation of a horizontal well is performed using a multi-step drilling technique comprising installation of an initial pilot hole, subsequent reaming of the pilot hole to the diameter required for well installation, and the installation of the well screen and casing materials.[1]

[1] Horizontal wells also can be installed by excavating a trench, emplacing the screen and casing, and backfilling. This method is generally best suited for shallow installations in areas where trenching is technically practical and is well suited for large diameter screen and casing. This method is not covered in detail in this document.

Directional drilling rigs used for environmental applications may be relatively small (Figure 2), because they are mobile allowing them to maneuver and easily operate in confined locations (e.g., in operational areas around buildings). However, larger units are available and may be necessary depending on the depth and length of the wells to be installed. Multiple horizontal wells may be installed from the same setup location. This can result in a significant reduction in drill rig movement, setup, and site restoration costs, and limits drilling impacts on site activities.

Figure 2. Common Directional Drilling Rig

<u>Reamer</u>

A piece of equipment that is attached to the end of the drill to enlarge the borehole to the designed diameter required to install the well.

The drill rig is rated by its pullback force (i.e., the force available to pull the casing and screen through the borehole). The required pullback force is based on soil type, size of borehole, length of borehole, and how straight the borehole was installed (boreholes that exhibit little or no tortuosity require less pullback force than those with a high degree of tortuosity). For average soil conditions, the required pullback force for 1,000 ft of well is 40,000 pounds of force (lb_f). Most environmental applications require only a small or medium rig, which can generate upwards of 100,000 lb_f. However, rigs are available that can generate more than 1,000,000 lb_f (DTD, 2004).

Drilling typically is performed using a mud rotary auger. The mud generally is a mixture of water and bentonite; however, although less common, it also may include proprietary polymers to facilitate removal of drill cuttings. These polymers are designed to biodegrade and therefore generally do not involve any special type of permitting or disposal requirements (DTI, 2020). The cutting tool on the drill head is selected based on site-specific lithology and can include carbide tipped blades and various types of bits. Mud motors, which rotate a cutting bit as the drilling mud passes through the drill head, are advantageous for drilling through rock, but are more complicated to operate (DTD, 2004). Horizontal wells may be installed using surface to surface drilling (Figure 3) or blind hole drilling (Figure 4) described below:

- **Surface to surface drilling** is performed by advancing the drill head into the ground at an angle until the target depth is achieved, after which the drill bit continues along the design length (ranging from less than 100 ft to greater than 2,000 ft). Drilling mud is used to evacuate cuttings from the entry hole location. After the desired well screen length of the borehole has been achieved, the drill head is guided to the ground surface at an angle. Upon penetrating the ground at the exit location, a reamer is attached to the drill string along with the well materials, which are then pulled back through the hole to the entry location. Greater well lengths (>2,000 ft) can be achieved using surface to surface drilling compared to single entry drilling (below) and surface to surface drilling allows for wells to be accessed from two locations. However, there is a greater setback distance requirement (setback on each side of the screen) and twice the blank casing is required compared to single entry drilling.

- **Blind hole (single entry) drilling** is performed in a similar manner to surface to surface drilling; however, the drill head does not break ground surface at a second location. After the design length of the borehole containing the screen section has been achieved, the drill string is removed, and a reamer is attached to increase the size of the borehole and prepare it for the well materials. Less well materials are required for blind hole drilling and a setback distance is only required on the entry side of the well. However, blind hole drilling cannot achieve as long of a well (<1,500 ft) as surface to surface drilling.

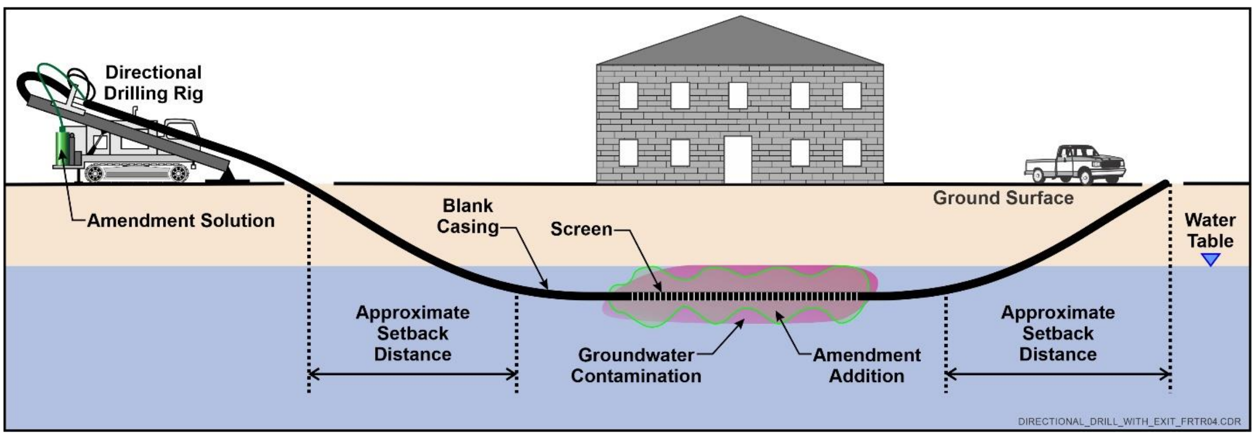


Figure 3. Surface to Surface Drilling

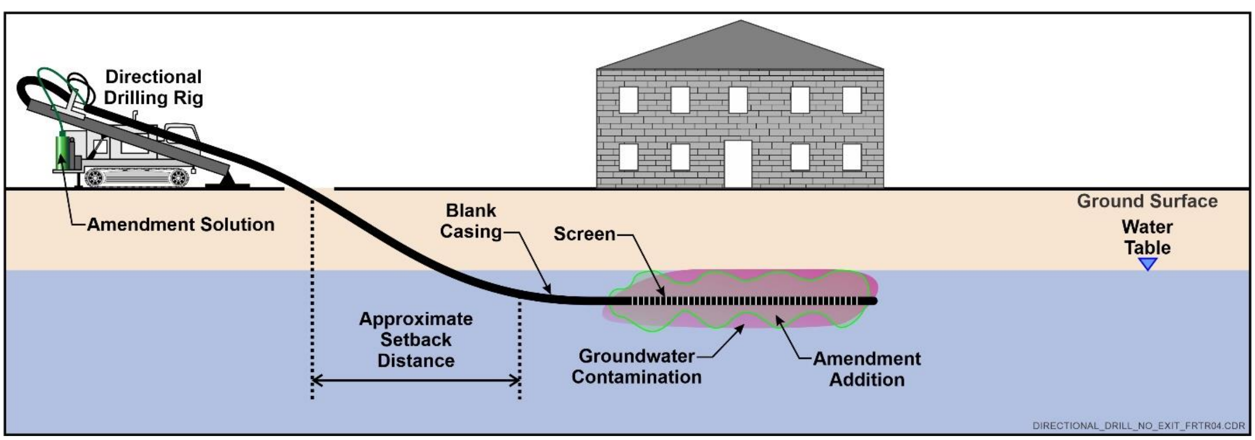


Figure 4. Blind Hole Drilling

2.4 WHAT ARE THE OPTIONS FOR WELL MATERIALS?

A variety of materials can be used to construct horizontal wells including stainless steel, polyvinyl chloride (PVC), fiberglass-reinforced epoxy, high-density polyethylene (HDPE), high temperature polyethylene, and porous polyethylene (Purdue University, 2007). All materials must be compatible with the intended use of the well. Chemical, pressure, and temperature compatibility must be considered. For instances, if highly oxidizing reagents will be introduced into the aquifer, PVC or stainless-steel casing and screen may be required. Conversely, it may not be possible to use standard Schedule 40 PVC well casing and screen if high pressures are expected, and thicker Schedule 80 PVC or steel materials may be required. Horizontal well installations in earthquake zones are not subject to special requirements; however, a flexible material such as HDPE could be considered if deemed necessary.

Pre-packed systems are commercially available but are not frequently used because they can become perforated during or after installation, which results in sedimentation of the well (DTD, 2020). Furthermore, proper development of conventional wells can achieve effective performance, eliminating the need for pre-packed filters. These integrated systems utilize a combination of inner and outer screens and various types of filtration materials including fabric/mesh, gravel, glass beads, and sintered metal (DTD, 2020), which help to prevent fine-grained silts and sands from clogging the screens. Manufacturers should be consulted for specific design and installation requirements for the type of well that will be used.

Installation of horizontal wells also must consider tensile and bending stresses. In general, the schedule of pipe that is used for remediation wells is designed to accommodate anticipated bending stress and, typically, the bending stress placed on the pipe during installation is in excess of what would be experienced during shrinking or swelling of the soils (DTI, 2020). Bending stresses can be minimized by advancing very straight sections of borehole and creating a gradual angle of transition from the surface to the horizontal point below grade facilitate the installation of stiff casing materials (and pre-packed screen systems). Reaming the borehole to several times the pipe diameter also improves the ease in which the well materials can be pulled through the hole, allowing less flexible materials to be used.

2.5 WHAT ARE APPROPRIATE SAMPLING METHODS?

It may be necessary to sample soil during installation of a horizontal well, as well as sampling groundwater before and after application of a remedy. Soil sampling can be challenging but can be accomplished by attaching a sampling tube to the end of the drill string to collect a sample from the face of the borehole (DTD, 2004). However, this is a slow and laborious procedure and oftentimes, depending on site-specific lithology, it is difficult to maintain an open borehole. Therefore, at some sites, it may be more technically practical and cost effective to advance vertical boreholes to the desired depth from which samples can be collected.

Groundwater sampling may be performed using packers to isolate a specific target interval along the length of the horizontal screen similar to what is performed in vertical wells when it is desired to sample a specific interval. In some cases, multiple wells with dedicated sampling tubes can be installed in a single borehole (see segmented well systems below) and dedicated sampling cartridges can be installed (as used in the horizontal reactive treatment media well [HRX well™] described below).

