ESTCP

EXECUTIVE SUMMARY

Vertebrae™ Segmented Horizontal Wells for Monitoring PFAS Mass Discharge

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ESTCP Project ER20-5026

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ACRONYMS AND ABBREVIATIONS

A-DTS	active fiber optic distributed temperature sensing
AFFF	aqueous film-forming foam
DoD	U.S. Department of Defense
DTS	distributed temperature sensing
ESTCP	Environmental Security Technology Certification Program
EVS	Earth Volumetric Studio
GAAF	Grayling Army Airfield
HDD	horizontal directional drilling
HDPE	high-density polyethylene
HPT	hydraulic profile tool
IDW	investigation-derived waste
ITRC	Interstate Technology & Regulatory Council
K	hydraulic conductivity
PFAS	per- and polyfluoroalkyl substances
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonate
RSD	relative standard deviation
SWTT	single-well tracer test
VAP	vertical aquifer profile
VWS	Vertebrae™ well system

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1.0 INTRODUCTION

Chemical of concern mass flux/discharge estimation is challenging because it requires high-resolution measurements of both chemical of concern concentrations and groundwater flux, which can be highly variable spatially due to orders of magnitude variations in concentration and hydraulic conductivity in short distances. Mass flux can also vary through time due to seasonal flow system dynamics, water supply well operations, and remediation activities. Therefore, technologies that provide repeatable, high-resolution mass flux/discharge datasets that can efficiently target the important zones within heterogeneous plumes are needed to optimize remediation performance and determine when to transition to less aggressive technologies and long-term monitoring.

Of the methods that are available to measure chemical of concern mass flux/discharge, the transect method is probably the most insightful and commonly used because it couples with characterization (Guilbeault et al. 2005; Einarson et al. 2010; Interstate Technology & Regulatory Council [ITRC] 2010; Einarson 2017). Traditionally, the transect approach involves vertically drilled permanent or temporary (i.e., snapshot) borings, well clusters, or multiport systems oriented perpendicular to groundwater flow across a groundwater plume. However, this approach can be costly because it requires many individual vertical boring locations (which requires surface access) given typical high spatial variability in plumes, and many hundreds of feet of drilling with uncertainty in the horizontal direction between vertical locations. This is especially important if the target interval is relatively deep or requires high vertical resolution monitoring or sampling at each location along the transect. Direct chemical of concern flux approaches such as passive flux meters (Annable et al. 2005; Klammler et al. 2007) are also generally applied at high spatial resolution along monitoring transects, typically using vertical deployments and conventional wells rather than multiport systems.

The conventional transect method for characterizing chemical of concern mass flux relies on a series of temporary or permanent vertical monitoring points providing data in vertical profiles along a transect across the entire plume, perpendicular to groundwater flow (ITRC 2010). The monitoring points are sampled to provide concentration data across the control plane at appropriate lateral and vertical spacing to capture the plume concentration distribution (boundaries and internal variability). An appropriate method for measuring groundwater flux at similar high resolution is also required and the combined groundwater concentration and flux data are used to assess chemical of concern mass flux/discharge across the transect (note: this is focused on the mobile groundwater phase and water phase, and does not capture mass stored as sorbed phase within the plume, which can be significant in many lithologies and relevant to site management decisions). The purpose and scope of this project was to demonstrate the Vertebrae™ well system (VWS), a next-generation, segmented, nested horizontal well technology (Koenigsberg et al. 2018) for monitoring changes in chemical of concern mass flux/discharge emanating from source zones and high-concentration areas through time (Figure ES-1, below). During the past decade, more than 200 VWSs have been installed in the field for general plume monitoring, remediation fluid injections, air sparging, and soil vapor extraction; however, they have not been specifically designed to monitor mass flux/discharge and have not previously been used for per- and polyfluoroalkyl substances (PFAS) chemicals of concern.

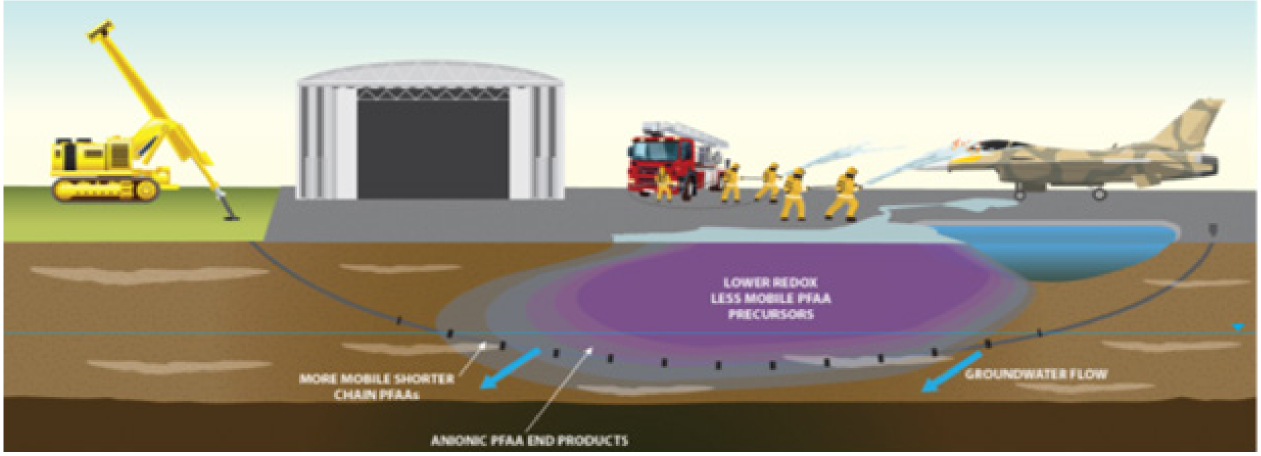

Figure ES-1. Conceptual Depiction of a Vertebrae™ Well System Measuring PFAS Mass Flux/Discharge.

Further development of the application of the VWS technology will benefit the U.S. Department of Defense (DoD) and the environmental community at large because it will contribute to advancement with both cost and effectiveness in understanding chemical of concern mass flux/discharge in site assessment, remediation, and monitoring. In particular, the VWS will enable precise and repeatable monitoring of mass concentrations and discharge with intervals oriented to intersect zones with high concentrations/flux emanating from complex source zones through time, support more reliable risk assessment, remedy performance assessment and optimization, and transition from active to passive remedies. The technology is applicable to many types of groundwater impact; however, it offers particular potential for monitoring mass discharge changes from PFAS sources through time. Scaled up across the portfolio of DoD sites, this could result in significant total savings for remedy implementation through: more reliable characterization; better risk assessment, flux-based decision making, and remedy design; and operation with improved performance monitoring.

