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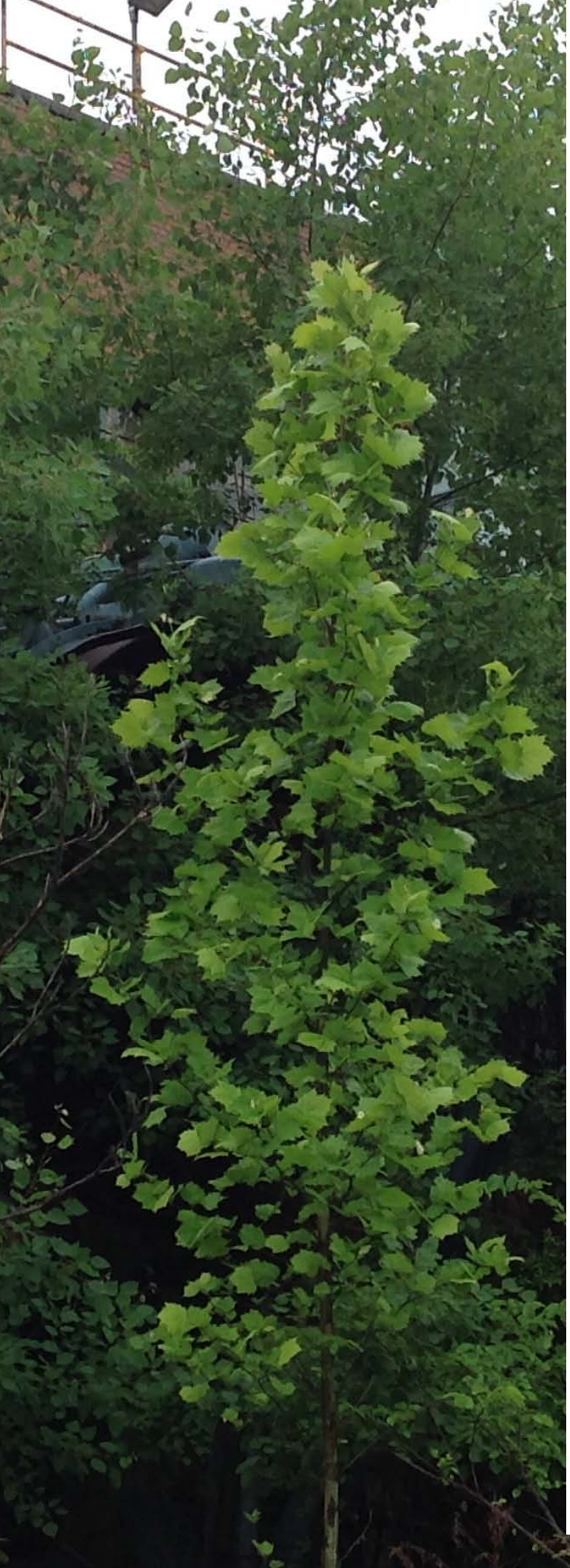
United States Environmental Protection Agency

Comparative Evaluation of Contaminant Mass Flux and Groundwater Flux Measurements in Fractured Rock Using Passive Flux Meters

PROJECT REPORT

Office of Research and Development
National Risk Management Research Laboratory



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Site photographs taken on location at the former Naval Air Warfare Center (NAWC), West Trenton, New Jersey
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DISCLAIMER

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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ACRONYMS

