The Ozark Underground Laboratory's

POINT VELOCITY PROBE HANDBOOK

A handbook prepared for the use of clients and colleagues of the Ozark Underground Laboratory

2021

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Introduction

The Ozark Underground Laboratory (OUL)

The Ozark Underground Laboratory, Inc. (OUL), is a private consulting and contract studies firm specializing in groundwater tracing and other hydrogeological services. The OUL is under the direction of Tom Aley, President and Principal Hydrogeologist, and has been in continuous full-time operation for over 48 years. We are not affiliated with any academic institution, and we have no academic responsibilities which could interfere with full client service. The OUL has designed and either conducted, or assisted with, over 4,000 groundwater traces on every continent except Antarctica. More recently, the OUL has expanded services to include assistance to clients who wish to use Point Velocity Probes in problem-solving investigations. This handbook is a fundamental part of providing these services. Our clients include environmental and engineering firms, other corporate and private entities, and federal, state, and local agencies.

OUL Services for Point Velocity Probe Related Studies

The goal of OUL in providing support for Point Velocity Probe (PVP) related studies is to assist clients and colleagues in conducting high-quality problem-solving investigations with an emphasis on attention to detail. To do so, the OUL will utilize the same approach successfully applied to the consulting work focused on dye tracing investigations for over 48 years.

PVPs provide direct measurements of groundwater velocity and flow direction. They have been developed as a result of over a decade of research and associated field testing. The author of this handbook, Trevor Osorno, has been directly involved in this research and development of the PVP family of tools as part of his masters and doctoral work and joined the OUL in 2020 as a Senior Staff Hydrogeologist. He has over 7 years of experience in the development and field application of PVP related tools on industrial and research sites worldwide and has provided numerous on-site trainings, webinars, and short courses on multiple aspects of groundwater velocity characterization efforts. Therefore, the OUL is well qualified to provide study design, on-site training for data collection, training on data analysis and interpretation, and to provide professional data analysis, quality assurance, and reporting as needed for PVP related investigations.

Solinst Canada Ltd. has recently begun the commercial manufacturing of the PVP family of tools, and the OUL is working with them to further develop and expand the use of these instruments in solving hydrological problems. The Solinst probes are sold as individual units that require assembly prior to deployment. The OUL has the expertise to advise clients on the most appropriate units and sampling designs for addressing the needs of their projects. The OUL also provides services necessary for assembly and field verification of the individual units. This ensures that OUL clients receive field-ready devices, shipped to their field sites, ready for deployment with the accompanying documentation required for analysis. The OUL can also address the data reduction analysis needs and questions of our clients.

Purpose of this Document

This document a companion document to the Ozark Underground Laboratory's Groundwater Tracing Handbook and is to be used as a practical reference on the PVP family of tools for our clients and colleagues. It:

- Includes information on the utility of direct groundwater velocity measurements.
- Provides detailed descriptions of all the tools within the Point Velocity Probe family.
- Provides case studies where PVP measurements proved to be useful.
- Provides directions to published works where additional, more in-depth information is available.

Why Direct Groundwater Velocity Measurements?

Three common questions of a groundwater investigation are:

- Where does the water go?
- How long does it take to get there?
- What happens along the way?

A detailed discussion of the importance of groundwater velocity measurements and a review of groundwater velocity measurement techniques can be found in "Groundwater Velocity" by J.F. Devlin, available for free download as a part of the Groundwater Project (https://gw-project.org/books/groundwater-velocity/) (Devlin, 2020).

Briefly, groundwater velocity is of fundamental importance to groundwater investigations, particularly those connected to groundwater contamination. In addition to addressing the three common questions listed above, a detailed understanding of the groundwater velocity field at a site provides useful insights into a variety of common issues and processes, including: transformation rate constants, oxidation or reduction capacity, groundwater mixing, residence times, and contaminant mass flux across boundaries.

Darcy's Law has underpinned groundwater velocity estimation for the last several decades. When Darcy's Law is used at appropriate scales, it has been shown to provide accurate and economical estimates of velocity. It should be noted that utilizing Darcy's Law in this fashion assumes an aquifer to be simple, homogeneous, and a continuous porous medium over the scale being tested. However, natural aquifers, no matter their simplicity, never fully honor these assumptions.

In addition to the underlying assumptions of Darcy's Law, the parameters required for Darcy-based estimates of groundwater velocity are subject to uncertainties. Most notable among the uncertain parameters is hydraulic conductivity (*K*), a measure of an aquifer's ability to conduct water. The difficulties in accurately and precisely characterizing *K* are commonly credited as the greatest source of uncertainty in Darcy's Law calculations. These difficulties arise from:

- geologic processes of deposition and sedimentation, that cause *K* to vary by orders of magnitude over centimeter-scale distances
- the uncertain representativeness of *K* measurements, especially as related to the scale of the tests (Butler, 2005)

- the time variance of *K* under conditions of high microbial activity, or chemical reactions that result in aquifer clogging or dissolution, or when invaded by fluids with differing physical or chemical properties (e.g., Schillig et al., 2011; Kamolpornwijit et al., 2003)

In addition to the *K*-related uncertainties, errors associated with hydraulic gradient measurements also contribute to velocity estimation error. These arise from:

- challenges in discerning differences in water levels in closely spaced wells
- challenges in discerning differences in water levels in highly permeable sediments
- problems arising from water levels obtained from wells that intersect geologic units in poor hydraulic connection
- similarly constructed wells that are not hydraulically connected to each other due to poorly developed well screens
- water levels collected from wells installed at different depths that may intersect different hydraulic units
- errors arising when waters of different density are present in the wells being sounded, as might occur in deep groundwater systems or near coastlines where seawater intrudes into aquifers.

Lastly, it should be noted that the accuracy and representativeness of porosity estimates, specifically effective porosity, can contribute uncertainty to Darcy-based groundwater velocity estimates.

Despite the potentially large parameter uncertainties associated with Darcy's Law, Darcy-based estimates of groundwater velocities has provided a go-to, low-cost, method that has commonly served as the final word on flow patterns and rates in aquifers. However, with the ever-increasing utilization of *in situ* remediation techniques, the need to better understand flow characteristics and other issues, described above, Darcy's Law may not be sufficient on its own to generate groundwater velocity estimates that meet the growing requirements for accuracy and precision. Instead, direct groundwater velocity measurements, at the scale of the process of interest, may be better suited for this task going into the future.

Point Velocity Probe Family of Tools

The Point Velocity Probe family of tools comprises five unique tools designed for direct groundwater velocity measurements across a wide range of geologic settings. All of the tools within the PVP family operate on the same principles and utilize the same surface components that can be shared between systems to achieve cost savings. Moreover, once trained on the operation of one PVP tool, individuals can readily transfer their knowledge and expertise to the entire family of tools. A brief summary of each tool's key details including ideal measurement environment, measurement type, calibration requirement and average measurement duration can be found in Table 1. This table can also be used along with the decision tree as a helpful resource when selecting what tool is best suited for the study site and objectives (Figure 1). A more detailed description of each tool type follows, below.

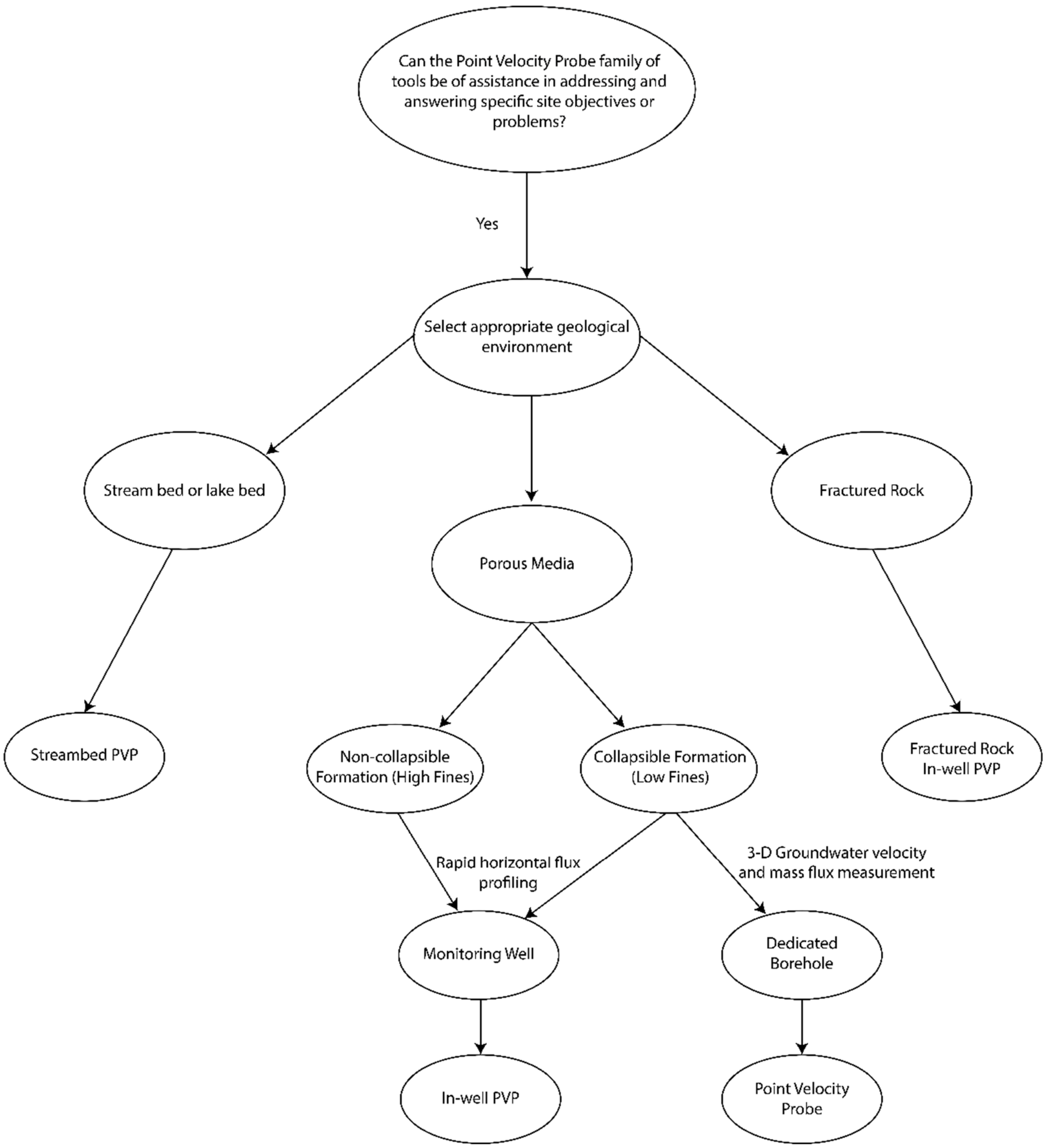

Figure 1. Decision tree for the selection of the appropriate Point Velocity Probe tool based on the geological setting of the study site.