2.0 OBJECTIVES

The overall goal of this project was to demonstrate and validate the Vertebrae™ horizontal multiport well system as a technology for reliable long-term monitoring of chemical of concern mass flux/discharge from PFAS source zones. Specific performance objectives are presented in Table ES-1, below.

Table ES-1. Performance Objectives.

Performance Objective	Data Requirements	Success Criteria	Success Criteria Achieved?
Quantitative Objectives			
1. Accurate and reliable placement of screens in subsurface.	Bore-path drilling navigation data, and post-installation geophysical survey data.	Eighty percent (%) of all drilling navigation data agree within 1.5 foot (elevation) of the bore path elevation and 80% of the as-built data agree within 1.5 foot of the planned target depth elevations.	**Yes** Six of six screens along horizontal section were within 1.5 vertical feet of the target elevations and positions.

Table ES-1. Performance Objectives. (Continued)

Performance Objective	Data Requirements	Success Criteria	Success Criteria Achieved?
2. Validate methods for groundwater flux measurement with VWSs.	Hydraulic conductivity, hydraulic gradient, tracer test data, active fiber optic distributed temperature sensing (A-DTS) data.	Complete successful field testing of methods. For each method, estimates that are repeatable (±25%) and agree with the averages from all the methods within 25% according to an analysis of variance statistical test (within 25% at an 80% confidence).	**Yes** Both the A-DTS and single-well tracer test methods were considered to have achieved success for this performance objective, based on modified criteria.
3. Assess comparability of samples collected from VWS screens to grab samples.	Concentration data from Vertebrae™ screens and co-located vertical cores/wells or groundwater grab samples.	Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) concentrations measured from the Vertebrae™ screens agree within 1 order of magnitude for at least 75% of co-located grab samples.	**Yes** Sample results from the VWS were consistent with conventional sampling methods.
4. Demonstrate method to identify appropriate mass flux zones to target Vertebrae™ placement.	All currently existing hydraulic, hydraulic profile tool, and groundwater grab sample concentration data as well as additional high-resolution data developed during the pre-design investigation.	Achieved if a relationship between pre-design data availability and the predicted mass discharge measured from the resulting VWS designs can be developed, and if this relationship indicates the VWS design will yield a mass discharge estimate within ±25% of the estimated derived from other data.	**Partially** A clear relationship between data used and the calculated mass discharge was developed via a practical method. However, the analysis did not yield results that agreed within ±25%.
5. Validate VWS application for quantifying mass flux/discharge along transects.	Mass flux/discharge estimates normal to groundwater flow for VWSs and conventional vertical borings/ wells installed along a nearby transect. These estimates will be derived from PFAS concentration data and darcy flux values determined from hydraulic testing, tracer testing, the A-DTS.	Mass flux/discharge estimates with VWSs agree with conventional approaches within 25% with equal or lower uncertainty estimated through propagation of uncertainty statistical techniques.	**Yes** None of the methods meet this statistical level, however, this may have been an unrealistic success criterion. The average results for both the hydraulic profile tool (HPT) and distributed temperature sensing (DTS) agreed with the Earth Volumetric Studio (EVS) result within an order of magnitude and event-to-event variability was similar for all of the methods. This implied that the differences in methods were related more toward a systemic consistent bias rather than precision and repeatability. Consequently, the results supported the use of VWS for PFAS mass discharge estimation.

Table ES-1. Performance Objectives. (Continued)

Performance Objective	Data Requirements	Success Criteria	Success Criteria Achieved?
6. Verify materials' compatibility with PFAS.	Rinsate blank and PFAS stock solution samples after contact with VWS components.	PFOS and PFOA are less than the United States Environmental Protection Agency maximum chemical of concern levels of 4.0 nanograms per liter in rinsate blank samples and PFAS loss from the sample due to sorption to well materials is less than 10% or the analytical precision (whichever is greater) for each tested compound.	**Yes** The VWSs could be tested prior to production for certification to be free of primary PFAS analytes.
Qualitative Objectives			
1. VWS can assess chemicals of concern and conditions along the flow path in a longsect configuration.	Chemical of concern concentrations data from longsect VWS, monitoring wells, and vertical aquifer profile samples.	PFAS concentration data collected from different screen intervals located progressively downgradient follow discernable and consistent trends, indicating the samples represent locations along a constant flow path.	**Yes** Samples from the VWS were generally consistent with other sample types and exhibited high spatial correlation.
2. Demonstrate integrity of grout seals to isolate individual screen segments.	Pressure data from injection tests and A-DTS temperature data measured under passive and active (heated) conditions.	Pressure data do not show clear evidence of seal failure and A-DTS data delineate continuous seals that are at least 5 feet long between each well screen.	**Yes** Grout seals in the horizontal section were placed where intended and were largely functioning as intended (hydraulic separation).
3. Identify challenges and limitations of VWSs.	Feedback from drillers, installation, and monitoring personnel and project technical staff.	Challenges and limitations are understood and can be readily mitigated.	**Yes** No implementation or operational challenges were identified that would limit widespread application.
4. Assess robustness of the technology.	Feedback from geologists and field staff regarding observed ruggedness and performance of screens, sampling ports, connections, and other well components.	No fundamental design flaws/limitations identified, and no systemic problems experienced during installation and sampling.	**Yes**

3.0 TECHNOLOGY DESCRIPTION

The VWS is a single, small-diameter horizontal well that contains multiple isolated screen segments as individual ports, each with a small-diameter tube connected to ground surface. Essentially, it is an engineered multiport well that is installed horizontally instead of vertically (Figure ES-2, below). The VWS can provide another transect method option as a complement or alternative to the conventional vertical installation transect option. The VWS is unique, with many discrete screen zones running horizontally along its length and separate, small-diameter tubing plumbed from each screen to the surface. Grout, which is tremied in, is used to isolate the individual tailor-designed screen intervals. The VWS technology can be applied as a variation of the conventional transect approach.

The difference is that the monitoring points are installed horizontally instead of vertically, with improved coverage along the width of the plume at targeted depths with highest concentrations or flux, but with generally lower vertical resolution due to practical limits on placing multiple systems at different depths. The VWS approach is novel and advantageous because multiple closely-spaced measuring points across a transect can easily be installed from a single boring (reducing costs) and chemical of concern zones that may have been previously inaccessible via vertical boreholes can be characterized. Currently, detailed geologic information is not readily available during the drilling process; therefore, an accurate understanding of chemical of concern distribution within the site hydrostratigraphy from high-resolution characterization using direct-push methods or vertical borings to obtain profiles is required to optimize placement of the horizontal wells and to select target intervals for the monitoring zones.