ATV	Acoustic Televiewer
bgs	Below Ground Surface
BHD	Borehole Dilution
cm	centimeters
DCE	cis-1,2-dichloroethene
DNAPL	Dense Non-Aqueous Phase Liquid
EPA	United States Environmental Protection Agency
ft	feet
FLUTe™	Flexible Underground Liner Technology
FRPFM	Fractured Rock Passive Flux Meter
gpm	Gallon per Minute
HPFM	Heat Pulse Flow Meter
in	inch
KCl	Potassium Chloride
KVA	K-V Associates, Inc., presently known as Kerfoot Technologies, Inc.
LPM	Liters per Minute
m	meters
µg/L	micrograms per liter
mg/L	milligrams per liter
mm	millimeters
mS/cm	milliSiemens per centimeter
MSPFM	Modified Standard Passive Flux Meter
NAWC	Naval Air Warfare Center
ORD	Office of Research and Development
OTV	Optical Televiewer
PFM	Passive Flux Meter
PVC	Polyvinyl Chloride
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/ Quality Control
RARE	Regional Applied Research Effort
RPD	Relative Percent Difference
TCE	Trichloroethene
TOC	Top of Casing
UF	University of Florida
USGS	U.S. Geological Survey
VOC	Volatile Organic Compound

ABSTRACT

Cost effective and reliable techniques are needed for the characterization of contaminated fractured rock aquifers. Two important characteristics of contaminant transport are groundwater velocity (or flux) and contaminant mass flux. Conventional methods for characterization in fractured rock cannot directly measure groundwater or contaminant mass flux. Therefore, the purpose of this project was to assess the ability of two technologies, the modified standard passive flux meter (MSPFM) and the fractured rock passive flux meter (FRPFM), to measure groundwater and contaminant mass flux in fractured rock. These measurements were compared to more conventional fractured rock characterization methods, including a borehole dilution (BHD) test. The comparative study of these techniques was conducted in a well at the former Naval Air Warfare Center Research site located in West Trenton, New Jersey. This research site, which consists of fractured sedimentary rock, is operated by the U.S. Geological Survey (USGS) as part of the USGS Toxic Substances Hydrology Program. Tests conducted in the well centered on a transmissive fracture identified at 28.7 m (94 ft) below ground surface through previous characterization activities.

Average groundwater flux measurements from the BHD test, MSPFM, and FRPFM were 1.5 cm/day, 2.6 cm/day, and 2.7 cm/day, respectively. Estimates of groundwater flux based on the MSPFM and FRPFM were very similar, but were almost a factor of two higher than the BHD test results. Measurements of groundwater flux vertical distributions were also completed with the MSPFM and FRPFM. However, the spatial patterns of groundwater flux as measured with the MSPFM and FRPFM were not similar. Average trichloroethene mass flux measurements from the BHD test, MSPFM, and FRPFM were 18.8 mg/m^2/day, 31.5 mg/m^2/day, and 116 mg/m^2/day, respectively. Likewise, average cis-1,2-dichloroethene mass flux measurements from the BHD test, MSPFM, and FRPFM were 14.6 mg/m^2/day, 40.7 mg/m^2/day, and 68.2 mg/m^2/day, respectively. In both cases, the BHD gave the lowest estimates while the FRPFM gave the highest. As with groundwater flux, spatial measurements of contaminant flux based on the MSPFM and FRPFM were not similar. Differences in results between the technologies most likely stem from differences in measurement design and method, but natural variability in conditions during the tests may also be a factor. Moreover, damage to the FRPFM during retrieval may also have been a factor in the results obtained.

The MSPFM, compared to the FRPFM, was easier to implement, and is judged less likely to be damaged during deployment and retrieval. However, because of its design it is also more susceptible to sampling bias during deployment and retrieval. The FRPFM was the most complex method to use compared to the MSPFM and BHD test. The FRPFM was damaged during retrieval in this study, suggesting this technology is more fragile than the BHD test or MSPFM. At present, the best use for the FRPFM would be those applications where high resolution data is needed over short intervals. Further development of the FRPFM technology may result in a more widely applicable measurement method. Comparisons of the spatial distributions of groundwater flux and contaminant mass flux between the MSPFM and FRPFM as measured in this project indicate more research is needed to further assess the accuracy and reliability of the measured spatial distributions. Controlled experiments in which the true distribution is known would be helpful in this regard.