Table 1. Summary and Selection Resource for the PVP Family of Tools.

Tool Type	Overview	Ideal Measurement Environment	Measurement Type	Calibration Required?	Average Measurement Duration
Point Velocity Probe (PVP)	The PVP is the oldest and most widely utilized tool in the PVP family. The PVP is a point-scale measurement device capable of collecting co-located groundwater velocity and water sample measurements. Installations of PVPs require dedicated boreholes and permanent installations. PVPs have been deployed with great success in transects along critical boundaries and at various areas of concern at industrial sites worldwide.	Unconsolitated, saturated, porous media. General rule of thumb is less than 20% silt and clay fraction	Groundwater velocity with ability to measure horizontal, vertical, and composite flow directions (3-dimensions)	No. No additional measurements are required for determination of groundwater velocity	0.5 - 48 hours
HRX-PVP	An adaptation of the PVP for measurement of groundwater velocity in one-dimension, originally designed for use in the Horizontal Reactive Media Well (HRX Well®).	Unconsolitated, saturated, porous media. Designed and tested for use in cylindrical well casing or benchtop column experiments.	Groundwater velocity in one-dimension that is a function of the installation orientation of the tool	No. No additional measurements are required for determination of groundwater velocity	0.25 - 5 hours
Streambed PVP (SBPVP)	The SBPVP is a tool specifically designed to investigate groundwater surface water interactions. The tools sits on the base of a drivepoint that is inserted into upper 3 inches (7 cm) of lakebed and streambed sediments.	soft-bottomed lakebed and streambed environments	Groundwater velocity with the ability to measure strictly vertical groundwater surface water exchanges. Additionally, the SBPVP can measure the horizontal, vertical, or composite components of hyporeic flow.	No. No additional measurements are required for determination of groundwater velocity	0.1 - 5 hours
In-Well PVP (IWPVP)	The IWPVP is a tool specifically designed for the rapid characterization of groundwater flux within the screened intervals of groundwater monitoring wells within porous media aquifers. IWPVPs are easily deployed and recovered from monitoring wells and are therefore not dedicated instruments.	new or existing groundwater monitoring wells that have recently been developed to ensure good hydraulic connection with the surrounding formation	Horizontal groundwater flux within the monitoring well that can be calibrated to estimate the groundwater flux and/or seepage velocity in the surrounding formation.	Yes, because the measurements are conducted within wells the measured flux must be transformed to groundwater flux outside the well via a calibration line. An estimate of effective porosity is also required to further transform the estimated fluxes to velocities.	0.01 - 0.75 hours
Fractured Rock In-Well PVP (F-IWPVP)	The F-IWPVP is a tool specifically designed for the rapid characterization of groundwater flux within the screened intervals of groundwater monitoring wells and competent boreholes within fractured rock aquifers. F-IWPVPs are easily deployed and recovered from monitoring wells and are therefore not dedicated instruments.	new or existing groundwater monitoring wells or boreholes that have recently been developed to ensure good hydraulic connection with the surrounding formation and all drilling fluids have been flushed	Horizontal groundwater flux within the borehole that can be calibrated to estimate the groundwater velocity in the corresponding fractures or rock matrix. A qualitative measure of vertical borehole flow may also be possible.	Yes, because the measurements are conducted within boreholes the measured flux must be transformed to groundwater flux outside the well via a calibration line. Due to the nature of fractured media, an estimate of fracture apreture is required for accurate calibration or fracture velocites.	0.01 - 0.75 hours

Point Velocity Probe (PVP)

The Point Velocity Probe (PVP) was first introduced to the peer-reviewed literature in 2007 (Labaky *et al*., 2007). The PVP is designed to measure groundwater velocity in three-dimensions in unconsolidated, non-cohesive sediments without independent estimates of hydraulic gradient, hydraulic conductivity, or porosity (Gibson and Devlin, 2019).

PVP measurements rely on small-scale tracer tests conducted on the surface of the probe, in direct contact with the aquifer sediment (Figure 2). To accomplish this, the probe body is a cylindrical shell measuring about 2 inches (5 cm) in height with an outside diameter of 2.375 inches (6 cm) (Figure 2). PVPs are typically flush mounted on schedule 40 2-inch PVC casing and can be designed for single probe or multi-level deployment, with up to seven probes instrumenting a single borehole. On the surface of the probe, 8 detectors allow for tracer monitoring in three-dimensions (2 vertical flow detectors and 6 horizontal flow detectors). Three injection ports located at equal radial spacings around the PVP provide reassurance that no matter the installation orientation, at least one injection port will be located at a favorable orientation for the quantitative measurement of seepage velocity.

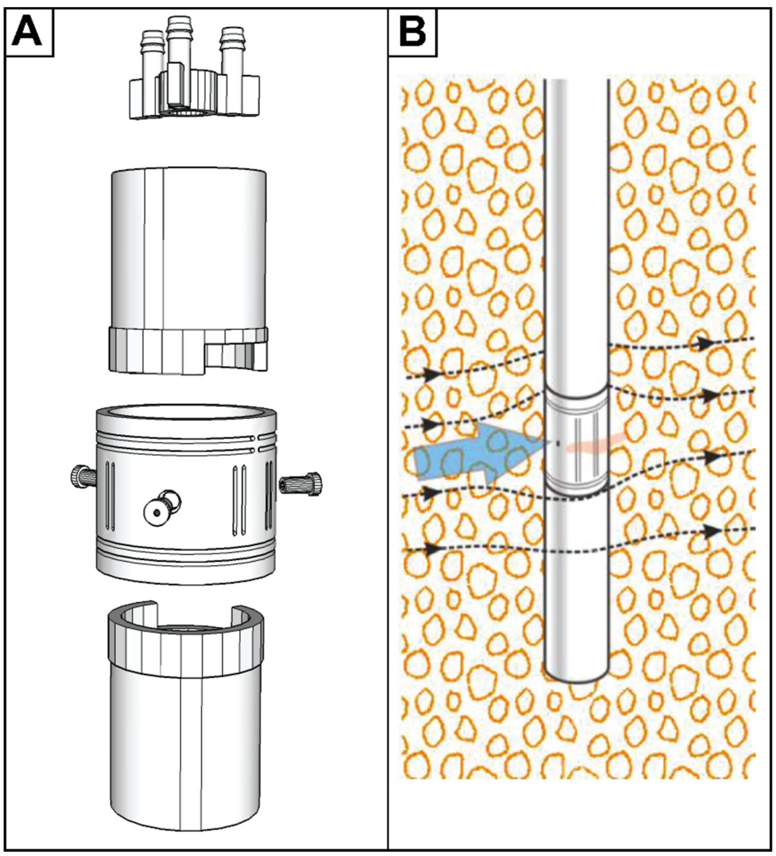

Figure 2. (A) Computer rendering of the PVP components and design. (B) Plan view schematic of the PVP illustrating tracer (red) movement across the surface of the probe and detection wires.

Typical tracers used in PVP testing, and for all the technologies described in this handbook, are deionized water or 1 g L^{-1} NaCl (table salt) solution using groundwater collected from the study site. As the tracer moves across the probe surface, the detection wire pairs measure the change in electrical resistivity as a function of time. Therefore, the aim in tracer selection is to achieve a strong contrast between the tracer solution and the site groundwater while minimizing the potential for density induced flow. The time record of electrical resistivity serves as the tracer breakthrough curve of the tracer solution. Since the travel distance and time of injection are known, the breakthrough curve can be fit with an analytical or numerical solution to the advection dispersion equation (ADE) to estimate the apparent groundwater seepage velocity. If two or more breakthrough curves are generated from multiple detectors on the PVP, for a given injection event, the groundwater flow direction of ambient groundwater (away from the probe) can be estimated. Note, PVPs provide measurements of groundwater velocity at a particular point in space and time.

As alluded to previously, PVPs are designed to be installed in fully saturated unconsolidated sediment (e.g., sand and gravel). In formations with a large fine (silt and clay) fraction, boreholes cannot be relied upon to collapse against the PVP body, resulting in unreliable tests. Based on experience, formations comprising fine fractions of less than approximately 20% are likely suitable for PVP deployment.

PVPs can be outfitted with water sampling ports so both water quality parameters and seepage velocity can be measured nearly simultaneously at close proximity (less than a one inch (1-2 cm) spacing between chemical and flux sampling points). This permits the snapshot estimation of solute mass fluxes.

As discussed in the 'Point Velocity Probe Case Studies' section below, the PVP has been used at a wide range of industrial and research sites over the past decade and has provided valuable information and insights into the processes controlling advective contaminant migration in the subsurface. Overall, the PVP is a tool we rely on heavily for critical information and insights that other, more traditional, site characterization efforts are not well equipped to measure or fully elucidate.

A detailed description of PVP installation and testing, including datalogger setup, can be found in the "PVP Standard Operating Procedures" and "PVP Installation Guide" documents. Briefly, a typical testing period for a PVP is conducted as follows:

1. PVP is installed into a dedicated borehole and the aquifer sediment is allowed to collapse around the instrument. The installation is allowed to relax and equilibrate for a period of 12 – 24 hours.
2. After sediment collapse, a period of quality assurance and quality control testing is conducted to ensure all components of the system are functioning properly. This period typically lasts 2 – 24 hours and consists of a series of large-volume injections, or 'over-injections', at each of the injection ports. A typical over-injection for the PVP is 5 – 10 mL. Over-injections also provide information on what ports will be most useful for PVP measurements.
3. Once all components of the system have been tested, data collection can begin. It is recommended that a background data collection period of at least 30 minutes is permitted prior to the initiation of any testing. PVP measurements are conducted by injecting 1 – 3 mL of tracer solution at a single injection port on the PVP. Data are then collected until all detectors have returned to background. The duration of data collection for PVP testing is a function of groundwater speed and can last anywhere from 0.5 – 48 hours.
4. After the completion of a PVP test, a repeat test can be completed by repeating from step 3.
5. Once PVP testing is completed for a field campaign, users should ensure all data are downloaded, all tracer lines are securely clamped, and all surficial components are properly stored.
    a. Note, if PVPs have been inactive for an extended period between measurements it is recommended that step 2 be repeated a day or two prior to the next sampling campaign.