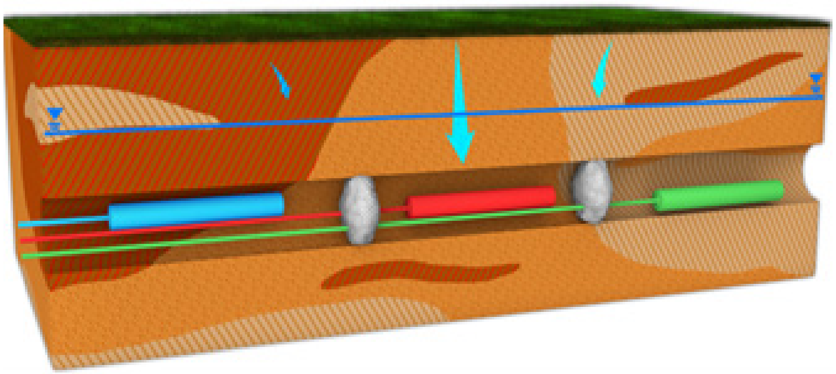

Figure ES-2. Vertebrae™ Well System (VWS).

The VWS contains multiple screen segments separated by grout seals with independent connections to the surface. It can be thought of as a nested well installed horizontally.

VWSs are installed using horizontal directional drilling (HDD), which is a mud rotary drilling process that uses a specialized rig and asymmetric bit to drill a curved borehole along a predetermined bore path and the prefabricated VWS is pulled into the borehole (Figure ES-3, below). The VWS is a multiport horizontal well that has been installed with as many as 18 discrete screened zones (however, these values are not upper limits; additional screened zones are feasible). To date, VWS wells exceeding 900 feet long and 45 feet deep have been installed, but longer and deeper wells with currently available drilling technology are feasible. The VWS can be thought of as a nested well with small-diameter tubes installed horizontally instead of vertically. Individual screen lengths range from 3 to 30 feet with separate 0.5–1.5-inch-diameter tubing plumbed from each screen to the surface. Multiposition monitoring along horizontal paths can be more efficient because it is aligned with hydrologically significant zones within and at the boundaries of aquifers parallel to layering typical of sedimentary facies. Grout is used to isolate the individual screen intervals within the horizontal well (shown on Figure ES-2, above) and reliable placement is key to effective installations tested herein. EN Rx, Inc. has developed a proprietary grout seal mixture to increase elasticity, longevity, and sealing efficiency to isolate the intervals in each horizontal boring. The VWS is compatible with all common chemical of concern types and has been used at sites with PFAS (this project was the first site where the VWS was deployed for monitoring PFAS), petroleum hydrocarbons, chlorinated solvents, metals, and high salinity.

Figure ES-3. Photographs of the Installation of the VWS.

Left: horizontal directional drilling and mud pit. Middle: asymmetric drill bit. Right: Preconstructed VWS immediately prior to pullback into the borehole.

4.0 PERFORMANCE ASSESSMENT

The data collected as part of this project were evaluated to determine if the success criteria for specific quantitative and qualitative performance objectives presented in Table ES-1, above, were achieved. This section discusses the assessment of each performance objective.

Quantitative Performance Objective 1: Accurate and Reliable Placement of Screens in Subsurface

This performance objective was intended to:

- Assess the reliability of bore-path navigation data for documenting as-built completion.
- Verify that the VWS can be successfully installed at planned target depth intervals.

The following data were collected to evaluate accurate and reliable placement of the VWS screens:

- A walkover locating system was used to track the position of the drill head. The position of the drill head was marked when an additional drill rod was added to the drill string (every 10 feet).
- The locations of the screens at the shallow and deep transects were determined using radio frequency inductive line tracing with a multifrequency transmitter and receiver.

The coordinates were then used to calculate vertical differences for comparison to the success criteria. The goal was to install the VWS within 1 foot of the planned target depth. However, there were inherent limitations in the accuracy of depth measurements collected during and after directional drilling. For these reasons, depth measurements during (drilling navigation data) and after VWS installation (geophysical methods) had an inherent irreducible uncertainty of +/- 0.5 foot. Therefore, the depth accuracy of +/- 0.5 foot was added to the goal of +/- 1 foot, resulting in the overall target tolerance limit of 1.5 feet.

The differences between the measurements were within the tolerance limit of +/- 1.5 feet for all six horizontal screens. The two screens on the slopes (one at each end) of the shallow transect were omitted due to decreased accuracy of the walkover locating system when drilling at an angle from horizontal. When drilling at an angle, the three signals (front, back, and center sight) emitted by the sonde traveled a longer distance to the receiver at the surface, which decreased the accuracy. A future recommendation (see Section 9 of the full report) was to avoid placing screens on the sloped portion of the wellbore, due to decreased locating accuracy. In addition, the angled screen orientation increased the potential for grout intrusion into the screen, which is another reason to avoid installing screens at an angle. *Based on the discussion above, the performance objective related to accurate and reliable placement of VWS screens in the subsurface is considered achieved.*

Quantitative Performance Objective 2: Validate Methods for Groundwater Flux Measurement with VWSs

This performance objective was intended to assess the reliability and usefulness of several different methods for measuring groundwater flux across a VWS. Groundwater flux across the transect was measured by multiple independent methods. The first method used hydraulic conductivity (K) estimated from hydraulic tests completed during hydraulic profile tool (HPT) in the VWS well screens and the measured site hydraulic gradient according to Darcy's Law. The second method was based on groundwater flux directly measured from single-well tracer tests (SWTT). The third method used data from active fiber optic distributed temperature sensing (A-DTS). Because the DTS system was only installed along the shallow transect, the groundwater flux and flow calculations for each method were compared for only the shallow zone.

Figure ES-4 (left), shows the average screen segment flows (average of eight monitoring events) for each of the primary comparison methods (HPT, SWTT, and A-DTS). Figure ES-4 (right) shows total transact calculated flow for each monitoring event. For comparison, this figure also shows average flows calculated using K-estimates based on size analyses from soil core samples ("Grain Size") and geostatistical-based (i.e., kriging) model of K-distribution based on all available K information at the site. The results-based HPT data were notably lower than the other two methods for all segments and events. It was likely that for the Grayling Army Airfield (GAAF), this was a biased-low method because the range for most K measurements at the GAAF (Figure 34, 30 to 300 ft/day) were near the approximate upper method limit for HPT testing (approximately 50 to 100 ft/day). Therefore, the HPT method was not considered reliable for the GAAF; however, it may be appropriate for sites with lower hydraulic conductivity.