SECTION 1
Introduction

1.1 Purpose

At contaminated groundwater sites, groundwater flux or specific discharge (q_0) and contaminant mass flux (J_c) are important parameters that can be used to understand the significance of contaminant loading to an aquifer, evaluate contaminant fate and transport, assess risk, design a groundwater remediation system, and assess remedial performance. The purpose of this project, funded by the United States Environmental Protection Agency (EPA) Office of Research and Development's (ORD) Regional Applied Research Effort (RARE), was to:

- Assess the ability of the modified standard passive flux meter (MSPFM) and the fractured rock passive flux meter (FRPFM) to measure q_0 and J_c in a fractured bedrock setting, and
- Compare and contrast the MSPFM and FRPFM results with results obtained using investigative methods typically deployed at sites to characterize fractured bedrock hydrogeology. These methods include open-hole methods: borehole geophysical logging, vertical component borehole flow meter under pumped and ambient conditions, Flexible Underground Liner Technology (FLUTe™) transmissivity profile, dilution testing, and low flow or wireline groundwater sampling at various depths; and a closed-hole method: packer testing/ sampling.

Work on this project was conducted in accordance with the Quality Assurance Project Plan (QAPP) prepared by EPA (EPA, 2015). This report details the results of this project and provides a comparative evaluation of the MSPFM and FRPFM technologies relative to conventional fractured rock characterization methods, including an assessment of how easily the technologies can be adopted at other fractured rock sites.

BHD testing

1.2 Roles and responsibilities

The project was performed by personnel from the University of Florida (UF) and CDM Smith with technical oversight from the EPA ORD and the EPA Region 2 Superfund Program. The MSPFM is an adaptation of the passive flux meter (PFM), which was patented by UF (Hatfield et al., 2002) and currently licensed by EnviroFlux, LLC for commercial use. The FRPFM was patented by UF (Klammler et al., 2008) and is not currently licensed for commercial use. Tasks to be completed by UF were specified in a sole-source contract and tasks to be completed by CDM Smith were specified in Task Order Number 015 under STREAMS II subcontract No. 9-312-0213151-51241L.

1.3 Methods for estimating groundwater flux and mass flux

The borehole geophysical methods typically deployed at sites to characterize fractured bedrock hydrogeology, some of which are described in Section 3.1, cannot directly measure q_0 or J_c.

A borehole dilution (BHD) test, when combined with groundwater sampling from the test interval, can be used to estimate q_0 and J_c. As explained in Section 2 of this report a BHD test, using packers to isolate the test interval, was used to calculate q_0 and to collect samples for volatile organic compound (VOC) analysis from the test interval. The use of packers has the advantage of reducing or eliminating vertical flow in the test interval which otherwise interferes with accurate q_0 measurements. The packers also allow VOC concentrations to be determined in specific zones.

Borehole dilution tests can also be conducted in an open borehole using methods that rely on either replacing the water in the borehole with low conductivity, deionized water (hydrophysical logging, Wilson et al., 2001), by injecting salt solution (Michalski and Klepp, 1990), or by introducing dye (Pitrak et al., 2007). All of the open-hole methods monitor the dilution process by running a probe up and down the borehole repeatedly to collect data on fluid conductivity or color intensity. Collecting groundwater VOC data from the open hole could be done with a pump or, preferably, by packer sampling after the dilution test is completed. Packer sampling can isolate zones for sampling from vertical flow in the borehole. Borehole dilution methods are not commonly used in many investigations at this time.

According to Hatfield (2015), while q_0 and J_c can be estimated from observed contaminant concentrations in fractured rock boreholes and depth-averaged groundwater flows calculated or measured under open-hole conditions, this approach is not likely to produce accurate estimates of q_0 and J_c for at least two reasons. First, the open borehole induces flow which is not natural or ambient and second, the open-hole methods take a “snap shot” at one point in time and do not account for variations in flow and concentration over time.