2.6 HOW IS THE HORIZONTAL WELL INSTALLED IN THE TARGET LOCATION?

Horizontal wells can be very long and may cut across varying lithologies, which can impact the direction that the drill head moves through the subsurface. Hence, it is important to know the location and direction that the drill bit is travelling as the borehole is advanced. This can be achieved using one of three principal methods as follows:

- **Walkover navigation systems** are comprised of three components including a transmitter (sonde) installed in the drill head; a receiver, which is carried by a technician over the general area where drilling is being performed; and a display that is mounted in the drill rig cabin (DTD, 2004). The battery-powered sonde transmits a signal to the receiver that is converted into depth; pitch (the degree of inclination of the drill head from the horizontal plane) and roll (the degree of inclination from the vertical plane). This information is shown on a display allowing the drill operator to view the position of the drill head and make adjustments to ensure it follows the desired path through the subsurface. The technician must follow with the receiver near the drill head to ensure proper connectivity between the transmitter and receiver. Generally, this method is limited to a maximum depth of about 80 to 100 ft beneath ground surface (bgs) to ensure connectivity between the transmitter and receiver.
- **Wire line systems** are similar to walkover systems; however, the sonde is powered through a cable connected to the drill rig as opposed to a battery (DTD, 2004). Hence, the sonde can operate for indefinite periods without requiring replacement or recharge of a battery, making this method useful for long boreholes. In addition, data transmitted by the sonde are sent through the cable that provides the power to the transmitter in the cabin eliminating the need for a technician to maneuver the receiver in proximity to the transmitter, allowing the operator to make necessary adjustments to maintain the desired borehole path. Because connectivity between the transmitter and receiver is not a concern, deeper depths can be achieved using this method than the walkover navigation system. However, operation of wire line systems can be time consuming since an additional section of wire must be added each time additional sections of drill rod are introduced (DTD, 2004).
- **Gyroscopic steering tools** are direct and accurate methods to monitor the position of the drill head. Various data are transmitted directly from the drill head to the drill rig cabin, which are viewed in real time as the operator advances and controls the direction of the drill head. Although accurate and fast, they are the costliest of the three techniques and require substantial training to operate (DTD, 2004).

2.7 DOES THE HORIZONTAL WELL NEED TO BE DEVELOPED?

Wells should be developed after installation to remove drilling mud and other particulates from the well screen. Jetting/flushing and over-pressurization are effective development methods. However, swabbing and surging, commonly performed to develop vertical wells, are not very effective. Periodic development may be required during application of the remedy to remove accumulated deposits or address biological or chemical fouling.

Development Method	Description
Jetting/Flushing	High pressure jets are introduced and conducted through the well, using high pressure water to spray and remove formation material and drilling fluids from the well screen. Very effective in clayey soils and in long well screens (DTD, 2004).
Over-Pressurization	High pressure is applied by pumping water into the well to remove debris from the slots. Most effective in shorter casing and sand formations.
Swabbing/ Surging	A surge block or other device containing wipers is placed into the well and quickly removed creating a surge of water that removes material from the well slots. Generally, not a practical method for horizontal wells due to the wells' great length and inability to move the swab fast enough through them to generate the necessary force to remove debris.

2.8 HOW CAN A UNIFORM FLOWRATE BE ACHIEVED DURING OPERATION?

Uniform distribution of introduced amendments or withdrawal of fluids from the well can be difficult to achieve across the length of a horizontal well screen. For a given slot size, fluids may preferentially enter or exit the screen at the portion closest to the pump as opposed to the portion further away from the pump due to the pressure drop across the length of the screen. Also, long runs of horizontal screen may span various soil lithologies, exhibiting large differences in hydraulic conductivity and creating preferential pathways from various portions of the screen into or out of the formation.

Wells must be designed properly based on their intended application. Wells into which fluids can be introduced or withdrawn from either end of the well (i.e., surface to surface installation) will be designed differently than those with only one entrance/exit. Wells having a single entry may be designed with a screen slot size that may be smaller or spaced further apart at the entry portion of the well, while spaced closer together toward the portion further from the entry. Segmented well screens are also an effective means to improve uniform introduction into or removal of fluids from horizontal wells (see Section 3.0). Some specialized drilling companies offer proprietary software to aid in the design of horizontal wells depending on the anticipated end use of the well and should be consulted during the design process.

2.9 IS FOULING AN ISSUE? HOW CAN IT BE MITIGATED?

Figure 5. Fouled Well Screen

Fouling is a process whereby the well screen, filter media, and/or the surrounding formation become clogged (Figure 5). Common types of fouling include biological, inorganic precipitates, and gases, all of which can occur simultaneously. Fouling tends to be most problematic during operation of remedies that change the chemical characteristics of the aquifer. For instance, biofouling can be problematic in wells used to introduce amendments (electron donors) to enhance biodegradation. A thick gelatinous substance can form on the well screen, which can interfere with its operation. Alternatively, chemical fouling might occur when remedies that rely on the introduction of chemical reagents, such as ISCO or ISCR, or result in a change in aquifer pH and oxidation reduction potential (ORP) are applied either due to the formation of reaction byproducts or precipitation of naturally-occurring minerals in groundwater. In addition to fouling associated with application of a specific type of remedy, biofouling also can be problematic at some sites if the drilling mud used contains a biodegradable polymer, which can be a food source for naturally-occurring microorganisms.

The extent of fouling in horizontal wells may be evaluated using an in-well camera, which may be performed at regular intervals (e.g., quarterly) as applicable based on site conditions and the remedy being applied. Fouling can be addressed with non-toxic coatings, disinfectants, and other additives. Acid, and other commercially-available chemical products can be added and surged in wells to remove scale and other deposits. In all cases, it is important to ensure that the chemicals and methods used are compatible with the well materials and would not damage the structural integrity or interfere with the intended function of the well. Additional information pertaining to biofouling and controls can be found in the Environmental Security Technology Certification Program (ESTCP) report titled “A Review of Biofouling Controls for Enhanced In Situ Bioremediation of Groundwater.” (ESTCP, 2005).

3.0 RECENT ADVANCES IN HORIZONTAL WELL APPLICATIONS

The methods and materials used to design, install, and operate horizontal wells for environmental remediation applications continue to evolve. Incremental advances in drilling technology and locating equipment have helped to reduce cost and decrease installation times. Advances also have been made in well screen design and software systems to design wells with the goal of achieving more uniform flow into or out of wells across the entire length of the screen. Two recent notable advances in well systems include the following:

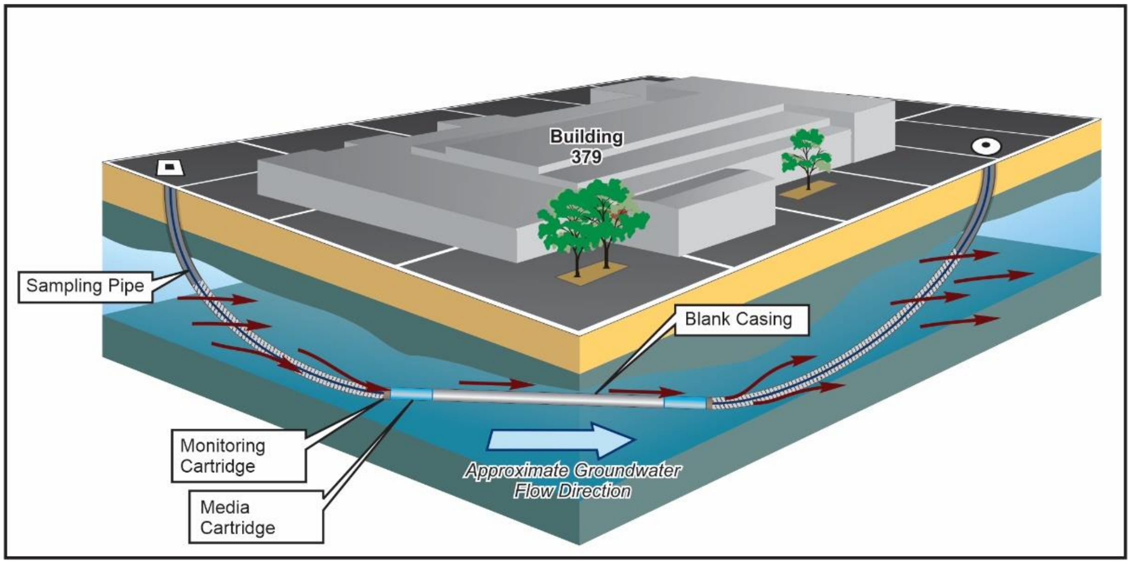
- **Segmented well systems** incorporate multiple screen sections in a single borehole separated by impermeable barriers. These systems can eliminate issues associate with preferential flow into portions of the screen located in more permeable parts of the formation that can occur through a single screen installed across varying lithology that can have order of magnitude differences in permeability. Segmented well systems can be used to inject amendments, as well as extract fluids providing a degree of versatility not available using conventional horizontal wells.

  Segmented wells are installed in a similar manner to a conventional horizontal well. However, after the borehole is drilled and reamed, a sleeve containing multiple well screens, equipped with small diameter tubing is placed into the well, after which the tubing is removed while leaving the well screens in place. Grout is introduced using a tremie pipe (or comparable method) between the screens to ensure that each individual unit is isolated. As many as 13 screens can be installed in a single horizontal borehole (Koenigsberg et al., 2018).

- **Horizontal reactive media treatment well (HRX Well™)** is a large diameter well (typically 12 inches) filled with reactive treatment media. A wide range of treatment technologies can be implemented using an HRX Well™ including: 1) adsorption (e.g., activated carbon or ion exchange), 2) ISCO (e.g., potassium permanganate and other oxidizing agents), 3) ISCR (e.g., zero valent iron), and 4) EISB (e.g., electron donors such as wood chips or chitin). HRX wells can be used to passively treat source areas, as well as to create reactive barriers to prevent migration of downgradient plumes (Divine et al., 2018).

  The HRX Well™ is installed parallel to groundwater flow (Figure 6). Because the material inside the well is designed to be more permeable than the aquifer, under passive flow conditions, the well exhibits a tendency to focus the flow from the aquifer into and through the well. Groundwater is treated by the amendments inside the well, prior to being discharged from the downgradient portion of the well (Crimi et al., 2017). Treatment widths of greater than 50 ft are possible for passive configurations (Divine et al., 2018).