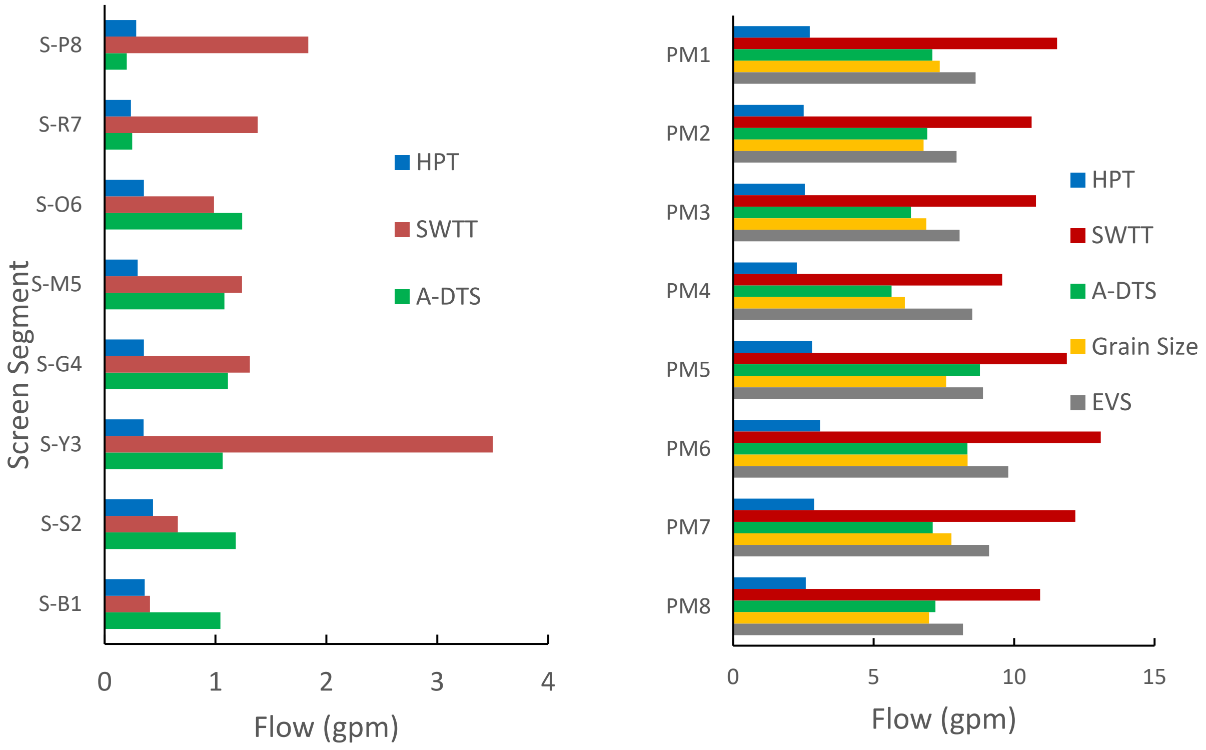

Figure ES-4. Average Screen Segment Flows (left) for HPT, SWTT, and A-DTS, and Total Transact Calculated Flow for Each Performance Monitoring Event (PM1, PM2, etc.) for All Methods (right).

The results for the DTS and SWTT methods were similar for some screen segments and monitoring events, however, there were some screen segments where the SWTT method was up to twice as high as the DTS method. Based on the highly uniform K distribution at the site, it was unlikely that much higher permeability zones existed at those screens, and rather the SWTT method may have been less reliable or biased high at these locations. In the Demonstration Plan (Divine et al. 2021c), it was proposed that success would be evaluated individually for each of the three methods and the performance objective would be considered to be achieved if:

- Repeated flux estimates for a specific method had an average relative percent difference (RPD) of <±25%.
- If through application of statistical analysis of variance, the result for a specific method agreed within 25% at an 80% confidence with the average of all methods.

If one method was determined to have failed, its result were excluded from the average. The relative standard deviation (RSD) for total transect flow across all eight monitoring events was similar, 14 and 10% for the DTS and SWTT methods, respectively. Because the HPT data were considered biased low, this second component of the success criteria could not be evaluated as stated. It was believed that some SWTT results for individual screens may have been biased high because the low geologic heterogeneity was expected to result in more uniform values across screen sections; however, conclusive data were not available requiring that the SWTT results be considered less reliable than the HPT results. Therefore, both methods were considered reliable and application of an averaging and complimentary approach likely resulted in the best estimate for the GAAF.

Based on modified criteria, both the DTS and SWTT methods were considered to have achieved success for this performance objective.

Quantitative Performance Objective 3: Assess Comparability of Samples Collected from VWS Screens to Grab Samples and Conventional Monitoring Wells

This performance objective was intended to demonstrate that the groundwater samples collected from VWS screens were comparable to groundwater samples collected by conventional sampling methods commonly used in site characterization investigations, such as grab (e.g., vertical aquifer profile (VAP)) samples obtained from direct-push drilling systems and samples from vertical monitoring wells. This performance objective was defined to confirm the overall representativeness of samples collected from the VWS and still accommodate irresolvable variances that may have been the result of plume spatial variability caused by small-scale aquifer heterogeneity and flow system, and source variability and inherent differences in sampling methods.

Samples were collected quarterly from each individual screen in each VWS. These results were compared to nearby co-located groundwater samples from vertical borings and multilevel or conventional monitoring wells. These included one-time VAP grab samples collected as part of the prior Environmental Security Technology Certification Program (ESTCP) project at the GAAF (ER19-5203) and this ESTCP project. New multilevel and conventional wells installed during this project were also sampled multiple times. Sampling of these wells coincided with sampling of the VWSs.

The high-resolution groundwater data generated from the previous ESTCP project at the site (completed in 2019) were evaluated to provide a basis for the success criteria for this performance objective. Numerous borings were installed previously, and VAP groundwater samples were collected from six to eight discrete intervals for each boring, generally between 15 and 50 feet below ground surface. Because the interval between 20 to 30 feet was the most important, the RSD of all samples collected from this interval was calculated for each boring. In general, RSD values ranged from less than 10% to more than 100% and appeared to be independent of concentration magnitude. The average RSDs for PFOA and PFOS were 77 and 73%, respectively. Considering the uncertainty and limitations of the data, the average RPD for these data for the target interval was estimated to be 80%. In general, sample results from the VWS were consistent with conventional sampling methods. The average RSDs for PFOA and PFOS were 59 and 62% (less than the goal of 80%), range from 1 to 182%, and appeared to be independent of concentration magnitude. *This comparison confirmed the overall representativeness of samples collected from VWSs and the criteria for this performance objective were considered achieved.*

Quantitative Performance Objective 4: Demonstrate Method to Identify Appropriate Mass Flux Zones to Target VWS Screen Placement

This performance objective was intended to assess the practical and cost-effective use of prior site information and pre-design vertical characterization data to design a VWS that was optimally placed and would yield reliable chemical of concern mass flux/discharge information. Data used to support the assessment of this performance objective included all previously existing HPT and VAP groundwater grab sample concentration data as well as additional high-resolution data collected during the pre-design investigation. These data were incorporated into the existing 3-D site model (EVS model) used in a complimentary effort to design the placement locations of the VWSs.