Horizontal Reactive Media Well (HRX Well®) Point Velocity Probe (HRX-PVP)

The Horizontal Reactive Media Well (HRX Well®) Point Velocity Probe (HRX-PVP) is a specially designed PVP for the measurement of flow through saturated cylindrical columns (Cormican *et al*., 2021; Divine *et al.*, 2020). In particular, the HRX-PVP was designed to be emplaced in a section of the novel HRX Well® technology packed with coarse sand (Figure 3). However, the HRX-PVP can be used in a variety of applications and is not limited to use in only HRX Wells®.

The HRX-PVP operates on the same basic principles as the PVP with a small-scale tracer test conducted on the surface of the probe, in direct contact with the saturated sediment. The probe consists of an approximately 3.5-inch-long plastic cylinder with an outside diameter of about 1 inch that contains the injection port and detector wire pair. The cylindrical section of the probe sits on a 3/8-inch steel rod that provides structural support and allows for the device to be centralized within the measurement cartridge (Figure 3). Typically, the probe only contains one set of detector wires since the flow direction in such an enclosed system is likely to be known in advance. However, in an oscillatory flow system that features flow direction reversals, detector wires can be attached on either side of the injection port to permit a measurement to be obtained anytime in the cycle.

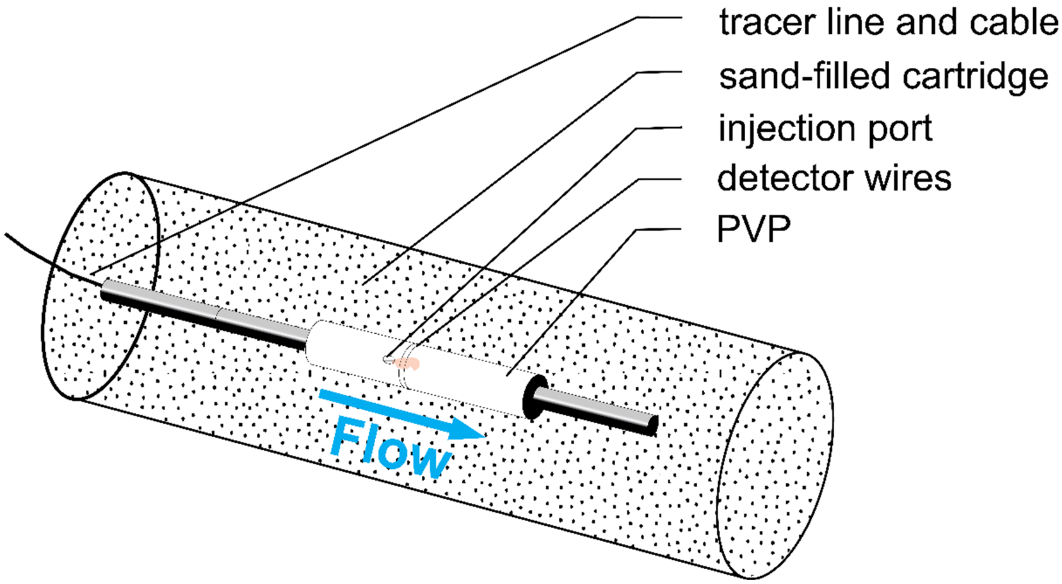

Figure 3. Schematic of the HRX-PVP within a sand-filled cartridge illustrating tracer (red) movement across the surface of the probe and detection wires. Modified from Cormican *et al* (2021).

Testing for the HRX-PVP is very similar to that of the PVP, with the tracer test conducted on the surface of the probe. Due to the short travel distances (injection port to detector wires) relative to the travel distances of the PVP, the time of measurement tends to be shorter than that of the PVP. The shorter travel distances also typically result in a lower volume of tracer being required for testing.

Like the PVP, no calibration is required for determination of the seepage velocity. Additionally, no independent estimates of hydraulic parameters such as hydraulic conductivity or effective porosity are needed to obtain estimates of groundwater velocity.

Since the principals of operation of the HRX-PVP are very similar to the PVP, the reader is referred to the previous procedural instructions for the steps to run a test. A detailed description of the HRX-PVP installation and testing can be found in the "HRX-PVP Standard Operating Procedures" document.

Streambed Point Velocity Probe (SBPVP)

The Streambed Point Velocity Probe (SBPVP) is a modified PVP that sits at the end of a metal drive point designed to measure fluxes across the top 3 – 4 inches (7 – 10 cm) of streambed or lakebed sediment, near the groundwater-surface water interface (Figure 4) (Cremeans and Devlin, 2017). The SBPVP can be fabricated to measure flow in either (or both) the vertical and horizontal directions through a streambed or lakebed (Cremeans and Devlin, 2017; Cremeans *et al.,* 2018; Cremeans *et al.,* 2019; Cremeans *et al.,* 2020).

The SBPVP consists of a 1-inch diameter drive point tip attached to 3/8-inch stainless steel rods. The probe is comprised of one injection port, two vertical detector wire pairs, and one horizontal detector wire pair (Figure 4A). When only the vertical component of flow is being measured, a hyporheic shield is attached to the SBPVP to isolate the vertical component of flow from any horizontal component of hyporheic flow that may be present (Figure 4B). If horizontal flow is targeted for measurement, the shield is not used. Additionally, horizontal measurements require two tests, with a slight rotation between them. This follows from the construction of the probe with a single detector for horizontal flow measurement – recall from the PVP description that two measurements at different angles to the ambient flow are required to determine horizontal seepage velocity magnitude and direction. Note, in some cases, flow can be determined in three-dimensions using the SBPVP, when signals are obtained from both the horizontal and vertical detectors.

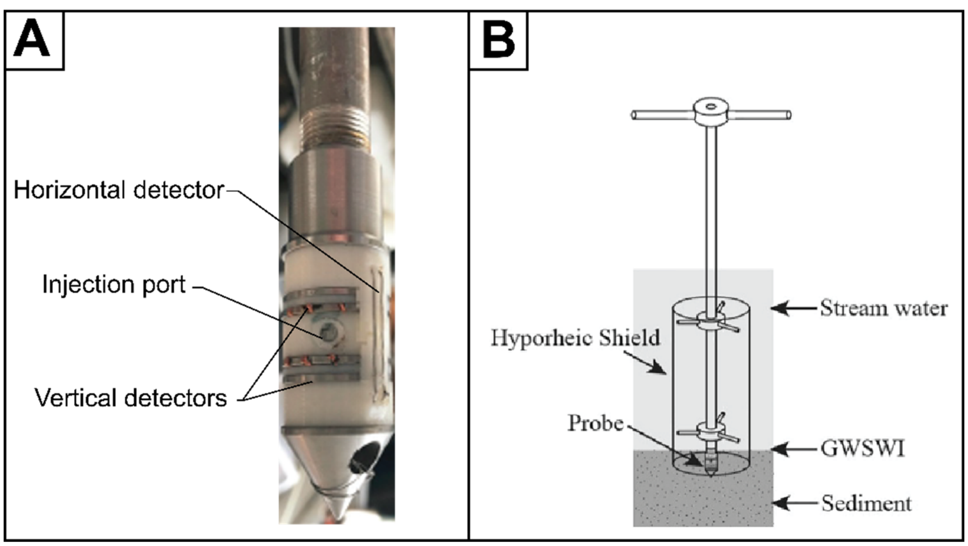

Figure 4. (A) photograph of the updated SBPVP with horizontal detection capabilities. (B) schematic of SBPVP deployment with the hyporheic shield for determination of vertical groundwater velocities at the groundwater-surface water interface (GWSWI) (odified from Cremeans *et al* (2018)).

Testing for the SBPVP is very similar to that of the PVP as the tracer test is conducted on the surface of the probe. Due to the short travel distances (injection port to detector wires), similar to the HRX-PVP, the overall measurement times tend to be shorter than those of the PVP. The shorter travel distances also typically result in a lower volume of tracer being required for testing.

Like the PVP and the HRX-PVP, no calibration is required for determination of the seepage velocity. Additionally, no independent estimates of hydraulic parameters such as hydraulic conductivity or effective porosity are needed to obtain estimates of groundwater velocity.

A detailed description of SBPVP installation and testing, including datalogger setup, can be found in the "SBPVP Standard Operating Procedures" document. Briefly, a typical SBPVP test is conducted as follows, focusing on the operation of the probe:

1. Emplace the SBPVP at the desired measurement location by advancing the probe into the streambed or lakebed approximately 3 – 4 inches (roughly 7-10 cm). Once the SBPVP is seated, verify the SBPVP is anchored so that it is able to stand under its own weight and does not experience significant movement due to wind or water currents. To minimize noise in the data, it is critical to take the necessary steps to achieve a stable emplacement.
2. A period of 10-15 minutes of background data collection should be collected prior to the first test.
3. Ensure the tracer line and syringe are completely filled with tracer all the way to the injection port. This is done by injecting 1 – 2 mL of tracer ('over-injection') before the first tests and leaving the probe in place for several minutes to allow excess tracer outside of the probe to be washed downstream. Over-injection tests also provide quality control and quality assurance that all components are functioning properly by registering strong signals on all detections simultaneously.
4. After the over-injection signals have returned to baseline, data collection can begin. A typical test starts with an injection. SBPVP injections use approximately 0.1 – 1 mL of tracer. Data are collected until all detectors have returned to baseline (typically 0.1 – 5 hours, though this depends on the seepage rates and can be much greater). If only vertical velocity measurements are being made, duplicate measurements can be acquired by repeating this step without any movement of the SBPVP between measurements.
5. If horizontal flow measurements are being made, the first test must be followed by a second test with the SBPVP rotated 10° – 15° while the SBPVP is still seated within the sediment. Between tests where there has been a rotation, time should be allowed for stabilization of background signals, which is usually within 5 minutes. Once the signals have stabilized, another test can be initiated.
6. Once the measurements at a location are complete, the SBPVP can be relocated or cleaned and packed for storage.

In-Well Point Velocity Probe (IWPVP)

The In-Well Point Velocity Probe (IWPVP) is an adaptation of the PVP designed for the rapid characterization of horizontal groundwater velocities within the screened intervals of groundwater monitoring wells (Osorno *et al.*, 2018). An advantage of this device is that new or existing site infrastructure can be utilized to obtain flux measurements in addition to establishing monitoring locations. Additionally, IWPVPs can be deployed, removed, and redeployed at various wells across a site (assuming proper decontamination and cross-contamination preventions are observed).