  HRX Wells™ are designed to facilitate flow through them (Figure 6). A screened section is included at the upgradient portion of the well, which transects (at an angle) the contaminated interval from the top zone of contamination to the horizontal portion of the well. A monitoring cartridge connected to a tube that runs through the screen and casing to the surface for sample collection is installed in the horizontal portion of the well, followed by one or more cartridges that contain the treatment media, a blank section of horizontal casing, and a second series of treatment cartridges and monitoring cartridge and sampling tube. A second screen is installed in the downgradient portion of the well from which the treated water exits.



Source: Adapted from ESTCP ER-201631

Figure 6. Conceptual Illustration of the HRX Well^{TM}

4.0 APPLICATIONS OF HORIZONTAL WELL TECHNOLOGY

The DoD has installed and operated horizontal wells at numerous sites to facilitate application of remedial technologies. Four case studies are summarized, highlighting the efficacy of the applications and lessons learned. Table 1 summarizes key aspects of each case study. Additional details and findings are presented in the remainder of this section.

Table 1. Horizontal Well Case Studies

	NAVAL STATION NORTH ISLAND, CA	NAVAL SUPPORT FACILITY, INDIAN HEAD, MD	ROBINS AIR FORCE BASE, GA	PUCHACK WELL FIELD SUPERFUND SITE (USACE), NJ
Contaminants	Volatile organic compounds (VOCs) (predominantly trichloroethylene [TCE]), LNAPL	Carbon tetrachloride, tetrachloroethylene (PCE)	JP-4, JP-8, dissolved phase constituents	Hexavalent chromium (Cr^{6+})
Remedial Action Objective	Prevent vapor intrusion	Prevent migration and unacceptable risks to human receptors from COCs in the shallow groundwater	Reduce concentrations of dissolved-phase hydrocarbons to below their established site-specific remedial goals	Treat plume containing Cr^{6+} in excess of the New Jersey Department of Environmental Protection (NJDEP) Groundwater Quality Standard (GWQS)
Remedy	SVE, steam enhanced LNAPL recovery	ISCO	Biosparging	In situ geochemical fixation
Objective of Horizontal Well(s)	SVE, steam injection, LNAPL recovery	Groundwater extraction	Introduce air	Introduction of a 60% sodium lactate solution
Number of Horizontal Wells	8	2	5	1
Screen Length (ft)	130 to 350	79, 109	540 to 850	450
Screen Slot Size	0.010-inch	0.010-inch x 1.6-inch-long	NA	Variable. 0.0155 to 0.0160 square inches per foot
Well Diameter (inches)	3	3	4	4
Well Casing/Screen Material	SCH. 10 stainless steel	SCH. 80 PVC	SCH. 80 PVC	PVC (SCH unknown)
Well Installation Type	Blind hole (2) Surface-to surface (6)	Blind hole	Blind Hole	Blind Hole
Locating Method	Walkover	NA	NA	Gyroscope

NA – Not Available
SCH – Schedule

4.1 ENHANCED CONTAMINANT RECOVERY, VAPOR MITIGATION, AND HEAT TRANSFER USING HORIZONTAL WELLS AT NAVAL AIR STATION NORTH ISLAND, CALIFORNIA

4.1.1 Background and Objectives

Building 379 at Naval Air Station North Island (NASNI), California overlies a half-mile-long groundwater plume consisting of chlorinated volatile organic compounds (VOCs) resulting from spills and releases of various materials during day-to-day operations in the building. In addition, there is a non-aqueous phase liquid (NAPL) plume comprised of Stoddard solvent and jet fuel beneath the building. The NAPL has sequestered and contains very high levels of trichloroethylene (TCE), which is a predominant COC.

Vapor intrusion of VOCs into the building from the underlying plumes is a potential concern. Concentrations of TCE in sub-slab soil gas samples have been measured to contain up to 5,000,000 $\mu g/m^3$ and concentrations in indoor air above 8 $\mu g/m^3$ were detected at several locations in 2014. It is likely that the presence and operation of a buried steam line, which was once part of the installation utilities, may have exacerbated the concentrations of contaminants in indoor air. Temperatures as high as 110 °F (versus ambient temperature of 70 °F) have been measured in the NAPL plume, facilitating volatilization of the NAPL.

A time-critical removal action (TCRA) is being implemented to reduce concentrations of VOCs in the indoor air of Building 379. A primary component of the TCRA was to install and operate two horizontal SVE wells. Horizontal wells were selected because it was not feasible to install vertical wells within the building. In addition, the radius of influence (ROI) achieved using one horizontal well is much larger than the ROI that would have been achieved with vertical wells.

During installation of the wells, it was confirmed that elevated soil temperatures in the vicinity of the steam line were mobilizing the NAPL and that the presence of the steam line could be leveraged to facilitate NAPL and vapor recovery. Hence, as a second phase of the project, three additional horizontal SVE wells, two horizontal NAPL recovery wells, and three horizontal steam injection wells were installed to facilitate removal of NAPL and volatilize and recover VOC contaminants.

4.1.2 Design and Application

Two horizontal SVE wells, SVE-1A and SVE-1B (Figure 7), were installed during the first phase of the project (Battelle, 2015). The wells were installed parallel to one another (about 8 ft apart) oriented east-west immediately beneath Building 379 in an area where the highest concentrations of soil gas vapor had been measured. The wells were constructed 190 and 335 ft long, respectively, using 10-foot-long sections of 304 Schedule 10 stainless steel[2]. Each well was constructed with about 140 ft of 0.010 slotted well screen. Installation required an approximate 50-foot-long setback from the edge of the building. The longer of the two wells was installed at approximately 10 ft bgs, with a one percent dip towards the east, away from the entry point, to minimize the potential for accumulation of condensate in the riser pipe. The shorter well was installed at approximately 11 ft bgs, parallel to the ground surface. The wells were installed using a single hole entry (blind

[2] Stainless steel was selected based on its compatibility with chemicals anticipated to be encountered at the site including chlorinated volatile organic compounds, total petroleum hydrocarbons (TPH), and Stoddard Solvent.

hole drilling) configuration. The walkover method was used to locate the drill head. Readings were taken at least every 15 ft by a technician standing above and in proximity to the drill head.[3] These readings were transmitted in real time to a computer program, the output of which was used by the driller to adjust the drill path. After the drill head achieved the borehole termination location as specified in the design, the drilling fluid was recirculated for a period of time, the drill bit was removed, and the hole was reamed to expand the hole to facilitate placement of the well materials. A grout seal was installed in the riser section of each well to prevent short circuiting between the screen and ground surface and to minimize infiltration of surface water into the aquifer. The wells were developed using water and a clay dispersant, allowing sufficient time (minimum of 4 to 12 hours) for residual drilling fluid to de-flocculate and be removed from the well.

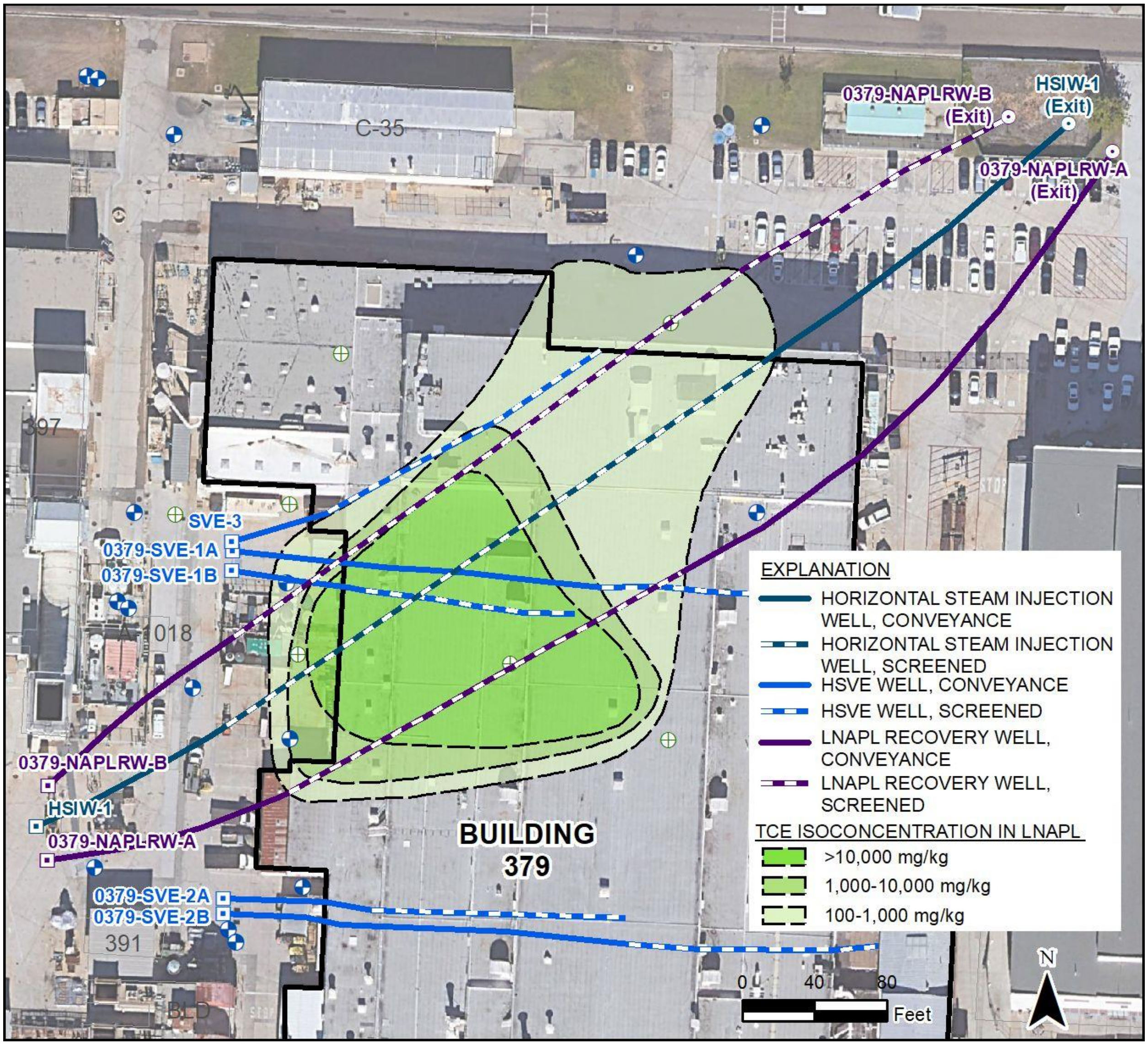


Figure 7. Horizontal Well Locations at Building 379

[3] More frequent readings were taken in areas where utilities were present.