The VWSs were designed to yield mass discharge estimates that agreed with the results from the EVS model which included all other available site data. This evaluation was specifically considered in quantitative performance objective 5.

To understand the amount of pre-design necessary to support a reliable design, a bootstrapping-type exercise was performed. PFOS mass discharge was calculated using all site data (i.e., 100% of data) and then some data were sequentially removed and PFOS mass discharge was recalculated. The predicted mass discharge values from these alternate designs were calculated and compared. These results are shown in Figure ES-5. The y-axis represents the calculated PFOS mass discharge values for each model normalized to the value from the 100% model. This was a practical approach whereby a relationship between the amount of pre-design data available and the predicted mass discharge measured from the resulting VWS design could be developed. As seen in Figure ES-5, similar PFOS mass discharge values were estimated when 100, 90, 80, and 60% of all available data were used. More significant variation was observed when 40 and 20% of the data were used. This implied that more than enough pre-design data were available to support the VWS design. This performance objective was considered partially achieved because a clear relationship between data used and the calculated mass discharge was developed via a practical method. However, the analysis did not yield results that agreed within ±25% of the mass discharge estimated independently from the other available site data (e.g., on Figure ES-5, below, calculated relative mass discharge values between 0.75 and 1.25). The average results from the HPT, DTS, and SWTT methods yielded results of 1.4, 1.6, and 6 respectively. However, as discussed further in quantitative performance objective 5, the ±25% target was likely overly and unnecessarily optimistic given the geologic complexities and concentration variability. As such, this performance objective may still be considered achieved.

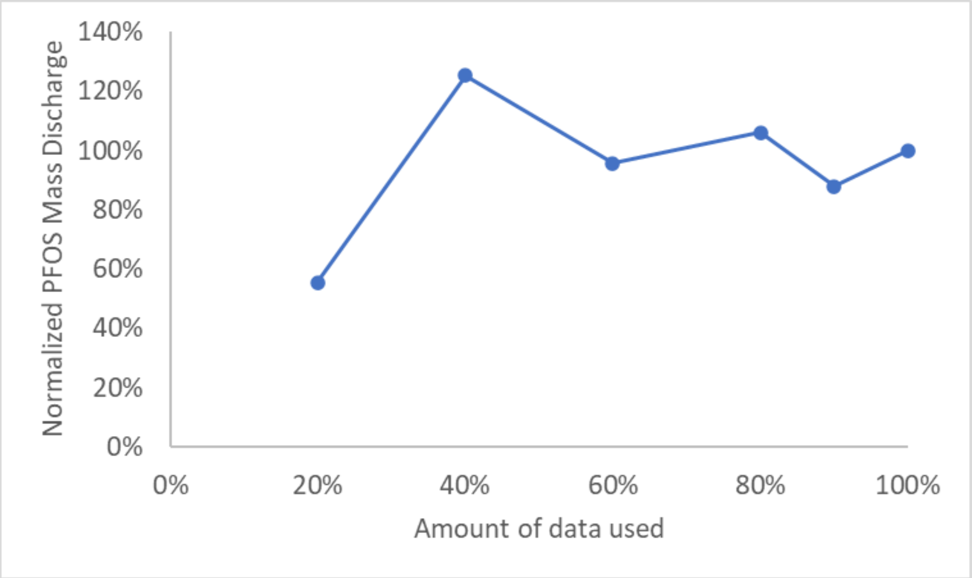

Figure ES-5. Relationship between the Amount of Available Data used and Calculated PFOS Mass Discharge.

Quantitative Performance Objective 5: Validate VWS Application for Quantifying Mass Flux/Discharge Along Transects

This performance objective was intended to verify the reliability of using VWS transects to measure PFAS mass flux/discharge. Mass flux/discharge normal to groundwater flow were calculated for the transect VWSs using groundwater samples collected from VWS well screens and the different measures of Darcy flux attributed to each of the screen zones (hydraulic testing, point-dilution tracer testing, A-DTS). These estimates were compared to mass discharges estimates developed from geostatistical modeling of hydraulic conductivity data from conventional vertical borings/wells installed along the same transect (most of these data were developed under prior ESTCP project ER19-5203 and were supplemented with new data collection) and PFAS concentrations measured in VWSs for each performance monitoring event. These analyses were completed in EVS and an example of the calculated PFOS mass flux distribution is shown on Figure ES-6, below (the hydraulic conductivity field is depicted in greyscale and the mass discharge distribution is depicted in color flood with the high values corresponding to warmer colors).

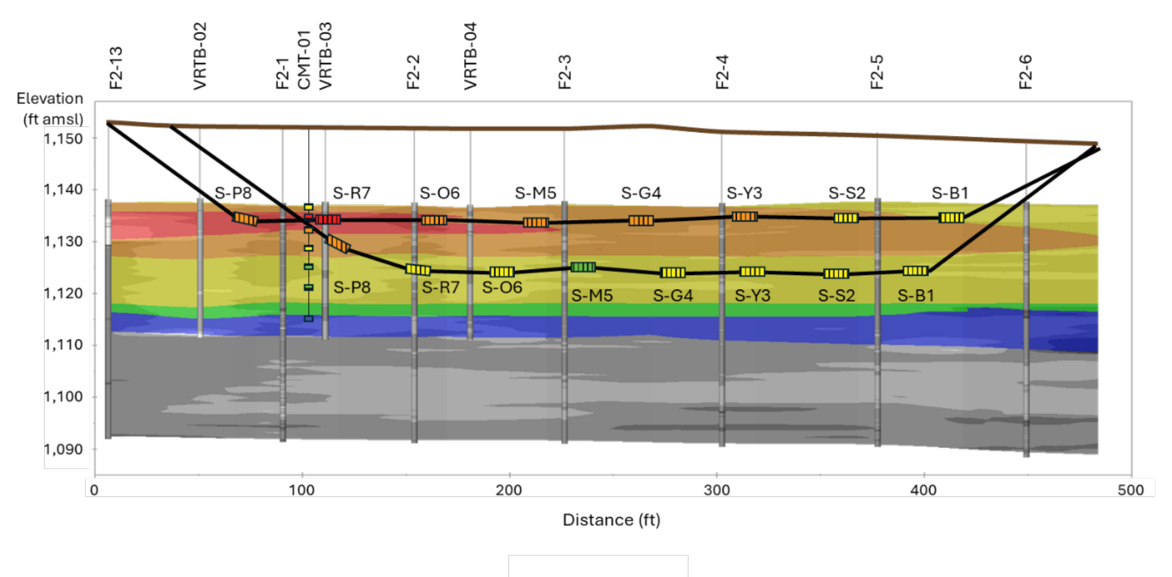

Figure ES-6. Example EVS Calculated PFAS Mass Flux Distribution for Performance Monitoring Event #2.