The IWPVP utilizes a funnel and channel design consisting of two perpendicular channels passing through the probe; the funnels interface the channels to the probe's perimeter and serve to collect and direct water to the channels (Figure 5). Additionally, the funnels widen the capture zone of each channel, magnifying the flux through the probe and decreasing the total time required for a measurement.

As mentioned in the introduction, all PVP tools operate on the same basic principles and with the same hardware on the ground surface. So, like the other PVP instruments, the IWPVP operates by conducting a small-scale tracer test (Figure 5). However, because the IWPVPs are placed in the water column inside a well, the tracer test is conducted in 'open' water within the body of the probe rather than on the probe surface, i.e., the tracer test is not conducted in a porous medium. Tracer is introduced into the center of the probe body (the mixing chamber) via a blunt tipped needle. To limit the impact of density induced flow, a passive mixing system is present in the central mixing chamber, and protective shoe designs are incorporated on the floors and ceilings of the channels to limit tracer detection to the mid-section of the channels (vertically) where ambient groundwater flow (rather than density flow) controls tracer movement.

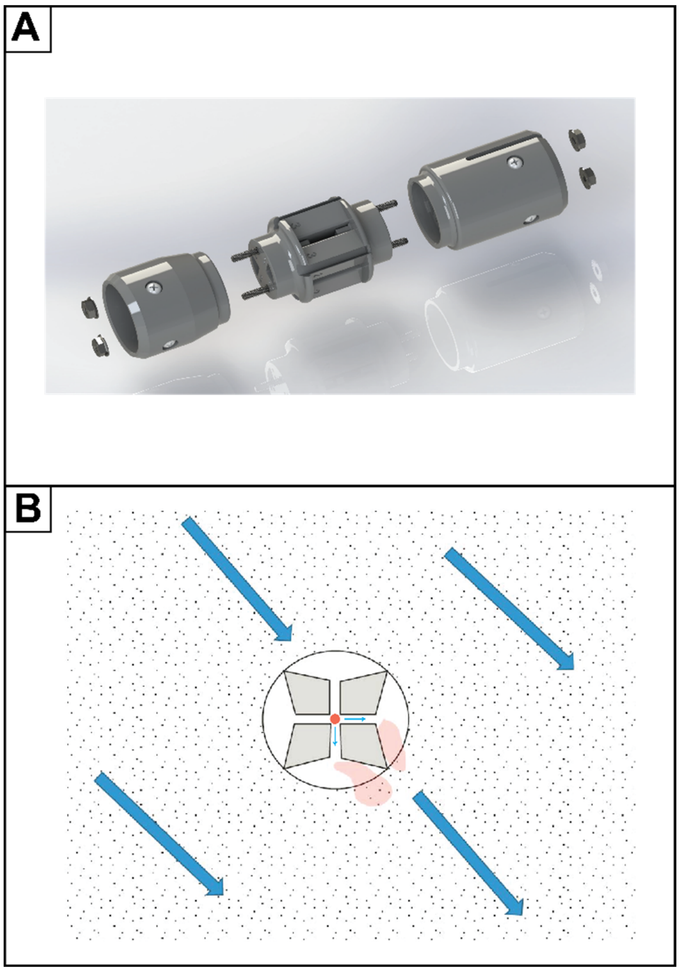

Figure 5. (A) Computer rendering of the updated modular IWPVP co-design by Solinst, the University of Kansas, and OUL. (B) Plan view schematic of the IWPVP illustrating tracer (red) movement through two measurement channels.

The measurement interval of an IWPVP is isolated within the well using a combination of neoprene and brush packers. Neoprene disk packers are used, top and bottom, to limit potential vertical flow within the well screen and measurement interval. These upper and lower packers are flexible, allowing the probe to easily move up and down the well, while maintaining a relatively low permeability once emplaced. Horizontal flow between the funnels is minimized using brush packers. The brush packers are also flexible, so movement of the probe within the well, including rotational movement, is possible. The brush and neoprene seals are not perfect but they do offer some resistance to flow. Since water flows through the probe with little resistance, the packers serve the purpose of attenuating flow that by-passes the probe. The brush packing system may also assist with well development by abrading deposits on the inside of the well screen that might reduce well efficiency. All packer systems on the IWPVP are easily replaceable and can be modified in the field to fit the borehole of interest.

IWPVPs can be mounted on PVC rods singly or in multi-level fashion with up to three IWPVPs on a single stand. The separation distance between multi-level IWPVPs can be customized to specifically address the questions and objectives of a study. Each IWPVP is modular and can be replaced at any time without the need to replace all components of the system (Figure 5).

Various sizes of the IWPVP are available for common monitoring well diameters. Custom IWPVPs can also be manufactured, by request, that are tailored to meet site or project requirements. To date we have profiled the following monitoring well sizes:

- 2-inch
- 3-inch
- 4-inch
- 6-inch

It is important to note that the probes – in particular the packing systems – are sized for the specific casing and well-screening in use. Specifications for the wells chosen for IWPVP tests should be made available at the time of ordering to ensure the amount of annulus is minimized and the packers make contact with the walls of the casing and well screen.

All in-well direct groundwater velocity measurement techniques require calibration to estimate the groundwater flux in the formation outside of the well screen. This is primarily due to flow convergence to the screened interval of a groundwater monitoring well. Additionally, a representative estimate of the effective porosity of the aquifer is also required to transform estimates of calibrated Darcy fluxes to estimates of the seepage velocities in the formation. Without estimates of effective porosity, only Darcy fluxes can be estimated.

Site-specific calibration lines should be obtained for the best results when Darcy fluxes outside the well screen (or seepage velocities) are desired. Factors contributing to unique calibration factors include but are not limited to:

- Well screen diameter and design (i.e., slot size and material)
- Probe size
- Measurement channel width
- Presence of sand pack

Calibration of the IWPVP is typically conducted in a nested storage tank (NeST) aquifer simulator using a section of the well screens relevant to the boreholes being tested/profiled (Bowen *et al.*, 2012; Osorno *et al.*, 2018). IWPVPs with dimensions identical to that used in field testing are installed within the sample section of the well screen and calibrated over a range of known fluxes through the porous medium of the NeST aquifer simulator. The slope of the calibration line, also referred to as the 'calibration factor', relates the measured velocity within the IWPVP to that of the formation. Typical calibration factors for IWPVPs in porous media range from 16 – 50. As a result, the IWPVP magnifies the rate of flow by up to a factor a 50, significantly decreasing the overall time required for a single measurement.

A detailed description of IWPVP installation and testing, including datalogger setup, can be found in the "IWPVP Standard Operating Procedures" document. Briefly, a typical IWPVP flux measurement, focusing on the instrument procedure, is conducted as follows:

1. Emplace the IWPVP at the desired depth in the screened portion of the well by advancing the probe slightly past the target measurement depth and then pulling the probe back up-hole to the target measurement depth. This step sets the neoprene and brush packers in a controlled and reproducible fashion. When the packers are set this way, they act as a break on downward movement in the well, stabilizing it position in the well.
2. A period of 10-15 minutes of background data collection is recommended.
3. A large volume injection of tracer ('over-injection') of 0.5 – 1 mL is performed to ensure the tracer line and syringe are completely full of solution and free of air bubbles. Movement of IWPVPs within the water column tends to displace tracer. Over-injection events also provide quality control and quality assurance that all components are functioning properly by stimulating detector responses in all channels simultaneously.
4. After the over-injection test signals have returned to baseline, data collection can begin. A typical injection volume for an IWPVP test is approximately 0.05 – 0.25 mL. Data are collected until all signals have returned to baseline (typically 1 – 45 minutes, but longer times are possible depending on the ambient seepage velocities).
5. Once all signals have returned to baseline, a duplicate test can be conducted or the IWPVP can be moved to the next sampling interval.
    a. For duplicate testing, repeat step 4
    b. For movement of the IWPVP repeat from step 1. It is recommended that profiling be conducted in an upward fashion, bottom to top, to keep IWPVP brushes oriented properly. If alternate profiling strategies are required it is important to note that when moving the probe downward you will have to progress past the desired measurement depth and pull the probe back, upward, to the target depth.
6. Once the measurements at a particular well have been completed, the IWPVP can be removed from the borehole to be cleaned for reinstallation and additional sampling or cleaned and packed for storage.

Fractured Rock In-Well Point Velocity Probe (F-IWPVP)

The Fractured Rock In-Well Point Velocity Probe (F-IWPVP) is identical to the IWPVP in design and function but can be utilized in both cased and uncased wells within fractured rock aquifers (Heyer *et al.*, in review) (Figure 6). Since the F-IWPVP and the IWPVP utilize very similar designs, the F-IWPVP is also available in a variety of sizes and can even be custom tailored to address specific site requirements.

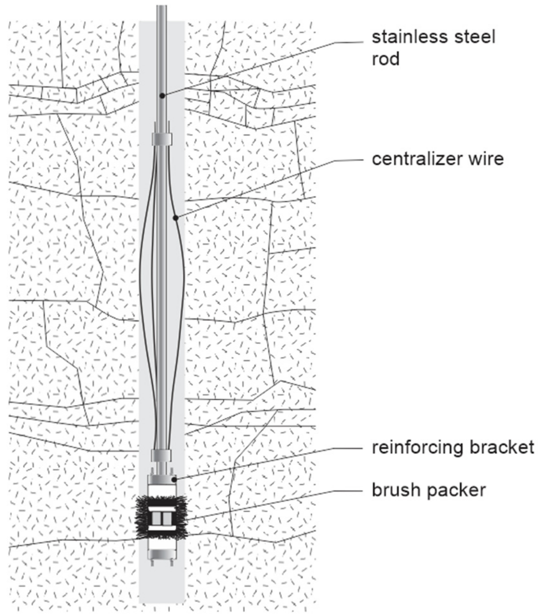

Figure 6: Schematic view of an F-IWPVP in a borehole showing the brush packers, reinforcing brackets, and spring-loaded centralizer wires. Taken from Heyer *et al* (in preparation).