The SVE system was operated for about 20 months prior to expanding the treatment system to include steam-enhanced LNAPL recovery. Approximately 6,000 lbs of VOCs were recovered during the first phase of the project.

The second phase of the remedy consisted of installing three additional horizontal SVE wells, two horizontal LNAPL recovery wells, and three horizontal steam injection wells. Design details pertaining to each type of well are summarized in Table 2. A walkover locating system like that used during installation of SVE-1A and -1B was used to position each of the wells. All wells were constructed using 10-ft-long sections of 304 Schedule 10 stainless-steel casing and screen with threaded connections. The SVE and steam wells were installed using the blind-entry method; however, the LNAPL recovery wells were installed using the surface-to-surface method. The surface-to-surface method was used to facilitate maintenance of the LNAPL recovery pumps that would be installed in these wells. All wells were designed and finished using methods like those used to finish and develop the horizontal wells installed during the first phase of remedial activities.

Seasonal and tidal groundwater fluctuations were considered when selecting the depth of the horizontal well. All historical groundwater elevations were reviewed by the project team to select the elevation that would capture the greatest amount of product and minimize the amount of water recovered.

Table 2. Horizontal Well Design Details – Phase 2

Well Type	Well ID	Screen Depth (ft bgs)	Diameter (inch)	Riser Length (ft)	Screen Length (ft)
SVE	HSVE-2A	10	3	90	130
	HSVE-2B	10	3	210	140
	HSVE-3	10	3	50	190
Steam	HSIW-1A	15	3	200	240
	HSIW-1B	15	3	170	250
	HSIW-1C	15	3	160	180
LNAPL Recovery	NAPLRW-A	25	6	470	260
	NAPLRW-B	25	6	380	350

Each of the three steam wells was installed about 3 ft below the LNAPL zone, with the objective of heating the LNAPL to greater than 40 °C to promote volatilization of VOCs. The SVE wells, installed above the steam lines, were added to facilitate capture of the VOCs from beneath the building as they volatilized. Finally, to address potential mobilization of LNAPL due to an anticipated reduction of viscosity and enhanced mobility at elevated temperatures, two LNAPL recovery wells were installed at depths above the steam injection wells and immediately beneath the LNAPL to capture it.

The steam injection lines were connected to the base steam supply line. Thermocouples to measure change in aquifer temperature were installed underneath and surrounding Building 379. Vapors are recovered from the subsurface using a positive displacement vacuum blower, air compressor, and vapor-liquid separator, all contained on a skid on a concrete pad and enclosed by a security fence. A condenser is used to condense the vapors into liquid (water and organic fractions) and treated using a condensate filter, oil coalescing filter, two heat exchangers piped in parallel, and two 1,000-lb vessels of activated carbon. The resulting condensate is stored in two 1,500 double-walled storage tanks prior to transporting it offsite for recycling.

4.1.3 Results

Levels of TCE in air in Building 379 decreased to below acceptable concentrations within a few weeks of operation (Figure 8). Concentrations have remained low allowing re-located tenants to return to the building. Operation of the steam injection system commenced about 1,360 days after initiating vapor extraction, resulting in a sharp increase in recovery of TPH and, to a lesser extent, VOCs. During the approximately four months the steam system was operational, the aquifer temperature increased from 70 to about 110 °F. The steam system was shut down because NASNI was no longer generating steam at the base. However, the aquifer temperature remained elevated continuing to result in an enhanced recovery rate of COCs. As of February 2020 (approximately 45 months of operation), about 6,800 gallons of condensed COCs have been recovered from beneath the building (Battelle, 2020). The Navy plans to continue operating the system until indoor air concentrations of TCE remain below the Environmental Protection Agency (EPA) Region 9 accelerated action level of 8 micrograms per cubic meter for TCE when the system is off.

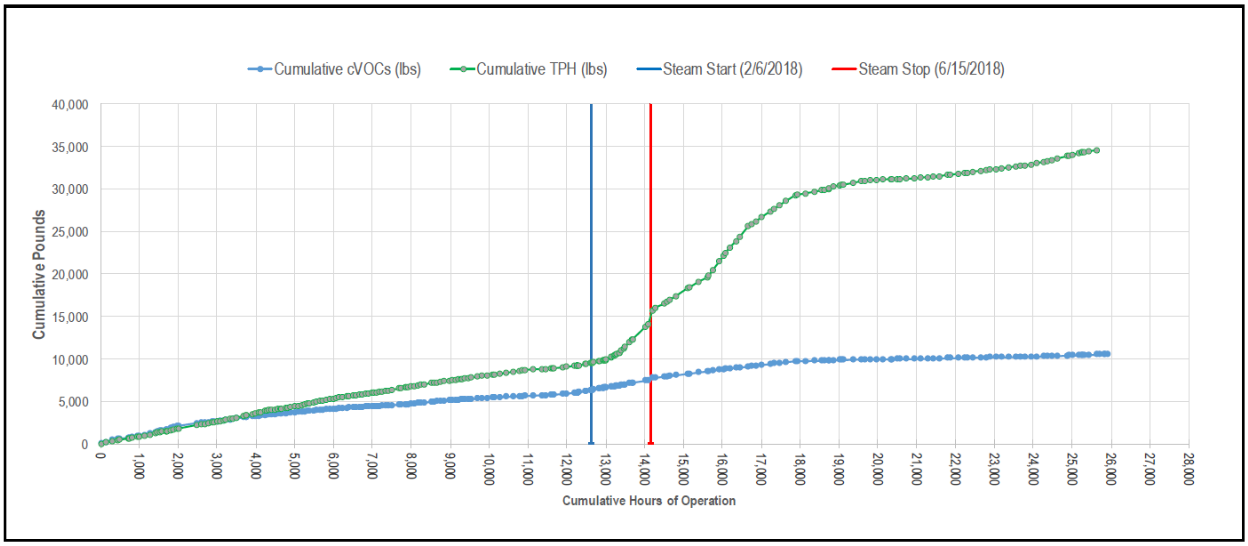


Figure 8. Contaminant Recovery Results at Building 379, NASNI, California

4.1.4 Lessons Learned

Quality control during installation of the horizontal wells is critical to the success of the project. Well materials are subjected to a variety of stresses during installation and buckling and other damage to the materials can occur (Figure 9). If the borehole turns are restricted, the well casing can buckle, which could require advancing a new borehole and/or procuring additional materials, adding substantial cost to the project. The functionality of the well should be tested by developing it and/or performing pump tests to ensure that it functions as designed.

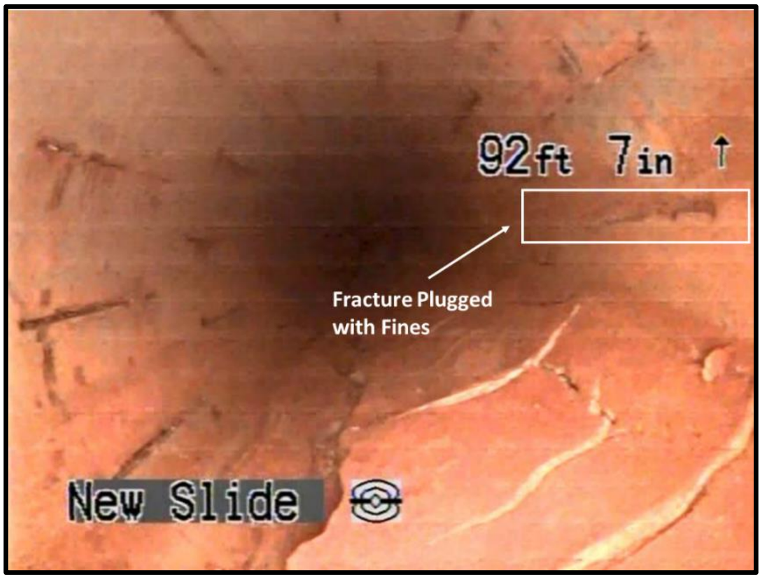
Source: Battelle

Figure 9. Well Screen Damaged during Horizontal Well Installation at NASNI

The electrical wires in the building interfered with the receiver used to locate the drill head making drill head guidance challenging. Using the wire line or gyroscopic steering tool methods, although more costly to operate, may have resulted in less interference, thereby minimizing installation time, and improving well location accuracy.

Similar to vertical wells, horizontal wells are subjected to biofouling and should be considered during design and operation. Maintenance to mitigate fouling tends to be more extensive for horizontal wells. At NASNI, the horizontal well had to be inspected using a borehole camera (Figure 10). A plugged screen was rehabilitated using wire brushes and high-pressure water.

Also similar to vertical wells, an evaluation of geology is necessary to appropriately design the slot screen width. Too thin of slots will restrict air flow. Too wide of a screen can lead to silt entering and accumulating in the well. Unlike vertical wells, horizontal wells do not have sand packs, and therefore, a properly designed slot size is critical to ensure proper function of the well. It is important to consult the driller and/or manufacturer to model the best slot sizing and spacing for the expected operation parameters.



Source: Battelle

Figure 10. Plugged Well Screen

A large working footprint is required in order to install the wells and must be a sufficient distance from the design location of the screened portion of the well to account for the setback distance required based on the angle of entry of the well and depth to the screened interval. In addition, a large amount of wastewater and drilling mud is generated during installation of the well, hence nearby space must be available to store the waste on site until it can be disposed of in accordance with local laws and regulations.

4.2 ADAPTIVE DNAPL TREATMENT USING AN ISCO RECIRCULATION TREATMENT SYSTEM AT NAVAL SUPPORT FACILITY, INDIAN HEAD, MARYLAND

4.2.1 Background and Objectives

Site 47, the Mercuric Nitrate Disposal Area, at Naval Support Facility Indian Head, Maryland, consists of an upland area that encompasses several buildings and a drainage swale. For about 8 years, mercuric nitrate was used at Building 856 as a catalyst for the production of missile propellant. It was reportedly disposed on the west bank of the drainage ditch near the southeast corner of the building in which it was used (CH2M Hill, 2013). Carbon tetrachloride (CT) also was used at the site, likely as a drying agent for explosives, which may have leaked from drums or have been poured into drains discharging to the environment. These practices resulted in a groundwater plume containing mercuric nitrate and CT. Tetrachloroethylene (PCE) also is a primary COC found in groundwater, but its origin is unknown. Dense non-aqueous phase liquid (DNAPL) is suspected immediately south of Building 856 based on the high levels of CT and PCE measured in groundwater (CH2M Hill, 2013).