The average PFOS mass discharge estimates for each method and for each monitoring event ranged from 58 to 326 mg/day (0.21 to 0.12 kg/year). Although the EVS-based method utilized the most site geological data, it should not necessarily be considered the "gold standard" since its results w highly dependent on geostatistical parameter values and associated data interpolation. This method consistently yielded some of the lowest values, suggesting some other methods (especially SWTT) may have provided estimates with a high bias. Regardless, the average results for both the HPT and A-DTS agreed with the EVS result within a factor of 2, and all methods fell within a factor of 3 agreement envelope (see Figure ES-7). Furthermore, the event-to-event variability, as measured by the RSD was similar for all of the methods (with EVS being the highest), ranging from 20 to 56%. This implied that the differences in methods were related more toward a systemic consistent bias rather than precision and repeatability.

In practice, remediation decisions were not made from specific mass discharge values or single estimates, but rather from trends in mass discharge over time. As such, all methods appeared to be reliable for this application. In most cases, estimating mass discharge from several methods would increase confidence in estimated values and provide insight regarding uncertainty of the estimates. Overall, the results supported the use of VWS for PFAS mass discharge estimation by multiple independent methods.

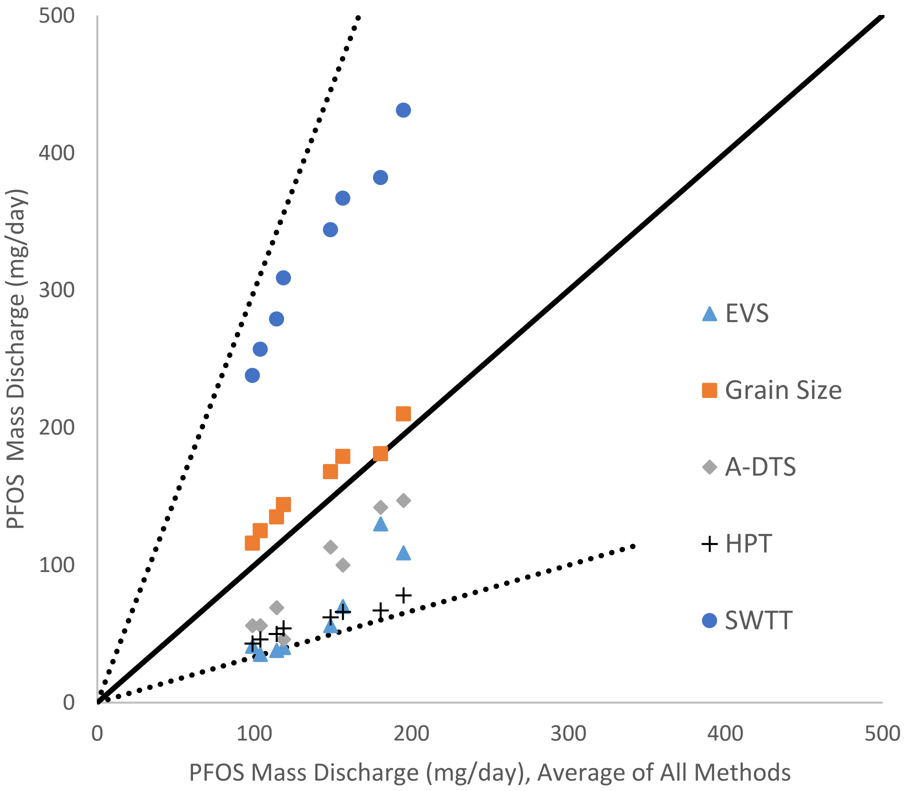

Figure ES-7. Comparison of PFOS Mass Discharge Estimates for Each Performance Monitoring Event to the Average Value for Each Method.

The solid line represents 1:1 correlation and the dotted lines represent an agreement envelope of a factor of 3.

Quantitative Performance Objective 6: Verify Material Compatibility with Per- and Polyfluoroalkyl Substances

This performance objective verified the expectation of PFAS compatibility based on previous published work and assessed the key components of the Vertebrate™ system that were in direct contact with sampled water.

Laboratory-based experiments were completed and focused on key VWS components including the sock polyester geotextile screen wrap, high-density polyethylene (HDPE) screen, and HDPE riser tubing. Specifically, rinsate experiments (passing clean water over system components to document no significant PFAS leaching) and soaking experiments (soaking key system components in a known PFAS solution to document no significant PFAS mass loss) were completed.

The criteria for this performance objective were considered achieved. No obvious signs of positive or negative bias that would affect data usability were identified. Based on the data collected in this study, the VWSs could be tested prior to production for certification to be free of primary PFAS-type analytes. In addition, sorption of PFAS to VWS materials was measured indirectly, and the results did not indicate the VWS materials were a significant sink for PFAS. *Therefore, leaching and adsorption biases were not practical to consider as interference when using VWS and the criteria for this performance objective were considered achieved.*

Qualitative Performance Objective 1: VWS Can Assess Chemicals of Concern and Conditions Along the Flow Path in a Longsect Configuration

Both the absolute concentrations of PFAS species and their relative abundance (i.e., concentrations of individual PFAS species relative to each other) may change along the flow path due to PFAS transport and fate properties, geochemical conditions, and release/source mechanisms. A longsect VWS configuration that is oriented along a groundwater flow path orientation may be useful for assessing these conditions and monitoring changes through time. This performance objective was intended to assess the feasibility and usefulness of a longsect VWS configuration.