The primary difference between the F-IWPVP and the IWPVP, is the calibration process. Due to the nature of fractured media, the groundwater velocity is dependent on the aperture of a fracture. Therefore, unique calibration factors may result from but are not limited to:

- Well screen design
- Borehole diameter
- Probe size
- Measurement channel width
- Fracture aperture and geometry

For an accurate calibration of F-IWPVP measurements, independent information regarding fracture aperture is necessary. We do not provide services to collect information of this nature, currently, but techniques to acquire supporting information is available through various contractors who work with FLUTe liners and various downhole geophysical techniques (Berkowitz, 2002; Keller *et al*., 2013; Pehme *et al.*, 2010; Renshaw and Dadakis, 2000; Shahbazi *et al.*, 2020; Sun *et al.*, 2020). When facture depth and aperture data are available, specific calibration lines can be generated using a laboratory fracture flow simulator or numerical modeling to transform F-IWPVP measured fluxes to fluxes within the fracture(s). Note, in fractured rock environment Darcy flux is equal to seepage velocity. When individual fracture measurements are not available, relative fluxes through the borehole can still be established to determine zones of high or low flux (Heyer *et al.*, in prep).

Another key consideration to keep in mind for the F-IWPVP is the potential for significant vertical flow within the borehole. Due to the nature of fracture rock, vertical short-circuiting of flow within the borehole between two or more transmissive zones can routinely occur. If significant vertical flow within the borehole is anticipated or observed in the field, a transition to a more reliable and impermeable packing system may be necessary. When this is the case, an inflatable packing system or k-packers may be the preferred packing system. However, such packers require additional time and equipment in the field making the brush packing system preferable under limited vertical borehole flow conditions.

Since the procedures for F-IWPVP are identical to those for the IWPVP, please refer to the previous section for procedural steps. A detailed description of the F-IWPVP installation and testing can be found in the "F-IWPVP Standard Operating Procedures" document.

Practical Applications of the PVP Family of Tools

In this section selected case studies are presented for each tool to showcase the various applications, data, and insights that can be obtained through their application.

Point Velocity Probe Case Studies

The PVP has been used at several industrial sites in the United States and abroad to better understand the spatial and temporal variability of groundwater flow fields. Here, we will briefly discuss case studies that illustrate the use of the probes in transects and in monitoring networks for both spatial and temporal evaluations of seepage velocities in transient systems. Geostatistical methods are also applied with the PVP data for the purposes of transect design and data analysis.

Preferential Flow Pathway Identification

The characterization of preferential pathways within the subsurface is critical for effective design and implementation of remedial systems and risk assessment. The PVP has been used, with success, in site characterization to identify the presence of preferential flow pathways.

The use of PVPs as a high-resolution characterization tool is well illustrated by work conducted at a site near Woodstock, Ontario, Canada (Devlin *et al*., 2012; Schillig *et al*., 2016). Briefly, PVPs were used to augment more traditional Darcy-based approaches to groundwater flow field characterization in a complex glacial outwash aquifer. The primary objective of the characterization effort was to assess the feasibility of stimulating *in situ* denitrification upstream of water supply wells. The Darcy-based investigation indicated that the seepage velocity at the site averaged about 0.7 m d^{-1}. Five multi-level PVP stands were installed with two of the multi-levels consisting of six PVPs each and the other three multi-levels consisting of seven PVPs each. The PVP results showed an overall flow direction towards the southeast which was consistent with the horizontal hydraulic gradient direction of the equipotential map, with an average groundwater velocity of 11 m d^{-1}. The PVPs also identified a discrete zone conducting water at velocities approaching 30 m d^{-1} (Figure 7). Subsequent, independent natural gradient tracer testing, using Bromide as the conservative tracer, confirmed the PVP measurements across similar depth intervals (Figure 7).

The discrepancy between the traditional Darcy-based velocities and the PVP and tracer test velocities is significant and has profound implications for the design and success of any *in situ* remedial systems such as the one proposed for denitrification at this site. Specifically, if the system were designed and implemented based on the Darcy-based estimates of average groundwater velocities, minimal denitrification would have resulted due to the high proportion of flow through a zone with low residence time. With the additional knowledge provided by PVP measurements and the tracer test, consideration could be given to a remedial design better tailored to the site.

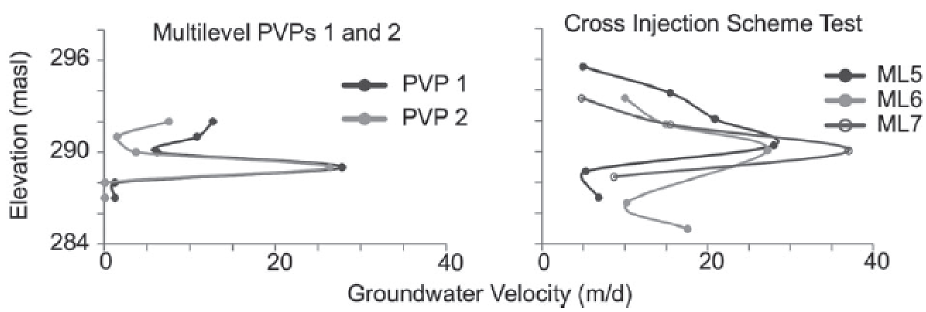

Figure 7. Depth versus groundwater velocity highlighting the preferential flow pathway transporting water at velocities observed by both PVPs and bromide tracer testing (bromide introduced by the cross-injection scheme, which flushes a zone between two wells oriented perpendicular to the ambient flow direction, modified from Schillig *et al.,* 2016).

Transient Heterogeneity

Many *in situ* remedial techniques rely on biological activity to breakdown contaminants. Yet, the impact of this activity and associated growth of biomass, is often overlooked by practitioners, which leads to potentially misleading interpretations of flow while remediation is occurring as well as after it is complete. As *in situ* remedial techniques become more widely used, characterization and monitoring of transient changes in surface heterogeneity should become more routine. The PVP is a tool that can address this need.

An example of PVP usage to track the transience of groundwater velocity, due to remedial activities, is a study conducted at the Canadian Forces Base Borden test site in Ontario, Canada (Devlin *et al.*, 2009; Schillig *et al.*, 2011). The study was conducted within sheet-pile alleyways where the aquifer was undergoing *in situ* remediation of BTEX compounds. The PVP measurements within the alleyways showed that groundwater velocities varied nonuniformly by up to a factor of three in response to enhanced biological activity downgradient of an oxygen-amended portion of the aquifer (Figure 8). Although a factor of three is within the bounds of uncertainty for Darcy-based estimates of seepage velocity, it is a sufficient enough variation to undermine remedial efforts at a particular site. In other cases, such as permeable reactive barriers, the temporal changes may be directly related to the clogging of treatment media. Accurate knowledge of changes in the groundwater velocity field, in cases such as this, may provide advance warning of incomplete treatment or flow bypassing the treatment media. Lastly, transient changes in the hydraulic conductivity of an aquifer may result in conceptual site models, based on pre-remediation characterization, to be outdated and misused.

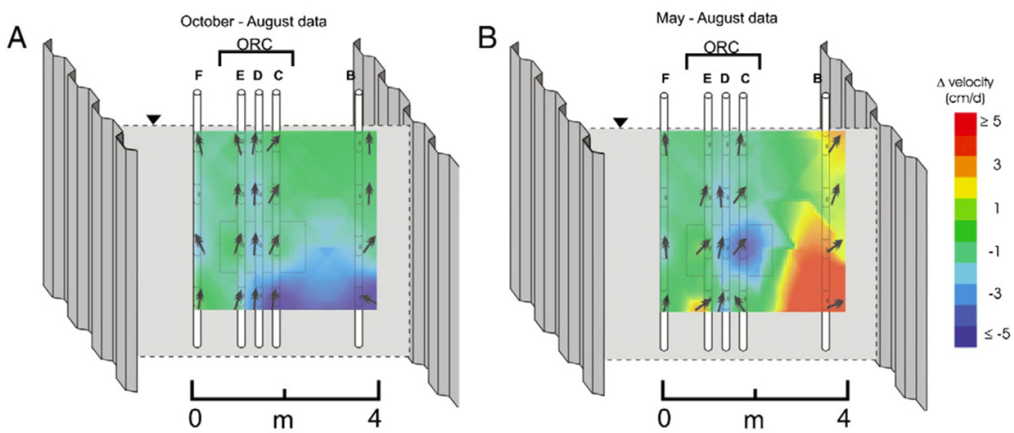

Figure 8. Groundwater velocity changes from background (August) after September oxygen additions to the petroleum contaminated aquifer within the gate. (A) October velocities minus the background velocities. (B) May velocities minus the same background velocities, as the aquifer recovered from the oxygen additions. Note the persistence of a low velocity zone in the May dataset. Cool colors indicate declines in velocity and warm colors indicate velocity increases since oxygen additions. Arrows indicate horizontal flow directions with arrows rotated vertically for ease of reading. Modified from Devlin *et al* (2012).

Mass Flux Transect Design and Analysis

When focusing on the quantification of mass discharge across a control plane, two primary factors, groundwater discharge and contaminant discharge, bear consideration. Therefore, a two-tiered approach for the estimation of groundwater and contaminant discharges and the associated uncertainties should be used. The approach for the estimation of contaminant discharge and the associated uncertainties involves a complex array of parameterization and is beyond the scope of this work. Here, the focus will be on the methods developed for direct groundwater velocity measurements to best estimate groundwater discharge, and it's associated uncertainties, across transects.

The methodology for the quantification of groundwater discharge across transects and their associated uncertainties, was presented by Osorno *et al* (in prep). Broadly, stochastic methods are used to develop hundreds to thousands of equally probable realizations of a given aquifer, leveraging existing site data and PVP measurements of groundwater velocity. The incorporation of complementary site data makes it possible to minimize the number of groundwater velocity measurements needed – and hence the cost to a project –to obtain the best estimates of groundwater discharge across a transect as well as quantifying the associated uncertainties and probabilities.

The stochastic approach to transect characterization is useful in the design of transects. For example, at the Borden site it was found that in order to achieve estimates of groundwater discharge across a transect within ± 10% with 50% confidence, a sample density of 0.6 points/m^2 was required (Figure 9a). To achieve higher levels of confidence, the level of sampling densities required can be obtained from a set of realizations generated for a given study site. This level of guidance has the potential to change the way transects are designed, using acceptable outcome levels *a priori*, therefore decreasing the overall cost of site characterization. Additionally, this methodology allows for the refinement of particular areas of interest along the measurement transect that may be highlighted by the initial round of installations and measurements (Figure 9b).

With the addition of micro-sampling ports for the collection of water samples at approximately the same depth that groundwater velocity measurements are conducted, the PVPs have the unique ability to conduct snapshot sampling of mass flux measurements across a transect. To date, 20 multi-level PVPs have been successfully installed and sampled for both groundwater velocity and low-flow water sampling.