Soil consists of sand and silty sand from the ground surface to approximate depths of 7 to 24 ft bgs, depending on the surface elevation and location. Underlying the sand is dense, gray clay that is more than 30 ft thick. The water table ranges from about 6 to 8 ft bgs and flows to the southeast.

Remedial action objectives (RAOs) as established in the Record of Decision (ROD) included preventing unacceptable risks to human receptors from exposure to COCs in the shallow groundwater and preventing migration of shallow groundwater with unacceptable concentrations of COCs to uncontaminated media (Naval Facilities Engineering Command [NAVFAC], 2013a). To achieve these RAOs, ISCO was selected as the remedy. A pilot test was first performed to determine its efficacy at the site followed by full-scale implementation (CB&I, 2014).

4.2.2 Design and Application

The full-scale remedial action consisted of installing and operating two new horizontal extraction wells (HEW-1 and HEW-2) and 18 new and 24 existing vertical injection wells to introduce ISCO amendments and recirculate ISCO-amended groundwater (Figure 11). Using the existing wells and the new horizontal extraction wells prevented interference with mission-critical activities performed in the immediate vicinity of Building 856, shortened the duration of drilling and injection activities, and mitigated drilling challenges associated with the extensive network of utilities in the area (CH2M Hill, 2013).

Flow and transport modeling was performed to determine the screen lengths of the horizontal wells, appropriate locations to install them, and evaluate potential injection and recovery rates to ensure adequate distribution and mixing of the amendments within the treatment zone (CB&I, 2014).

The horizontal extraction wells were installed using the single-entry (blind hole) method to a depth of about 13.5 bgs.[4] Three-inch-diameter well screen and casing were used to construct each of the wells. The well material is reported as Schedule 80 PVC. The total length of Well HEW-1 was 177 ft and that of HEW-2 was 147 ft. Both wells were equipped with about 70 ft of casing (riser). HEW-1 was constructed with 109 ft of screen, while HEW-2 was constructed with 79 ft of screen. The screen consisted of 0.010-inch x 1.6-inch slots. Each well was flushed with a high-pressure jetting nozzle to remove residual drilling fluid and minimize clogging of the well screen. The wells were then grouted with a mixture of 95% Portland cement and 5% bentonite (CB&I, 2014).

Thirteen of the 18 vertical injection wells were installed to maximum depths ranging from 18 to 21 ft bgs, and 5 were installed to a maximum depth of 12 ft bgs. Injection wells were constructed from one-inch-diameter Sch. 40 PVC screen and casing. A total of about 5 tons of drill cuttings and about 1,700 gallons of purge/jetting water were generated during the installation of the horizontal and vertical wells.

[4] This represents the depth of the beginning of the screened interval, the entry angle of which was 16.5 degrees.

The ISCO amendments, consisting of about 205,000 lbs sodium persulfate (at an average concentration of 179 g/L) and 351,00 lbs of 25% sodium hydroxide, was mixed with extracted groundwater and injected in three groups, each consisting of 18 wells. Several wells were included in more than one group in order to introduce and recirculate a greater mass of amendments into areas known to contain high levels of COCs (CB&I, 2014). Groundwater was simultaneously extracted from the two horizontal extraction wells to help generate a flow gradient and improve amendment distribution across the treatment area.

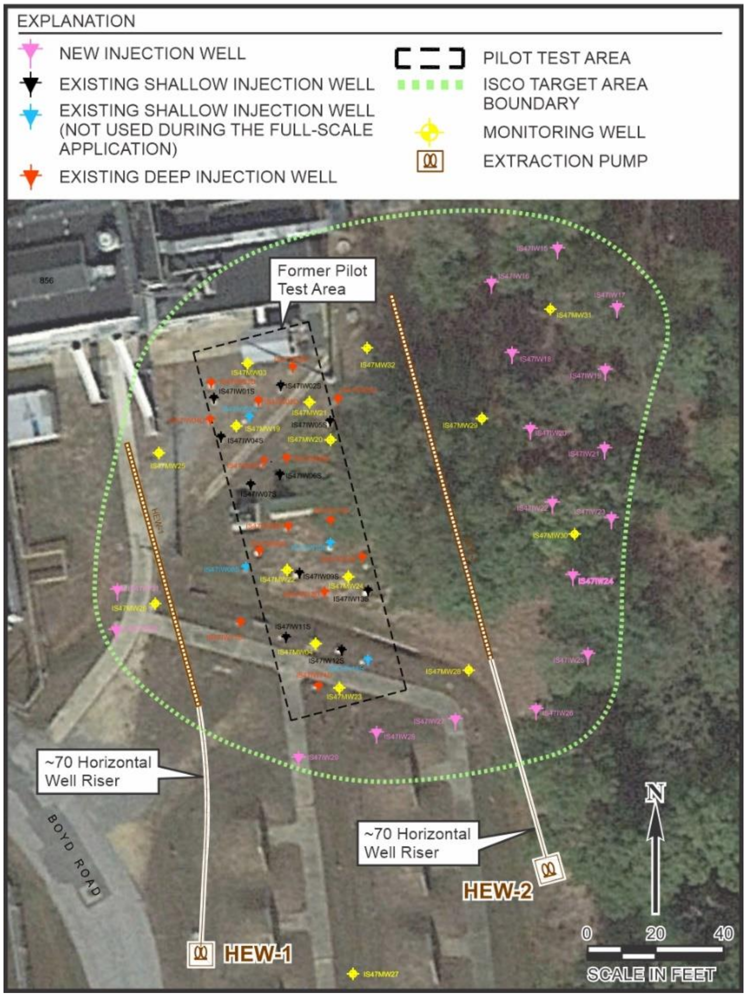


Figure 11. Full-Scale Horizontal Wells Installed at Naval Support Facility Indian Head

4.2.3 Results

Performance objectives were established as part of the design to help ensure adequate distribution of ISCO amendments within the treatment zone. These included achieving a minimum concentration of 10 g/L of persulfate and a pH greater than 10.5 in 75% of the monitoring wells located within the target treatment area, and obtaining a minimum concentration of 10 g/L of sodium persulfate and pH greater than 10.5 in the two horizontal extraction wells (CB&I, 2014).

An increase in pH was observed in all monitoring wells and 80% of treatment wells within the target area achieved a pH of at least 10.5, which is necessary for the alkaline activation of persulfate to occur. Similarly, sodium persulfate was detected in the majority (93%) of monitoring wells and a concentration of 10 g/L or greater was measured in about 77% of the monitoring wells indicating fairly good distribution, and just slightly less than the 80% performance objective. Additional monitoring data including changes in conductivity and ORP also were indicators that the amendments were fairly well distributed in the treatment zone.

The groundwater extracted from the horizontal wells occasionally exceeded the performance objectives of having a pH greater than 10.5 and a persulfate concentration greater than 10 g/L. However, readings were inconsistent, and oftentimes pH, persulfate, and other indicators (e.g., conductance and ORP) were low. These inconsistencies may have been a result of the time of day monitoring occurred, which set of injection wells was operating, formation/changing of preferential pathways in the subsurface, or a combination of these effects (CB&I, 2014).

Quarterly performance monitoring was initiated after the ISCO injection event and continues to the present. Monitoring consists of collecting groundwater and soil samples and analyzing chemicals of concern, total organic carbon (TOC), metals, persulfate[5], and occasionally other parameters (e.g., microbial composition, sulfate, sulfide), which have varied between monitoring events (CH2M Hill, 2019). Samples are collected from dedicated vertical monitoring wells. Samples have not been collected from the horizontal extraction wells.

Long-term monitoring has demonstrated a reduction of COCs (about a 57% reduction of CT), with the delineated plume smaller compared to baseline (e.g., prior to performing the ISCO injections [CH2M Hill, 2019]). However, chlorinated VOCs exhibit variable trends, some with decreasing concentrations, while others having increasing concentrations. Several factors are hypothesized to contribute to this result including: 1) there may be a DNAPL source within the treatment area acting as a continuing source to groundwater contamination, 2) persulfate may have been non-uniformly distributed during application due to heterogeneities in soil lithology and the formation of preferential pathways during recirculation, and 3) COC concentrations varied substantially within the treatment area and may not have been uniformly/adequately treated.

4.2.4 Lessons Learned

This case study illustrates the challenges associated with incorporating horizontal wells as part of a site remedy. The volume of groundwater that could be extracted from the horizontal wells was much less than anticipated. The extraction rate averaged about 5 gallons per minute (gpm) compared to a design rate of 38 gpm. Observation of air in the extracted groundwater indicated that the formation and wells were partially dewatered. Attempts to improve extraction included adjusting pump parameters, installing seals on the wells to improve vacuum, using a pulsed (on-off) extraction sequence, and reconfiguring foot valves; however, these modifications did not significantly improve the extraction flowrate (CB&I, 2014). To compensate for the low extraction flowrate, the ISCO reagents were added at a higher concentration to achieve the design mass in the aquifer. The lack of adequate extraction combined with the change in the design concentration of reagents introduced into the aquifer may have contributed to less effective distribution and treatment of COCs. Inadequate distribution of amendments in the area east of HEW-2 was confirmed based on pH results. Additional amendments were therefore injected into vertical injection wells to facilitate distribution in that area. Also, HEW-2 was converted to an injection well for the last two days of the application to facilitate introduction of amendments to the eastern portion of the site (CB&I, 2014).

Surfacing (daylighting) of groundwater was noted during application of amendments, which is a common occurrence at sites when water is introduced into the aquifer, regardless of the type of well (horizontal or vertical) used. Surfacing was mitigated by reducing the injection flowrate (and volume) into various wells. Daylighting may have been exacerbated by the inability to achieve the design extraction flowrate from the horizontal wells.

[5] Measurement of persulfate was discontinued after the 19-month monitoring event because prior measurements had indicated it had been consumed.