This performance objective was assessed using PFAS concentration data collected from the longsect VWS and compared to data along the flow path collected using vertical data collection methods (i.e., VAP samples and samples from multilevel and conventional wells). An eight-screen 477-foot-long VWS was successfully installed in a longsect configuration along an inferred groundwater flow path from the source area in a south-southeast direction. The average PFOS and PFOA concentrations from the longsect VWS and nearby VAP and conventional vertical monitoring wells were compared. In general, both the PFOS and PFOA data showed consistency between the sampling methods and followed a general trend where the first several measurements were similar (approximately 1,100 to 2,700 ng/L for PFOS and 30 to 102 ng/L for PFOA) and then increased by more than 10 times for PFOS (up to 13875 ng/L) and more than 5 times for PFOA (up to 239 ng/L) approximately 240 feet downgradient. Concentrations then declined somewhat at 275 and 310 feet downgradient. Also, the relative concentrations of primary PFAS species along the inferred flow path distance were consistent. The general consistency of VWS data with other sample types and the smoothness of the trend (i.e., high spatial correlation) suggested the well screens were located approximate along a common flow path and that VWS systems could be used to characterize chemical of concern concentrations in this way, and to assess chemical of concern transport processes along the flow path. *As such, the success criteria for this performance objective were considered achieved.* However, this application of VWSs will be more challenged at sites with significant geologic heterogeneity and variable flow direction.

Qualitative Performance Objective 2: Demonstrate integrity of grout seals to isolate individual screen segments

This performance objective was intended to confirm the integrity of the grout seals separating each well screen segment of the VWS. Seal integrity prevents groundwater from short-circuiting along the well bore and is necessary for sample quality and reliability as well as reliability of hydraulic tests in the screen intervals. Data from two independent methods were used to assess this performance objective.

A pressure transducer was inserted in VWS screen segments and water was added to adjacent screen segments to detect pressure increases from hydraulic tests in adjacent well screens. No hydraulic response was noted in individual screen segments from pressure changes in adjacent screens. The A-DTS system was used to measure temperature under passive and active (heated) conditions from the well bore. Because the different well materials (e.g., grout seals, sediments) exhibited a contrast in thermal conductivity, the position and continuity of seals along the full VWS length were mappable. Thermal response could be quantified two ways: temperature above background during curing and apparent thermal conductivity from A-DTS test. Pressure transducer data did not show clear evidence of seal failure or poor seal construction (e.g., immediate increase in pressure greater than 1 foot of head) during injection testing in adjacent screen intervals. The A-DTS data delineated continuous seals that were at least 5 feet long (mean 13 feet, maximum 20 feet) between the five horizontal screens for the shallow VWS. *Overall, grout seals in the horizontal section appeared to be placed where intended and were largely functioning as intended (hydraulic separation), as such, this performance objective was considered achieved.*

Qualitative Performance Objective 3: Identify Challenges and Limitations of VWSs

This performance objective aimed to gather existing practical site implementation and operational considerations to help guide the design of VWSs for monitoring PFAS mass flux/discharge for other sites. Surveys from project personnel involved in installation and system operation, monitoring, sampling, and hydraulic testing were conducted to document implementation challenges or practical considerations throughout the project. Drilling and installation challenges were assessed based on site geologic and hydrogeologic conditions, and experience with the HDD required for the VWS installations.

This performance criterion was considered successfully achieved because no significant implementation or operational challenges were identified that would limit widespread application of the VWS technology at a broad range of aqueous film-forming foam (AFFF) PFAS sites. Key lessons learned from this field demonstration included:

- Avoid installing screens at an angle.
- Limit entry/exit angles to prevent tight bends in VWSs.
- Irresolvable uncertainty in confirming as-built vertical borehole location resulted in a minimum target thickness of 1 to 1.5 feet.
- Currently evaluating alternative grout delivery methods such as a mechanical seal or other means to ensure more precise placement of grout seals.
- Well materials/construction significantly affect hydraulic test results.
- Understanding seasonal water table fluctuations will be important at PFAS sites due to the potential for PFAS to accumulate near the air-water interface. VWS screens installed in high-flux zones near the water table could become dry when groundwater levels decline.

Qualitative Performance Objective 4: Assess Robustness of the Technology

This performance objective assessed robustness of VWS components to identify if there were design flaws or limitations that should be addressed before the VWS technology is applied at other AFFF PFAS sites. Feedback was obtained from geologists and field staff regarding observed ruggedness and performance of screens, sampling ports, connections, and other well components. Key responses included the following:

- Feeding sampling tubes can be challenging; dedicated tubing is recommended to simplify sampling.
- Specialty fittings are required for tracer and slug tests.
- Tight bends may inhibit flow and should be avoided where the well risers enter the well vaults.
- Based on discussion with drillers it may be possible to obtained geologic information after the pilot borehole has been installed using nuclear magnetic resonance imaging geophysical sonde that is pulled through the borehole (e.g., Spurlin et al., 2019). This could be used to confirm geologic interpretations before final VWS design and installation.

This performance criterion was considered successfully achieved. No fundamental design flaws/ limitations were identified, and no systemic problems were experienced during installation and sampling. As of August 2023, more than 200 VWSs had been installed. Lessons learned from previous installations and this ESTCP project will be used to continue improving the design, installation, and sampling processes.

5.0 COST ASSESSMENT

All costs associated with design, installation, and monitoring of VWSs were tracked during the demonstration project. A simple cost model is presented in Table ES-2, below, and serves as general guidance for estimating the costs of installing VWSs. The costs did not include predesign characterization activities or performance monitoring and data analysis because their costs were highly site-specific and dependent on project objectives. For the VWS systems, the model was based on actual costs for this project and assumed three VWSs with a total length of 1,390 feet, eight screens per VWS (for a total of 24 screens), and one stand-alone horizontal fiber optic cable (for DTS).

Table ES-2. Cost Model for Installation of Three VWSs.

Cost Element – VWS	Data Tracked During the Demonstration	Unit Cost	Unit	Quantity	Cost
Materials: VWS components	Three VWSs with total length of 1,390 feet.	$103,000	Lump sum	1	$103,000
	Risers and grout lines: 0.75-inch HDPE.				
	Well screens: 1-inch-diameter HDPE with geotextile screen. Eight screens per system for a total of 24 screens.				
	A-DTS fiber optic cables.				
	Tracer wire: copper clad steel wire.				
Installation of VWSs	Utility locating and surveying.	$105,000	Lump sum	1	$105,000
	Drilling equipment mobilization.				
	Drilling, reaming, and well installation.				
	Well development.				
	Grout well seals.				
	Flush-mount vaults.				
Waste disposal	Waste characterization: analytical costs.	$3,000	Lump sum	1	$3,000
	Solid and liquid waste disposal: container rental, transportation, disposal.	$30,000	Lump sum	1	$30,000
Total (VWSs only)					**$241,000**