Open hole methods for estimating horizontal q_0 using borehole flow meters and hydrophysical logging are described in Wilson et al. (2001). The meters tested included the KVA heat pulse flow meter, the colloidal borescope, and the acoustic Doppler velocimeter in addition to hydrophysical logging (which measures fluid conductivity). These methods are not commonly used for the specific purpose of estimating horizontal q_0 in boreholes drilled in fractured bedrock at Superfund sites because the vertical flow commonly observed in these boreholes makes it difficult or impossible to obtain useful estimates.

High resolution temperature logging can be conducted in lined boreholes to locate and rank active (flowing) fractures under closed-hole conditions (Pehme et al., 2014). Closed-hole conditions can be approximated using a FLUTe™ liner or packers to isolate borehole sections (Cherry et al., 2007). The FLUTe™ liner seals against the entire borehole wall thereby eliminating the exchange of water and contaminant between fractures that occurs in open boreholes and in turn restores natural flows in fractures. At present, high resolution temperature logging is not typically used to characterize fractured bedrock boreholes at EPA Superfund sites.

Tracer injection during BHD testing

1.4 Definition of groundwater flux and mass flux

Groundwater flux, also called specific discharge, Darcy flux, Darcy velocity or filtration velocity, is the volumetric rate of flow per unit cross-sectional area. It is typically calculated using Darcy's law:

$$q_0 = \frac{Q}{A} = Ki \qquad (1\text{-}1)$$

where

q_0 = groundwater flux $[\mathrm{L/T}]$,

K = horizontal hydraulic conductivity, $[\mathrm{L/T}]$

i = hydraulic gradient $[\mathrm{L/L}]$,

Q = volumetric groundwater discharge $[\mathrm{L^3/T}]$, and

A = cross-sectional area $[\mathrm{L^2}]$.

Mass flux is the mass of a chemical (e.g., contaminants, amendments, and tracers) that passes through a defined cross-sectional area over a period of time. Contaminant mass flux represents the amount of contaminant mass transported by the volumetric groundwater discharge through a defined cross-sectional area. Mass flux is expressed as mass per area per time $[\mathrm{M/L^2/T}]$ (Kolditz, 2002; ITRC, 2010).

The mass flux can be calculated as follows:

$$J_c = q_0 * C_F \qquad (1\text{-}2)$$

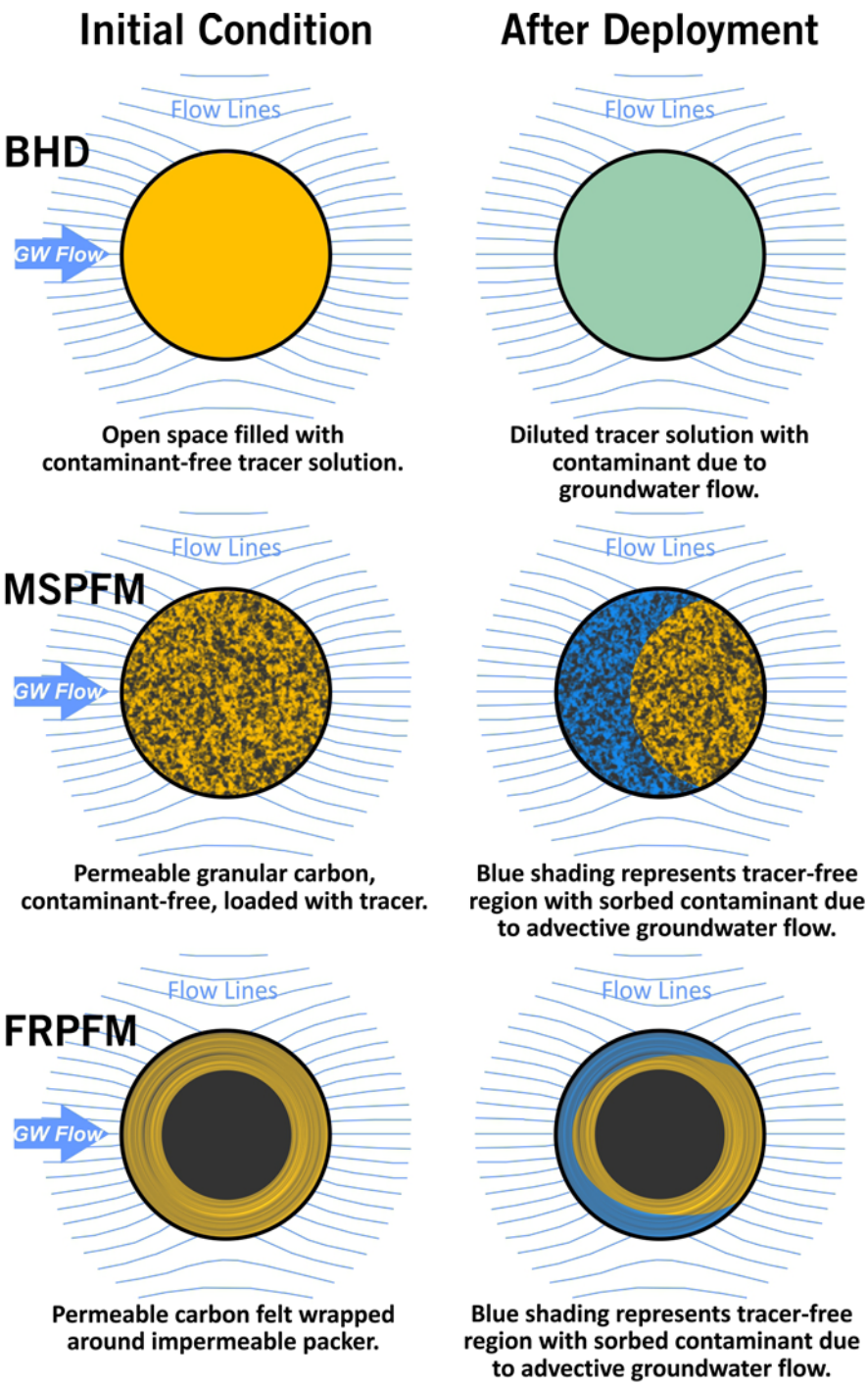
where

J_c = advective contaminant mass flux $[\mathrm{M/L^2/T}]$, and

C_F = concentration of contaminant in the groundwater $[\mathrm{M/L^3}]$.

Measures of q_0 and J_c are calculated directly from the MSPFM and FRPFM through tracer mass loss and contaminant mass accumulation over the deployment duration. These measures represent time-average values over the deployment duration. A detailed description of how q_0 and J_c are calculated using flux meter data may be found for the MSPFM in Hatfield et al. (2004), and for the FRPFM in Hatfield (2015). However, Figure 1-1 provides a conceptual illustration of the measurement theory for each of these methods as well as the BHD test. The ratio J_c/q_0 can be used to calculate the flux-averaged contaminant concentration, which is an estimate of the average contaminant aqueous concentration within the test interval. The average represents both a temporal average over the deployment duration, and a spatial average over the sampling interval. Estimates of q_0 and C_F were also obtained from a BHD test, and these results are compared to the q_0 and C_F values calculated from the flux meters. Previous work has shown good correlation between BHD and FRPFM results (Hatfield, 2015).