In summary, the horizontal extraction wells did not function as intended. The final construction completion report (CB&I, 2014) for this remedy recommended that if future data indicated additional ISCO injections are necessary, that the horizontal wells be replaced with vertical extraction wells and that additional injection wells be added to improve distribution of oxidant across the site. This case study highlights the importance of having a good understanding of the conceptual site model, in particular the lithology and hydrogeology. Changes in hydraulic conductivity along the length of the well and groundwater elevation can have a greater impact on the operation of a horizontal well compared to that of a vertical well and should be carefully considered during the design.

4.3 OPERATION OF A HORIZONTAL WELL BIOSPARGE SYSTEM AT ROBINS AIR FORCE BASE, GEORGIA

4.3.1 Background and Objectives

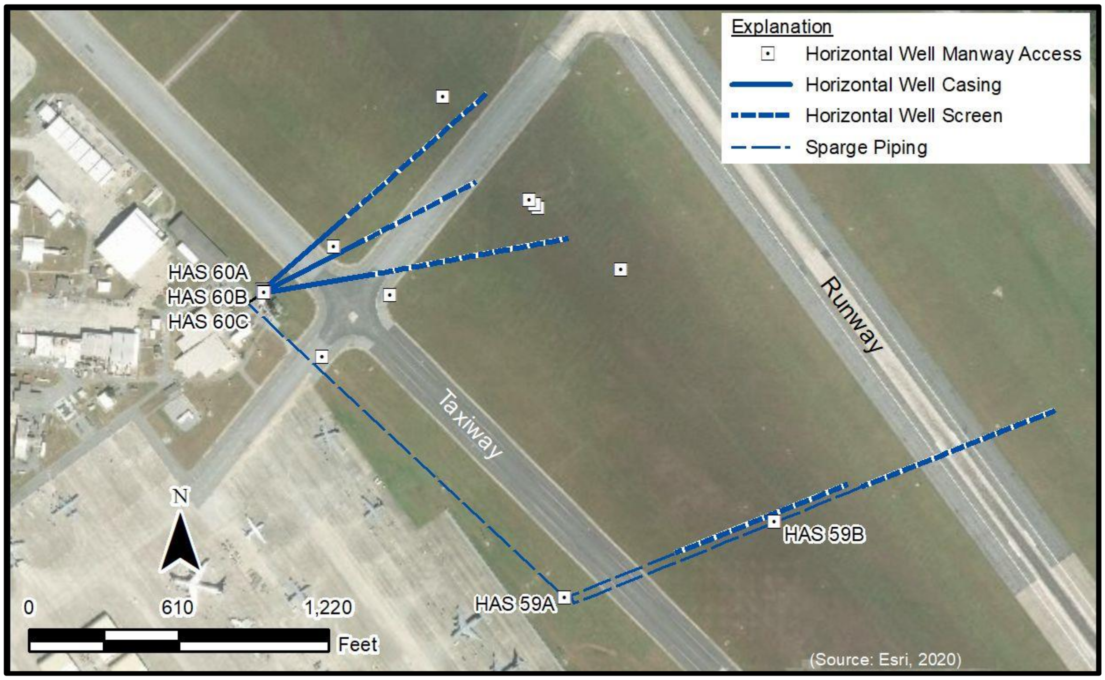
Solid Waste Management Units (SWMUs) 59 and 60 at Robins Air Force Base (AFB), Georgia contain two petroleum hydrocarbon plumes resulting from releases of jet fuel (JP-4 and JP-8) from pipes parallel to the airport taxiway. The plumes, which are ¼ and ½ mile long, occupy an area of about 56 acres and extend to a depth of about 65 ft bgs. Large portions of the plumes reside beneath active taxiways and restricted flight line areas. This existing infrastructure made the installation of horizontal wells more advantageous due to access restrictions. Site lithology consists of silty/clayey sand in the vadose and upper saturated zones, underlain by fine to medium sands and gravels interbedded with clay lenses. Depth to groundwater is about 12 ft bgs.

The corrective action consisted of biosparging performed by introducing air through horizontal wells. The objective was to reduce concentrations of dissolved-phase hydrocarbons, including benzene, toluene, ethylbenzene, and xylenes (BTEX) and 1,2,4-trimethylbenzene and 1,3,5-trimethylbenzene, to below their established site-specific remediation levels to achieve site closeout within five years (CH2M Hill, 2014).

4.3.2 Design and Application

The remedial design consisted of five 4-inch-diameter horizontal biosparge wells, three in the SWMU 59 plume and two in the SWMU 60 plume, generally installed perpendicular to the axis of the plume and groundwater flow (Figure 12). The wells were installed using a blind hole approach. Each well was approximately 1,200 ft long, with screened intervals ranging from 540 to 850 ft long installed between 50 to 70 ft bgs. The wells were constructed of Schedule 80 PVC casing and slotted screen sections.

Air was introduced through the wells at a flowrate that ranged from 200 to 300 standard cubic ft per minute (SCFM), at injection pressures varying from about 16 to 30 pounds per square inch (psi) using a continuous or pulse mode flow. Visual observations of air bubbling in various monitoring wells located up to 100 ft of the horizontal wells was an immediate indication of distribution of air within the treatment zone. Elevated concentrations (2 to 3 mg/L) of dissolved oxygen (DO) compared to baseline values (less than 1 mg/L) measured in monitoring wells further substantiated that adequate distribution of oxygen was occurring (CH2M Hill, 2014).



Source: CH2M Hill, 2014

Figure 12. Locations of Horizontal Wells at Robins AFB, Georgia

4.3.3 Results

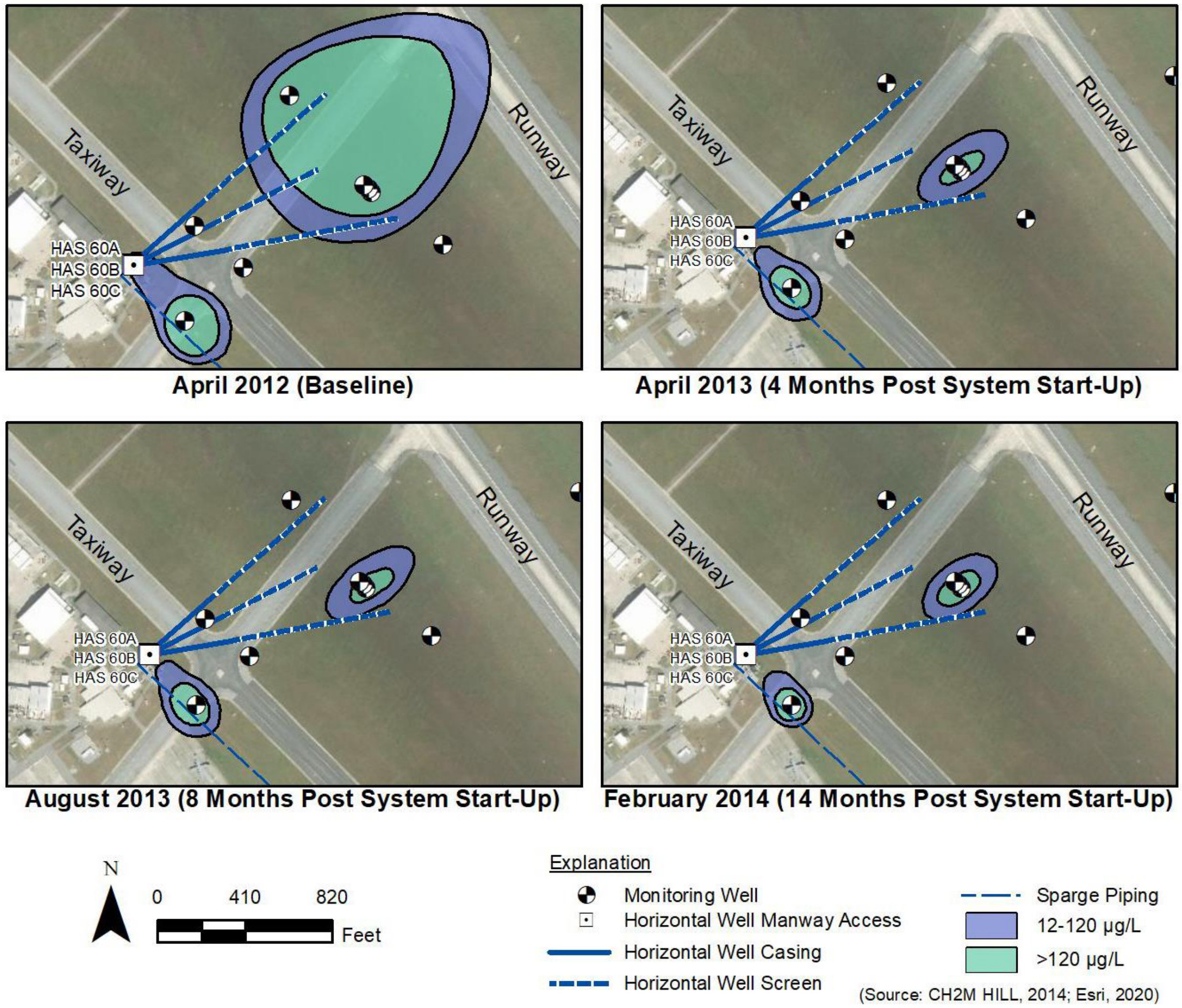
After approximately 14 months of operation, between 50 and 80 percent reduction of the COCs was realized (Figure 13). As noted above, increased concentrations of DO in groundwater indicated adequate distribution of air. In addition, elevated levels of carbon dioxide and methane measured in vapor samples collected from soil gas monitoring points provided a line of evidence that biodegradation was occurring.

4.3.4 Lessons Learned

Installation and operation of the horizontal wells was an effective treatment approach, eliminating interference with operation of the tarmac. The wells achieved effective distribution of air to promote biodegradation of the COCs within a relatively short period of time.

The blind hole boring approach was problematic due to flowing sands. Blind hole drilling requires that the drill head and associated rods be removed from the hole prior to reaming and installing the well. During removal of the drill materials, unexpected flowing sand collapsed the borehole, which encumbered the ability to ream and install the well materials. This challenge was overcome by using a proprietary technology developed by the driller that permitted the well materials to be introduced through the drill rods, so that when the rods were withdrawn the well screen and casing remained in place. This method can be used in boreholes that extend up to about 1,800 ft.