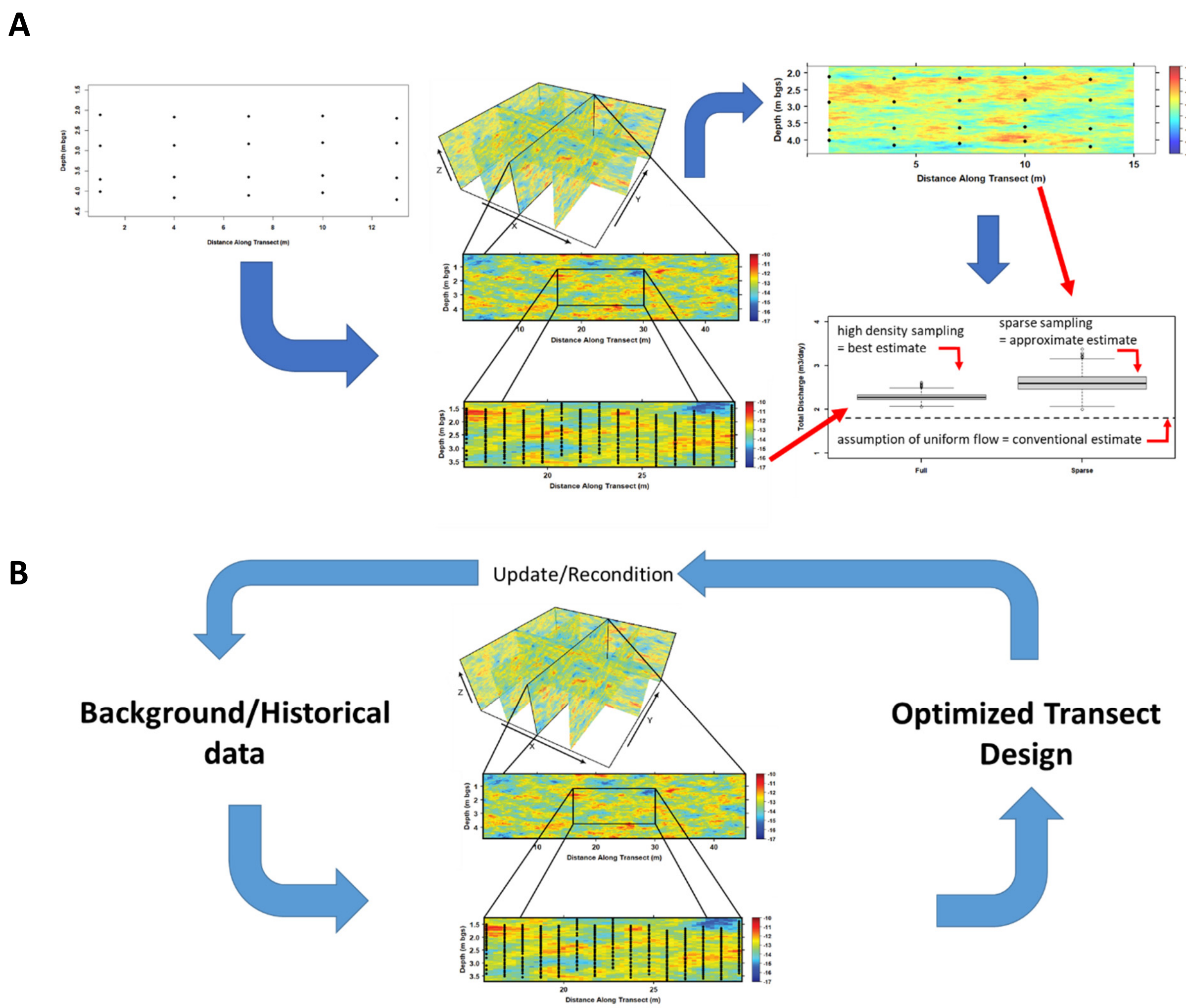

Figure 9. Conceptual work flow of optimized groundwater velocity transect design. (A) Workflow process for determining the lowest sampling density required while maintaining estimates of groundwater discharge within ± 10% with 50% confidence at the C.F.B. Borden study site. (B) Workflow process for development and refinement of transect design to achieve acceptable outcome levels *a priori.*

HRX-PVP Case Study

The success of passive remediation techniques relies on a sufficiently large capture zone and enough residence time within the treatment media for complete degradation and remediation of the contaminants of concern. This issue was central to the viability of the HRX Well® technology, patented by Arcadis. The HRX Well® is a horizontal well that is installed parallel to groundwater flow, and is packed with permeable reactive material that has a hydraulic conductivity 100 times or more that of the surrounding aquifer. The HRX Well® collects groundwater passively (an option for active capture is also available). Mapping the capture zone of a passive system is challenging for economic and technical reasons. Many of the difficulties are removed if the total flow through the HRX can be measured passively. Knowledge of the internal flow is easily translated to an equivalent capture width with readily available models, and in some cases a simple flux balance. A PVP device offers the measurement scale and passive functioning that match the needs of this technology very well.

A pilot test of the first HRX Well® was performed at the Vandenberg Air Force Base, north of in Santa Barbara, CA in 2018 and 2019. A detailed description of the well design and installation can be found in Divine *et al* (2018) and Divine *et al* (2020). Briefly, the well is about 570 feet (172 m) long and the horizontal section of the well was located at a depth of about 23 feet (7 m) below ground surface. On both ends of the horizontal section, angled well screens provided the permeability contrast to capture contaminated site water on the up-gradient end and discharge treated effluent on the down gradient end. HRX-PVPs were installed in first and last cartridge within the horizontal section of the HRX Well® to provide groundwater velocity data at the inlet and outlet (Figure 10). The groundwater velocity data provided field verification of capture zone size and residence time of water through the HRX Well®.

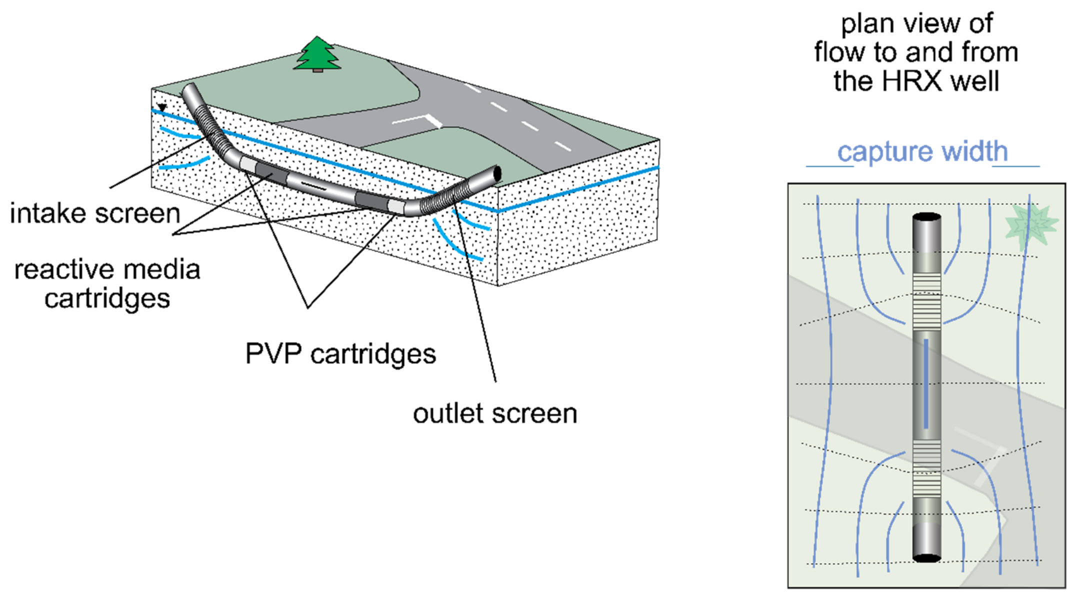

Figure 10. Schematic of the HRX Well®, left, showing the locations of the two HRX-PVPs installed at the upgradient and downgradient ends of the treatment section of the well. Estimates of groundwater velocities from the HRX-PVP were used to verify the passive capture of groundwater by the HRX Well®, illustrated in the plan-view schematic of the flow system, right. Modified from Cormican *et al* (2021).

A detailed explanation of the testing results is provided in Cormican *et al* (2021). Briefly, after the HRX-PVPs were installed, initial measurements indicated flow through the horizontal section of the well was an order of magnitude less than expected, based on numerical modeling. The installation activities were subsequently re-examined and it was found that the PVP cartridges had been installed without the outer seals required to prevent flow from by-passing the cartridge in the annuus between the cartridge and the inside wall of the well. The cartridges were subsequently removed and reinstalled with seals. Additional testing, after correction of the missing seals, confirmed that groundwater velocities through the HRX-PVP and treatment cartridges were in the range of the predicted values, suggesting that the HRX Well® was functioning as designed. The data were also used to independently verify the capture zone and residence time of the water within the treatment zone of the HRX Well®.

SBPVP Case Studies

The SBPVP has been used at several industrial and research sites in the United States and abroad to better understand the spatial and temporal variability of groundwater-surface water interactions. Below, two case studies and the unique insights and implications the SBPVP provide are summarized.

Contaminant Mass Flux into a Stream

Groundwater-surface water interactions receive much deserved emphasis in contamination and remedial studies, since they commonly represent boundaries where risk is experienced most acutely. In response to this, various characterization tools and methods have been developed to aid in the remediation of heterogeneous streambeds and lakebeds. The characterization of contaminant mass discharge into a meandering stream in Grindsted, Denmark with the SBPVP (and other tools) is one such example.

Detailed descriptions of the work completed in this study can be found in Cremeans *et al* (2018) and Cremeans *et al* (2020). The study utilized four measurement techniques (i.e, SBPVP, seepage meter, temperature profiling, and mini-piezometers) to determine the water flux across the streambed, with the ultimate aim of estimating the mass discharge of chlorinated ethenes into the stream. Comparison of all the technologies showed that all identified similar overall trends in groundwater discharge. However the seepage meter and temperature methods showed a significant bias low in their absolute results compared to estimates from Darcy's Law calculations with hydraulic gradients measured from mini-piezometers and hydraulic conductivities from slug tests. The SBPVP compared best with the Darcy approach, but provided significant advantages in time and manpower savings. Contaminant distributions in the streambed were mapped separately by the Technical University of Denmark. Combining these two datasets, a detailed picture of the spatial distribution of contaminant mass discharge through the streambed was obtained (Figure 11). It was found that a majority of the mass discharging was localized in a relatively small portion of the streambed (Figure 11). With this information, a targeted and effective remedial system could be designed to focus on the so-called 'hot-spots'.