The costs unique to the VWS are the well materials, with most components made of HDPE. For a typical VWS, the well materials will be roughly 50% of the installation costs (excluding waste disposal for drilling wastes). The cost of well materials have risen during the last couple of years due to high inflation rates and global supply chain issues. It is difficult to predict how material costs will change in the coming years. Most remediation professionals are already familiar with the primary factors that influence vertical drilling costs. Most of these same factors also influence costs associated with the HDD method used to install VWSs. Several variables impact VWS installation costs and each design is customized based on the objectives of the given project. The main cost drivers of the VWS technology are as follows:

- *Number of VWSs*. Unit costs for installation of a single VWS will be higher due to costs of mobilizing the directional drilling rig and associated equipment. The unit costs decrease when installing multiple VWSs.
- *Number of VWS segments and diameter*. A larger number of segments results in higher cost of well materials (dedicated riser and grout lines to each screen), additional time installing grout seals between the segments, more well development effort, and higher waste disposal costs due to the larger volume of liquid waste produced.
- *VWS length and depth*. Well length and depth have a significant impact on the overall installation costs because they strongly affect drilling and materials costs. For longer wells, larger investigation-derived waste (IDW) volumes are generated during drilling and reaming operations.
- *Lithology*. Difficult drilling conditions such as dense soils and cobbles result in slower drilling and therefore higher drilling costs. Drilling through bedrock and formations that are prone to flowing sand conditions (and resultant borehole instability) will also cause costs to increase.
- *HDD navigation*. A walkover locating system is most often used during installation of the VWSs. At some project sites, walkover locating may not be applicable due to electromagnetic interference, lack of access above the drill head, or drilling depth greater than approximately 70 feet. Expanded features for walkover tools have reduced the interference, and features like drill-to-box allow some avoidance of commons interference; however, at some sites, interference can require alternatives. In these cases, a more expensive wireline navigation system would be required.

The specific requirements, scale and geometry of each application will vary. However, product capabilities and limitations can provide a typical application scenario and scalability when examining the cost. To start, drilling speed in typical lithologies is approximately 300 to 400 feet per day (ft/day). Thus, a 300- to 400-foot well system can generally be installed in 2 days (1 day for drilling and 1 day for installation and development). Well systems significantly shorter than 300 feet cannot necessarily be installed in considerably less time, and cost per foot increases appreciably. From this point of 300 feet or greater to the maximum length of typical sleeve sizes (800 to 1,200 feet) the costs are approximately linear. Beyond this distance, rig sizes and sleeve changes increase costs significantly. Also, the well screen spacing and screen length are proportional to the plume width and, at these typical spacing distances, are practical and only marginal and linear cost increases are experienced over the total distance. A typical and scalable design with an estimated drilling and materials cost of $150,000 is summarized below (oversight and IDW disposal is excluded as these are varied conditions):

- A site with sandy to silty soils with a water table depth of 10 feet.
- Two VWSs installed with 1,000 feet total of drilling, providing either stacked or multiple transect positions. A total of 20 well screen positions.
- Risers (¾ inch) for probe and tracer access, with a 4-inch sleeve.
- A 20-foot installation depth, with little to no interference for locating tools.
- Standard vaults and finishing requirements.

- Straightforward drilling conditions, with no rock or other obstructions, and standard drilling mud blends.
- Mobilization of drilling equipment within the region.

6.0 IMPLEMENTATION ISSUES

VWSs are most advantageous for poorly accessible plumes. The subsurface zones beneath buildings, flightlines, and other operational obstructions, including natural obstructions (e.g., ponds, forested areas) can be accessed from alternate surface positions using this technology. However, for optimal design and to maximize the performance of this technology, the following key pre-qualifications and considerations are suggested:

- The concentrations and lithology of the plume should be well-understood.
- Previous penetrations, well installations, and other vertical environmental equipment should be considered as obstacles for the VWS installation. A buffer distance between the VWS and previous penetrations is recommended at 5 feet or greater.
- Depths greater than 60 feet may require additional setbacks and larger drilling equipment. Depths greater than 100 feet likely will require additional specialized tracking equipment.
- Utilities at the beginning and end of the bore must be properly marked and at known depths anywhere the depth of the bore is less than 10 to 15 feet.
- Walkover electromagnetic drill bit locating is used along the entire bore length; however, interference often exists inside buildings and other obstacles.
- VWSs are custom built and generally require 4 to 8 weeks for processing, construction, and shipping.

7.0 REFERENCES

Annable, M.D., Hatfield, K., Cho, J., Klammler, H., Parker, B. L., Cherry, J. A., Rao, P.S.C. 2005. Field-scale evaluation of the passive flux meter for simultaneous measurement of groundwater and contaminant fluxes. Environmental Science & Technology, 39(18), 7194-7201.

Divine, C., K. Hasbrouck, J. Wright, P. Curry, B. Parker, S. Chapman, C. Maldaner, J. Munn, L. Robinson, and S. Koenigsberg. 2021c. Draft Demonstration Plan, Vertebrae™ Segmented Horizontal Wells for Monitoring PFAS Mass Discharge. Version #2. September.

Einarson, M.D., D.M. Mackay, and P.J. Bennett. 2010. Sampling Transects for Affordable, High-Resolution Plume Characterization and Monitoring. Ground Water, 48(6), 805-808.

Einarson, M.D. 2017. Spatially averaged, flow-weighted concentrations – a more relevant regulatory metric for groundwater cleanup. Groundwater Monitoring & Remediation, 37(4), 11-14.

Guilbeault, M.A., B.L. Parker, and J.A. Cherry. 2005. Mass and flux distributions from DNAPL zones in sandy aquifers. Groundwater, 43(1), 70-86.

ITRC. 2010. Use and Measurement of Mass Flux and Mass Discharge. MASSFLUX-1. Washington, D.C.: Interstate Technology & Regulatory Council, Integrated DNAPL Site Strategy Team. www.itrcweb.org.

Klammler, H., K. Hatfield, M.D. Annable, E. Agyei, B.L. Parker, J.A. Cherry, and P.S.C. Rao. 2007. General analytical treatment of the flow field relevant to the interpretation of passive fluxmeter measurements. Water Resources Research, 43, W04407.

Koenigsberg, S.S., E.R. Piatt, and L.I. Robinson. 2018. New perspectives in the use of horizontal wells for assessment and remediation. Remediation, 28:45–50. https://doi.org/10.1002/rem.21575.

Spurlin, M., B., Cross, B., Barker, C., Divine. 2019. Nuclear magnetic resonance logging: Example applications of an emerging tool for environmental investigations. Remediation, 29:63-73.