Surfacing and entrapment of air occurred beneath the concrete and asphalt tarmac, resulting in increased pressure in the subsurface and visible bubbling of air through cracks and seams in the runway materials. This challenge was addressed by installing soil gas probes and monitoring pressures combined with throttling and pulsing the injection air flowrate to alleviate excess pressure in the subsurface.



Source:CH2M Hill, 2014

Figure 13. Reduction of 1,2,4-Trimethylbenzene at SWMU 60

4.4 REDUCTION OF HEXAVALENT CHROMIUM USING A DEEP HORIZONTAL INJECTION WELL

4.4.1 Background and Objectives

The Puchack Well Field Superfund site is in Pennsauken Township, New Jersey. The primary COC in groundwater, hexavalent chromium (Cr^{6+}), resulted from nearby metal plating operations. The resulting plume resides in three distinct water-bearing units defined as the Middle Aquifer, the Intermediate Sand, and the Lower Aquifer, extending to a depth greater than 200 ft bgs (CDM Smith, 2016). The areal extent of the plume exceeding the New Jersey Department of Environmental Protection's (NJDEP's) Groundwater Quality Standard (GWQS) of 70 µg/L for total chromium was approximately 180 acres. The ROD for the site required that the plume containing Cr^{6+} in excess of the NJDEP GWQS be treated using an in situ geochemical fixation technology (CDM Smith, 2016).

Remediation of the site was conducted in two phases. The first phase consisted of introducing sodium lactate (a reducing agent[6]) through 166 vertical wells in open areas such as parking lots and public roads. Although introduction and distribution of the amendment was effective using the vertical extraction wells, the second phase of remedial activities required treatment in neighborhood areas having various access limitations including subsurface utilities, overhead power lines, small private lots, etc. Hence, a horizontal well was selected to overcome these limitations (Mason et al., 2018).

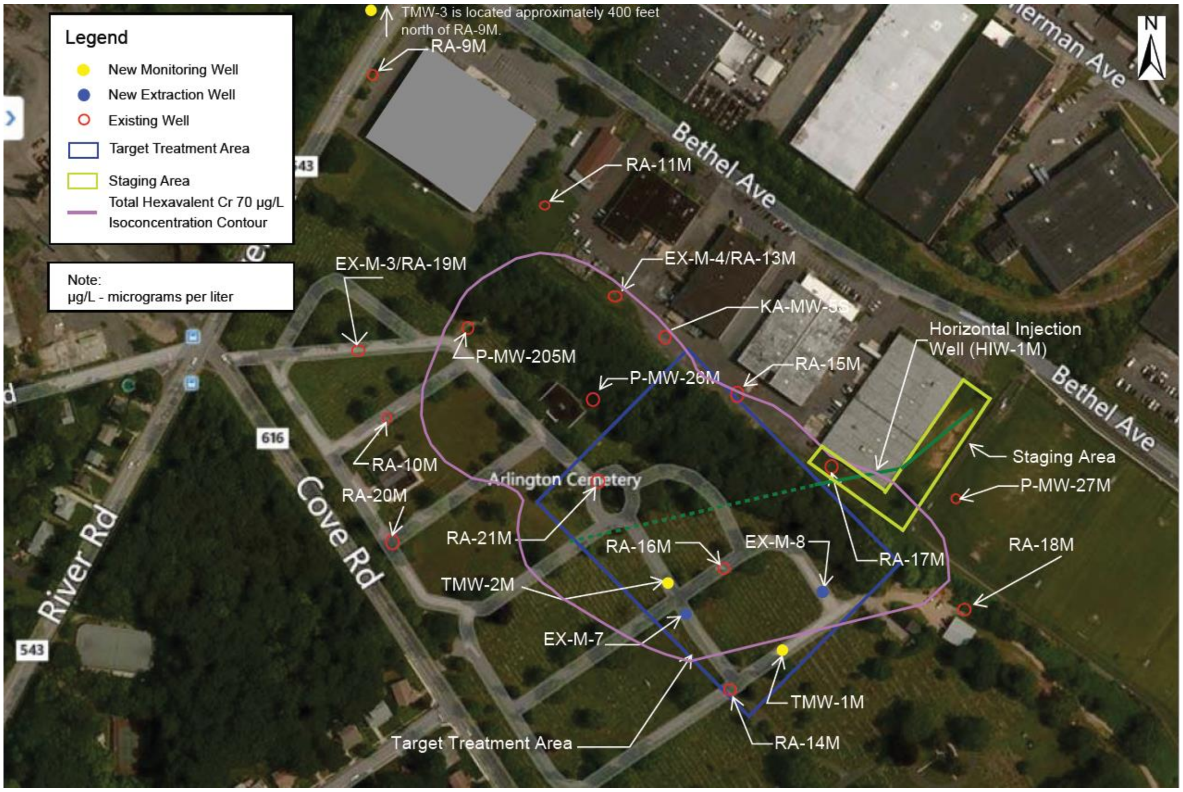
4.4.2 Design and Application

A pilot study was performed to evaluate the feasibility to introduce and distribute amendments through a horizontal injection well (Figure 14). A 4-inch-diameter horizontal well was installed from 90 to 100 ft bgs using the blind entry method. The total length of the well was 830 ft, including a 450-ft long section of slotted screen. The well was installed perpendicular to groundwater flow using a gyroscopic steering tool to guide the drill head. Two vertical wells were installed to extract the water that would be amended with the sodium lactate and introduced into the aquifer through the horizontal well. Two additional vertical wells were installed for monitoring treatment efficacy.

Engineering calculations were performed that consider the density and viscosity of the injected fluid, anticipated injection flowrate and pressure, and soil conductivity to design a slot size and interval that would facilitate uniform distribution of the injected fluid across the length of the well screen (Mason et al., 2018). This specialized design was necessary since there was a high likelihood that a greater fraction of the amended liquid would exit the horizontal well in the portion of the slotted screen closest to the injection pump if the slots were consistent across the length of the pipe. The final design incorporated a consistent opening width but extended the length of each slot over the length of the screened interval, resulting in the cross-sectional area of the slots ranging from 0.0155 to 0.0160 square inches per foot of screen (Mason et al., 2018).

A solution of about 260,000 lbs of 60% sodium lactate was mixed with the extracted water to form a solution of about 16,000 mg/L. The solution was introduced through the horizontal well at a flowrate of approximately 150 gpm (Mason et al., 2018).

[6] Degradation of the lactate by microorganisms results in a reduction of ORP and pH, which provides the conditions necessary to reduce Cr^{6+} to trivalent chromium (Cr^{3+}), which has limited solubility in groundwater and is less toxic.

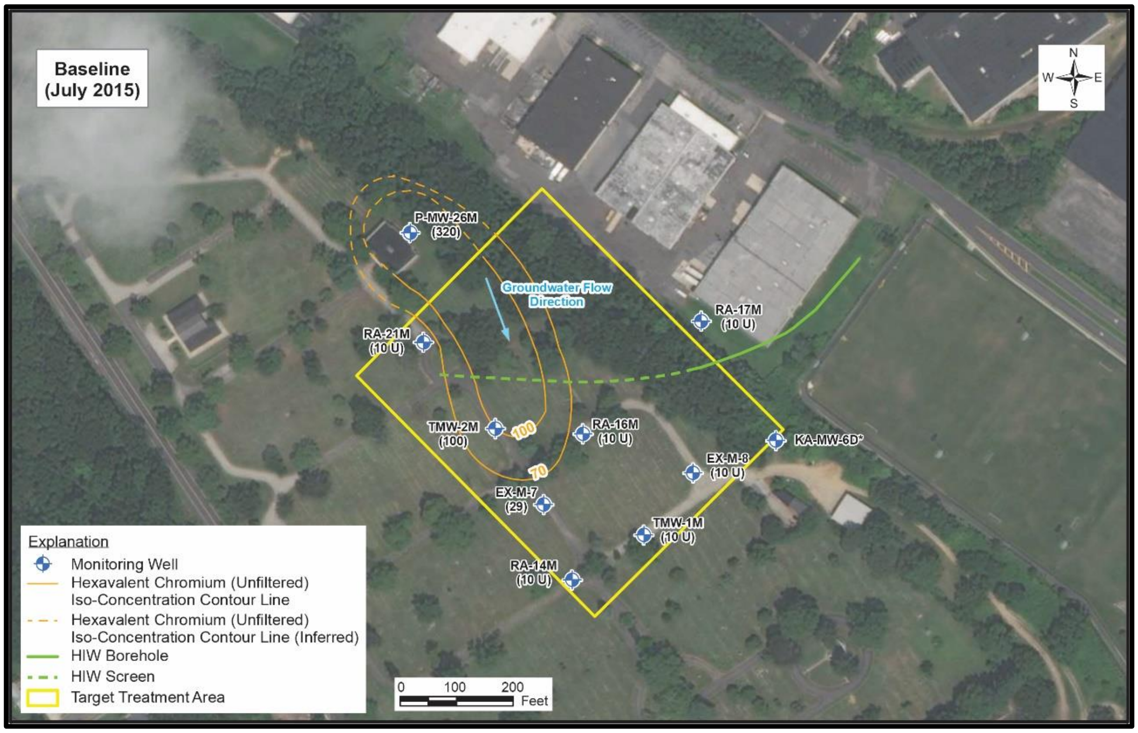


Source: Mason et al., 2014

Figure 14. Horizontal Well Pilot Test Layout at the Puchack Well Field Superfund Site