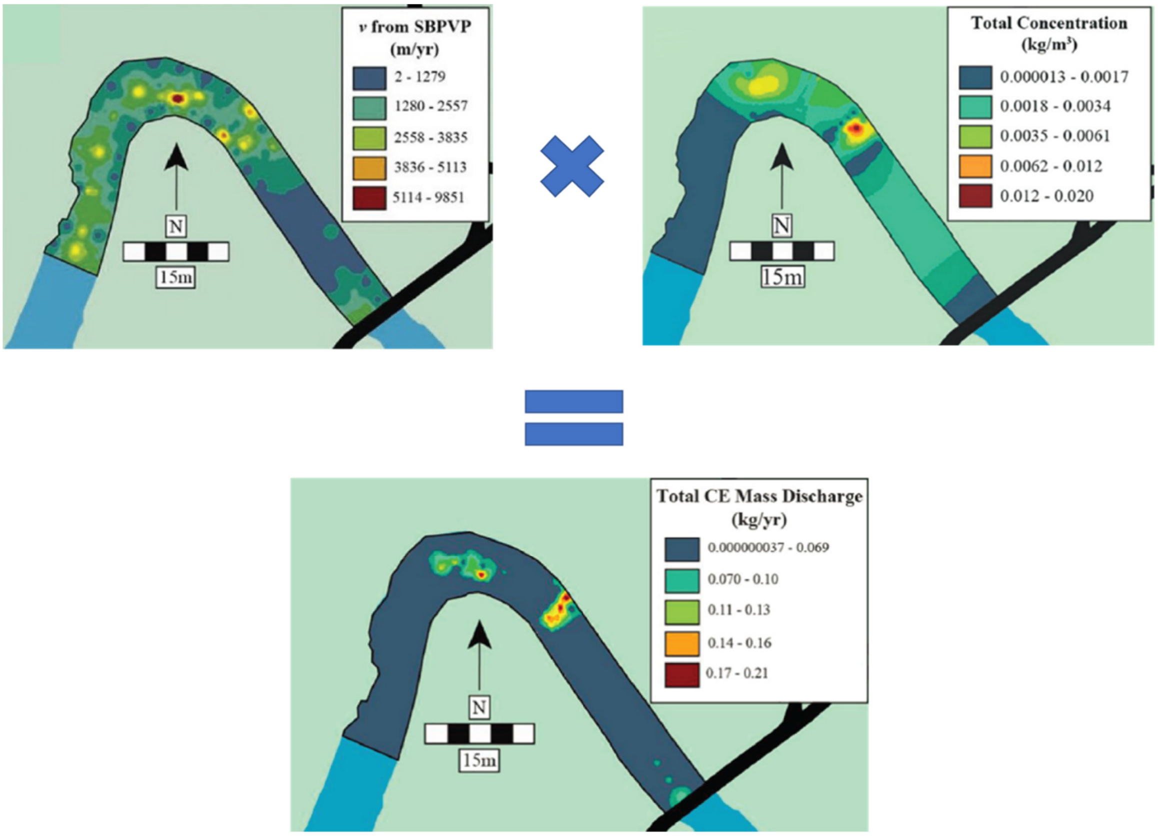

Figure 11. Distribution of vertical groundwater velocity (upper left) and aqueous concentration of chlorinated ethenes (upper right) along the study section of the meandering stream. The product of the two distributions, contaminant mass discharge (bottom center), highlights the discrete zones of high contaminant movement through the streambed into the stream. Modified from Cremeans *et al* (2018).

Assessment of Engineered Systems

Many engineered systems require the field validation of flow conditions throughout the lifecycle of the system. In addition, many engineered lakes may have leaks that need to be delineated and repaired. The SBPVP has proven to be quite useful in such applications.

A demonstration of the utility of the SBPVP within an engineered pond was described by Cremeans *et al.* (2019). This study took place at a passive remediation site where contaminated mine waters discharging at the surface, under artesian conditions, were collected and directed through a series of surface water detention ponds where the water was sequentially treated and ultimately discharged into a nearby stream. One of the detention ponds in the treatment process was a vertical flow bioreactor (VFBR) that chemically reduced metals in the contaminated water and bound them as organically sorbed species or solid sulfide minerals. One of the keys to the systems success was the uniformity of flow through the reactive media, that constituted the bed of the pond, and the residence time of the water within the bed. The uniformity of flow was assessed and confirmed to be uniform everywhere except one corner of the treatment cell, near the inlet pipe, where the force of the incoming water physically degraded the treatment medium, decreasing the overall hydraulic conductivity of that corner (Figure 12). The SBPVP measurements indicated that the metal attenuation rates in the field system were approximately two orders of magnitude greater that those anticipated in design testing.

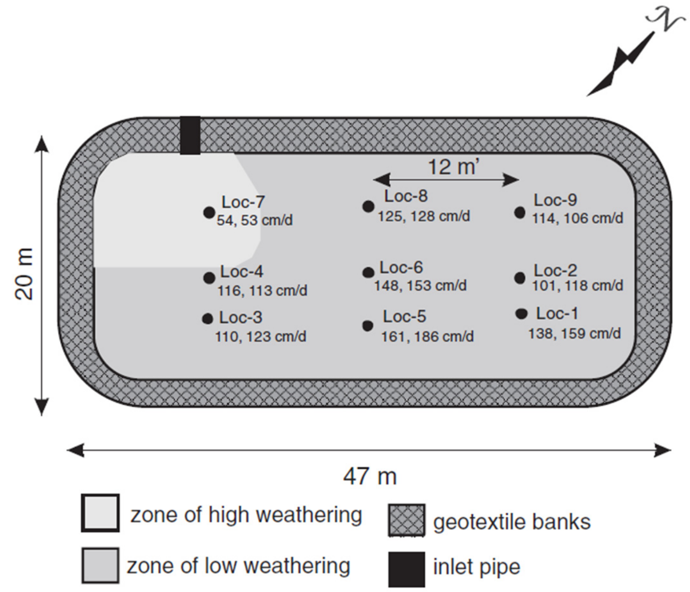

Figure 12. Plan view of the VFBR cell, showing the SBPVP sampling locations and estimated downward seepage velocities through the substrate. Taken from Cremeans *et al* (2019).

IWPVP Case Studies

IWPVPs have been deployed on several industrial sites around the world to better understand groundwater flow distributions. For example, groundwater flow across a heterogeneous alluvial aquifer on a former refinery site was mapped as part of a risk assessment program. The overall site geology was fairly heterogeneous comprised of approximately 20 feet of tight clays with spatially discontinuous lenses of sand and gravel. Drilling observations indicate that the sand and gravel seams were highly localized; boreholes less than 2 m apart showed lenses to be discontinuous over this interval. As the flow across the site is conceptualized to be controlled by presence and connectedness of the sand and gravel seams, IWPVPs were deployed to better understand the dynamics and distributions of the groundwater flow field.

The IWPVPs used for the profiling at this site were multi-level units with two IWPVPs separated by a two-foot vertical spacing. Over a testing period of 4 days, two operators were able to collect 218 measurements of groundwater velocity at 16 groundwater monitoring wells across the site. The measurements were then used to generate depth profiles of groundwater velocity for each monitoring well visited. This enabled the determination of the presence of preferential flow pathways with anomalously high seepage velocities relative to the average velocity for the site (Figure 13). Depth profiles were also used to investigate the lateral connectivity of high and low flow zones across the site. Additionally, average flow behavior for each measurement location was mapped on water table and plume contour maps to highlight areas where the complementary data did not agree. These regions were flagged as areas where further investigation is needed to better understand the groundwater flow system and potential causes for the discrepancy (Figure 13). The overall findings of the IWPVP investigation provided independent data on the spatial distribution and variability of the groundwater flow field for the first time at this site and generally confirmed the expected average trends in flow. However, the IWPVP measurements also identified some locations with anomalous velocities that appears to be consistent with plume distributions on the site. On this basis, the IWPVP survey enhanced the understanding of the site hydrogeology and helped guide the selection of future monitoring locations.

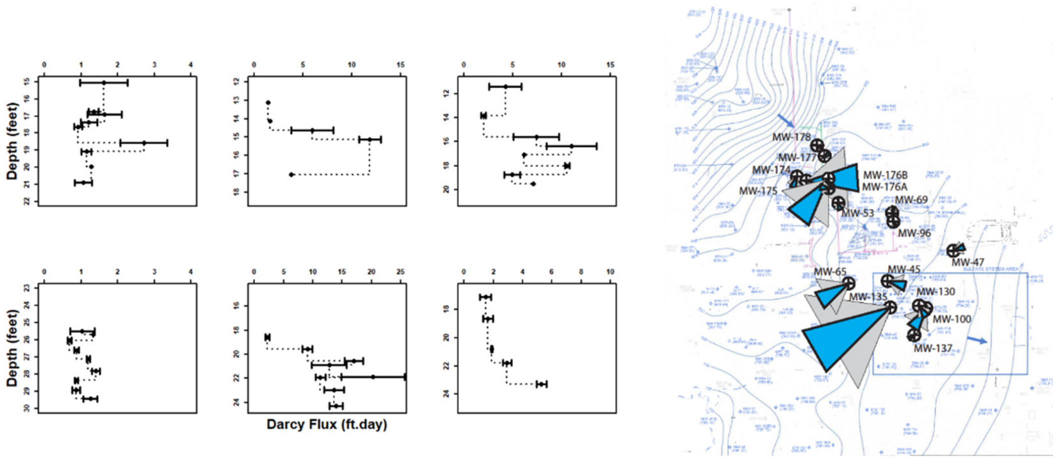

Figure 13. IWPVP depth versus flux profiles (left) for six of the 16 wells sampled throughout the four-day field campaign. The average flow behavior of the 16 wells sampled plotted on the water table contour map (right) allows for easy visualization of high and low flow zones as well as areas where IWPVP measurements highlight areas requiring further investigation to understand discrepancies between measurement methods. Modified from Osorno *et al* (2020).

F-IWPVP Case Studies

Preliminary laboratory and field findings for IWPVP adaptations to fractured settings (the F-IWPVP) are described in Heyer (2021), Heyer *et al* (in review) and Heyer *et al* (in preparation). A brief summary of the results of the above works is provided here.

Initial laboratory testing of the F-IWPVP was conducted in a physical model of a single fracture apparatus. The work focused on a two-inch diameter F-IWPVP design to measure the flow in fractures with two distinct apertures, 500 µm and 1290 µm. It was determined that the F-IWPVP was able to accurately measure the groundwater flux through the two fracture apertures over a broad range of groundwater fluxes (Figure 14). In addition to the linear response of the F-IWPVP to changes in flux through the fracture, the lab testing also verified the ability of the F-IWPVP to measure groundwater flow direction to within ± 20°.

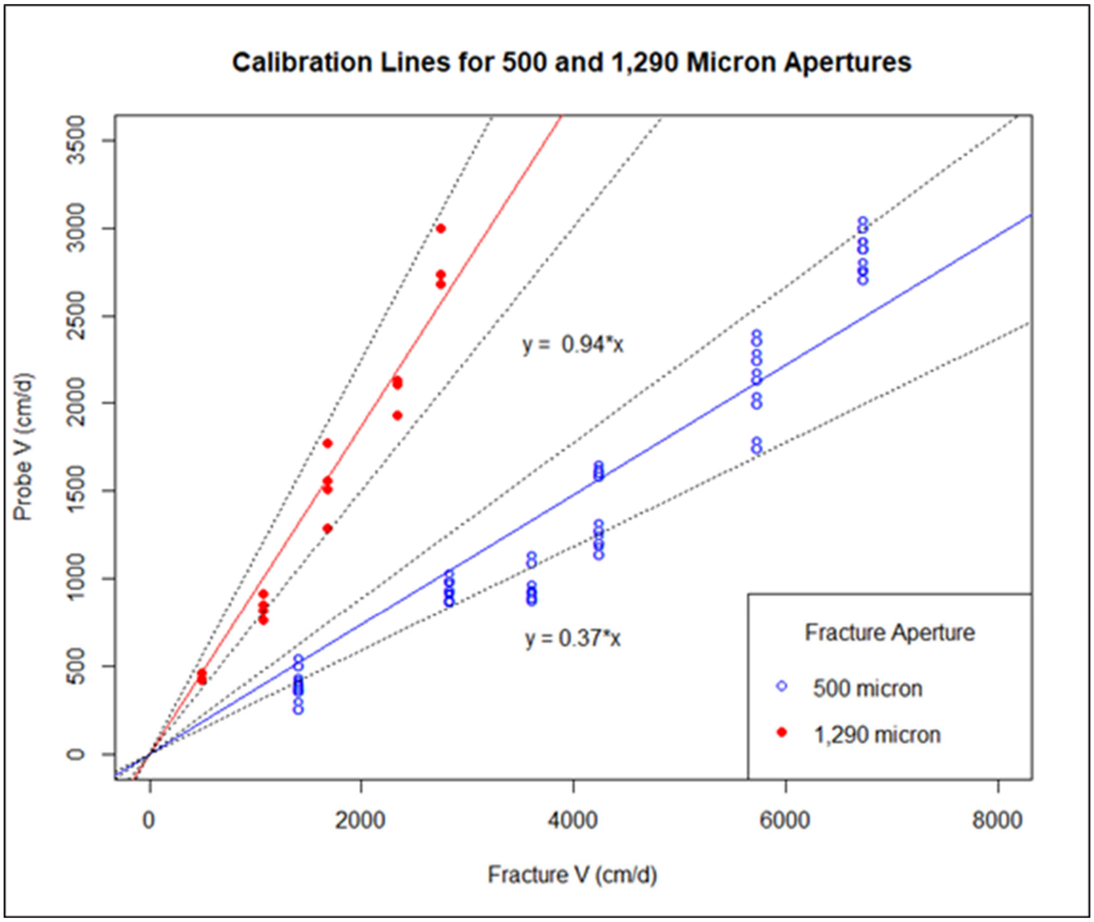

Figure 14. Linear relationship between measured F-IWPVP velocity and calculated water velocity through the fracture flow apparatus for two fracture apertures. The dotted lines indicate ± 25% error on calculated slopes.

Based on the promising results of the laboratory testing, initial field testing was conducted to verify the performance of the F-IWPVP in a fractured rock aquifer. The field testing was conducted at the Edwards Air Force Base, California, as part of a comparative study with groundwater flow sensors from another, independent, study. Depth profiles of groundwater velocity were collected from two boreholes using the F-IWPVP. The first was a 3-inch screened well that was also profiled with passive flux meters (PFM) and oxidation-reduction potential (ORP) sensors. The second was a 6-inch uncased borehole that had previously been instrumented with a FLUTe liner to profile the transmissivity of the borehole. All of the technologies used in this study compared well, with the relative water fluxes in the two wells showing strong similarities (Figure 15). Furthermore, with additional information on fracture apertures the F-IWPVP measurements can be calibrated for the estimation of absolute values of flux within the aquifer fractures. The F-IWPVP was also the only tool in the study capable of measuring groundwater flow direction. This feature was highly advantageous in documenting the effect of a brief (several hours), intense rainfall on the aquifer hydrogeology. The F-IWPVP showed that groundwater experienced a 180° shift in the flow direction in response to the precipitation event (Figure 16). Flow reversals, and their durations, can have significant impacts on remedial design and plume migration. This finding highlights a significant advantage of profiling with the F-IWPVP over other groundwater flow measurement techniques.

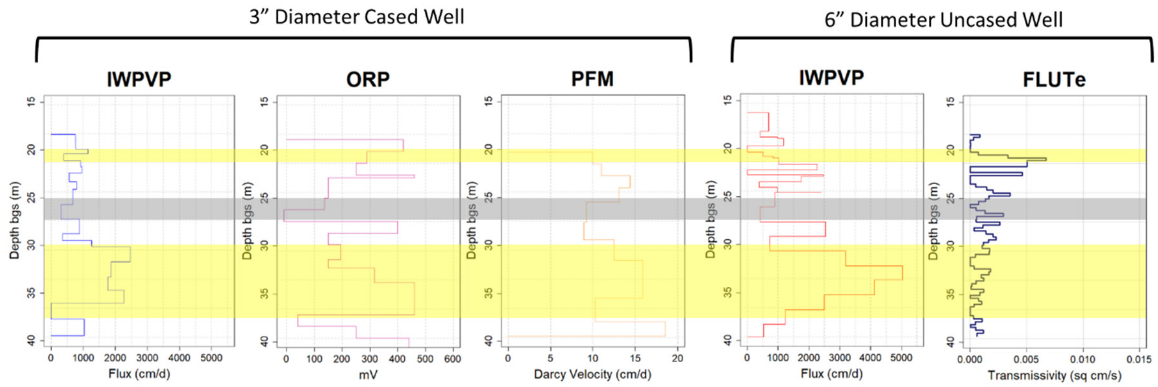

Figure 15. Comparison of depth profiles for all methods deployed in the two boreholes profiled at Edwards Air Force Base. Highlighted areas indicate similar trends of rate of flow with depth between profiles (yellow indicates areas of high flux and gray indicates areas of low flux). Modified from Heyer *et al* (in preparation).

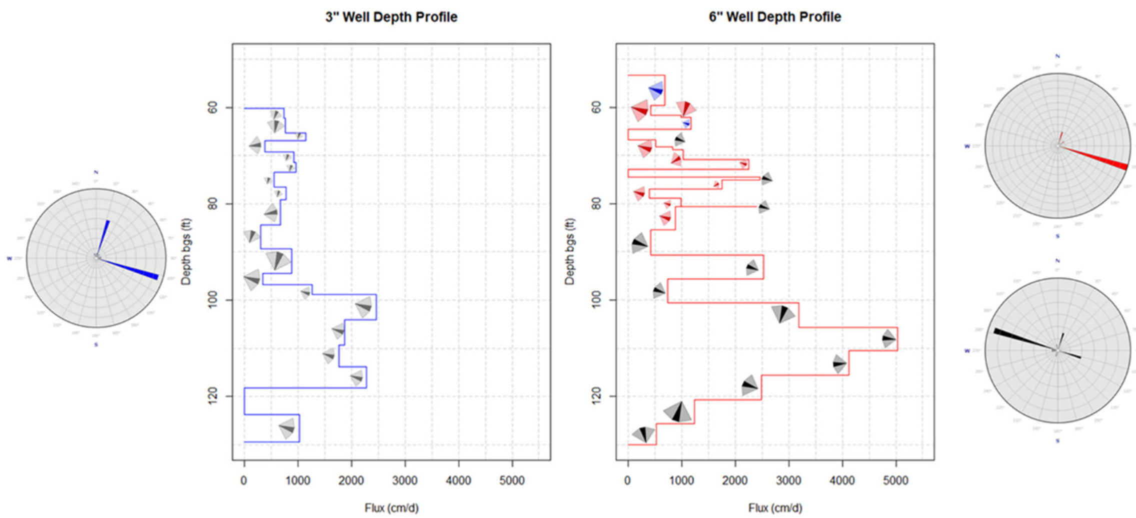

Figure 16. Depth profiles of F-IWPVP measured fluxes for the two boreholes profiled at Edwards Air Force Base. Rose diagrams show the general flow direction trend for each borehole. The blue and red rose diagrams refer to pre-rain event conditions and the black rose diagrams refer to post-rain event conditions. Modified from Heyer *et al* (in preparation).

Designing an Effective PVP Characterization Study

The biggest factor in the success of a PVP characterization study is the proper understanding of the problems or questions the study aims at addressing and a proper understanding of the environment in which the study will be taking place. There are a wide range of PVP tools that can be drawn upon, but each have their specific limitations. A summary of each device in the PVP family of tools is provided in Table 1. Additionally, a decision-making tree to assist in the selection of the correct device is provided at the beginning of the 'Point Velocity Probe Family of Tools' section (Figure 1)

There is no doubt that if you are looking to flow-based characterization to address specific problems or questions about a site, you are on the cutting edge of what characterization techniques are available. OUL is available to provide assistance as one of the few consulting firms with extensive experience in direct groundwater velocity measurement. With that said, do not be afraid to ask for help. With commercial probes being available through Solinst, a leader in groundwater monitoring technology, it is now possible to subcontract the instrumentation fabricated for a specific site or application and the expertise to ensure the best possible results from the work. As with any new tool, proper training and expertise in the design and field implementation will go a long way in the overall data quality and success of the project. The professional staff at OUL has had a hand in developing all of the PVP tools currently available and are available to provide expertise at any level to ensure all PVP related projects are conducted at the highest level possible.

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