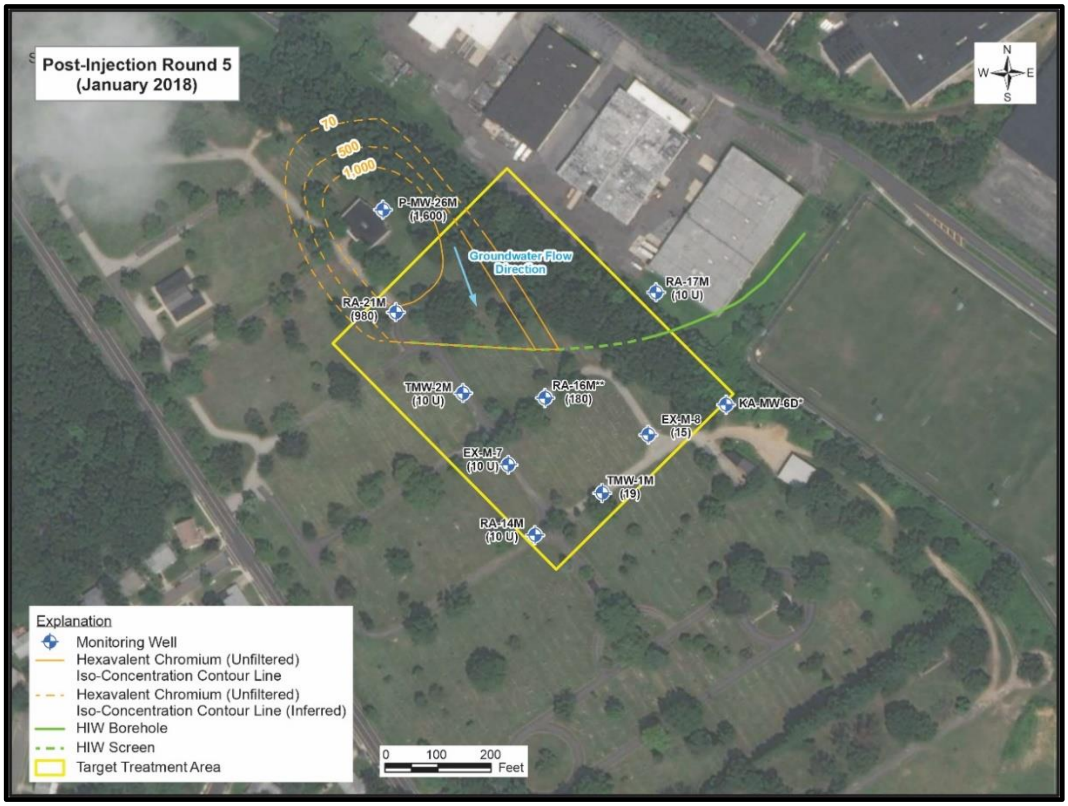
4.4.3 Results

Performance monitoring during the pilot test included measuring concentrations of COCs (Cr^{6+} and Cr^{3+}) in monitoring wells, total dissolved solids (TDS), groundwater quality parameters (pH, ORP, DO, temperature, turbidity) and chemical oxidant demand (COD), at 3, 9, 15, 22, and 29 months after introducing the lactate solution into the aquifer. A comparison of baseline data (Figure 15), prior to introduction of the sodium lactate to post-injection data (Figure 16) indicates that the amendments introduced into the aquifer through the horizontal well created a barrier perpendicular to groundwater flow that effectively reduced and immobilized the chromium contamination. However, TDS and COD data indicated that the lactate was not evenly distributed along the length of the plume, but nonetheless was distributed to a degree that achieved treatment across the cross section of the plume.



Source: Mason et al., 2014

Figure 15. Baseline Chromium Concentration Data

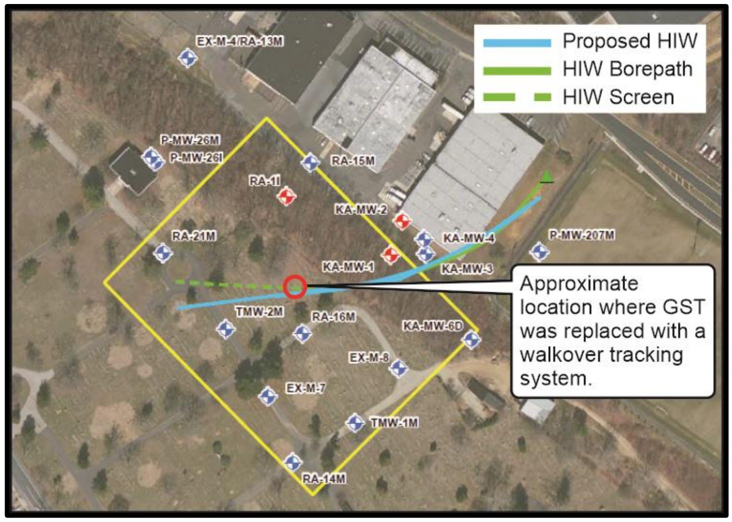


Source: Mason et al., 2014

Figure 16. Hexavalent Chromium Approximately 2.5 Years after Completing Injections

4.4.4 Lessons Learned

Injection of amendments through the horizontal well created a chemical barrier perpendicular to groundwater flow that effectively reduced and removed chromium from the groundwater as the groundwater passed through the treatment zone. Designing the screened section of the horizontal well with a variable slot size facilitated distribution across the treatment zone; however, uniform distribution was not achieved, with data indicating a greater portion of the injected solution entering the aquifer in the portion of the screen closer to the pump compared to the portion of the screen more distant (Figure 17).



Source: Mason et al., 2014

Figure 17. Deviation of Design versus Actual Well Location due to Positioning Error

It is important to design the fluid extraction system with sufficient capacity to provide the required flowrate to the injection system. The flowrate into the horizontal well was limited by the flowrate that could be extracted from the vertical extraction wells, which may have impeded uniform distribution of fluids into the horizontal well. Larger extraction pumps and/or more extraction wells may have alleviated this issue.

The gyroscopic positioning tool was a very accurate, but an expensive method to monitor the position of the drill head. However, changes in formation material interfered with operation of the tool. Therefore, the tool was replaced with a knock-off bit equipped with a magnetic transmitter and the walkover method was applied. The walkover method was less accurate, which resulted in a deviation of about 55 ft from the design (horizontal) endpoint. However, the well was installed accurately to the design depth.

The drilling fluids, which included a polymer to facilitate drilling and a solution to adjust pH, was difficult to manage and had to be disposed as investigation derived waste (IDW).

It is necessary to have sufficient aboveground space, unobstructed by site infrastructure to install the horizontal well. For this application, the driller prepared the full length of well casing and installed it continuously as a single unit.

5.0 SUMMARY

The DoD has used horizontal wells for a wide range of remedies including EISB, ISCO, ISCR, NAPL recovery, AS, SVE, and steam injection to facilitate progress toward achieving remedial goals. A main advantage of horizontal wells, and often a deciding factor for using them in lieu of vertical wells, is site access restrictions. Horizontal wells generally can be installed easily beneath infrastructure that may preclude the use of vertical wells. However, their high installation cost may make them a less attractive option at many sites. Although a single horizontal well can be installed in lieu of multiple vertical wells, which potentially can result in reduced life-cycle cost of the remedy. Table 3 provides a summary of advantages and limitations, which should be carefully considered prior to deciding to utilize them at a site.

Table 3. Summary of Advantages and Limitations of Horizontal Wells for Remediation Applications

Advantages	Limitations
Results in minimal disturbance to ground surface and operations	Difficult to place filter pack. Pre-packed screens may be required.
Can be installed under structures that cannot be compromised (e.g., buildings, tarmacs)	Very sensitive to change in groundwater table elevation
Can be designed to contact a larger horizontal surface area of contaminated media (optimum for thin plumes) and therefore have a large zone of influence	Can create a large volume of solid waste and development water based on total length of well
May achieve greater fluid flowrates due to larger screen area depending on aquifer conditions	Underground utilities and other structures can interfere with installation if not possible to steer around them
Can be oriented to take advantage of plume direction and orientation	May not be applicable for recovering LNAPL at sites with large groundwater table fluctuations
	Installation costs are generally greater than costs to install vertical wells, making horizontal wells best suited for areas where it is not technically practical to install vertical wells.

It is important to have a detailed understanding of the conceptual site model. The design of the well, the method of installation, and how it is operated is directly impacted by lithology, hydrogeology, depth of contamination, and presence of aboveground structures. These can be deciding factors for using horizontal wells in lieu of vertical wells. A summary of key findings important lessons learned pertaining to the installation and operation of horizontal wells are described in the remainder of this section.

5.1 INSTALLATION OBSERVATIONS

- A large open area is required for the drill rig and to store the IDW that is generated during installation of the well. The volume of IDW generated during installation of a horizontal well can be significant.
- Changes in lithology can impact the direction of the drill head. Care must be taken to ensure that the direction does not deviate significantly from the design.
- Electrical utilities can interfere with the receiver of some drill bit locating techniques. If utilities are present, a compatible method should be discussed with the driller and equipment manufacturer.
- Well casing and screen may be easily damaged during installation if the borehole is not reamed to sufficient size and/or the turning radius of the borehole is too small.
- Using the blind hole method, there is a possibility that the borehole can collapse as the drill head is removed from the hole prior to installing the well screen and casing. The surface to surface method eliminates this problem since the well casing and screen can be introduced through the exit location as the drill rod and head are pulled back and retrieved from the hole.
- Hydra-lock can occur during back reaming when drilling fluid becomes trapped in the borehole as the reamer is being removed. The resulting pressure must be relieved to remove the pipe (NAVFAC, 2013b).

5.2 OPERATION OBSERVATIONS

- It is difficult to achieve uniform introduction or removal of fluids into/out of long lengths of horizontal well screen. Specialty designed screen may improve the ability to achieve uniform introduction or removal of fluids; however completely homogeneous introduction or removal may not be possible, especially across long lengths of screen. Specialized horizontal drilling firms and screen manufacturers should be consulted during the design process to ensure a suitable screen design is selected based on project objectives and the type of remedy applied.
- Recirculation systems must consider extraction and injection flowrates to ensure that the volume of water injected is balanced with the water that can be extracted (or vice versa). For instance, if the volume of water extracted is less than the design volume to be injected, the injection flowrate will need to be reduced or pulsed, both of which could adversely impact the ability to achieve uniform introduction and distribution of fluids through the well screen and into the aquifer.
- As with vertical wells, fouling can occur in horizontal wells. However, it is more difficult to address fouling in horizontal wells due to their long screen length. Although methods are available to address fouling, such as brushing and jetting of fluids ranging from water to anti-fouling agents, these activities result in increased time and cost to the project.
- Surfacing (daylighting) of groundwater/amendments can occur while injecting into horizontal wells. However, this issue is not limited to horizontal wells, and occurs during introduction of fluids into vertical wells. Adjusting the injection flowrate and pressure can help to alleviate the problem. Recirculation systems also help to reduce surfacing since fluids are removed from the aquifer at approximately the same flowrate that they are introduced.

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