Monitoring flowrates during BHD testing



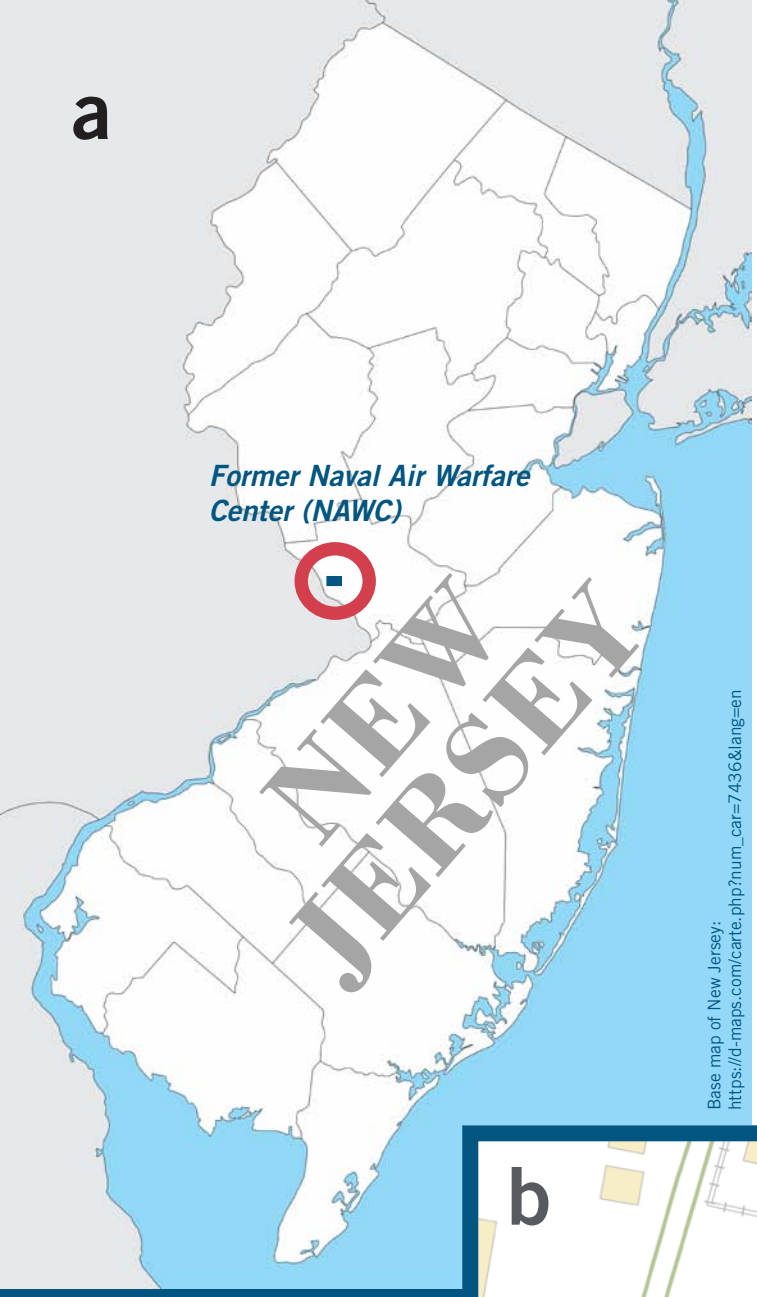
Groundwater flux is estimated from tracer dilution, as determined by measuring tracer concentration time series. Instantaneous mixing is assumed, and typically obtained using a pump. Contaminant concentration can also be measured in the solution to estimate contaminant flux.

Groundwater flux is estimated from the change in tracer mass over the deployment period, while contaminant flux is estimated from the accumulation of contaminant mass over the deployment period. These masses are based on sampling the sorbent matrix (shown here as granular activated carbon) after the deployment period.

Groundwater flux is estimated from the change in tracer mass over the deployment period, while contaminant flux is estimated from the accumulation of contaminant mass over the deployment period. These masses are based on sampling the sorbent matrix (shown here as permeable carbon felt) after the deployment period.

Figure 1-1. Conceptual illustration of the basis for groundwater and contaminant flux measurement using BHD, MSPFMs, and FRPFMs. Shown are cross-sectional views of each device at the start of the deployment and after a given deployment period. Groundwater flow is directed left to right.

Figure based on information provided in Hatfield et al., 2004, and Acar et al., 2013.



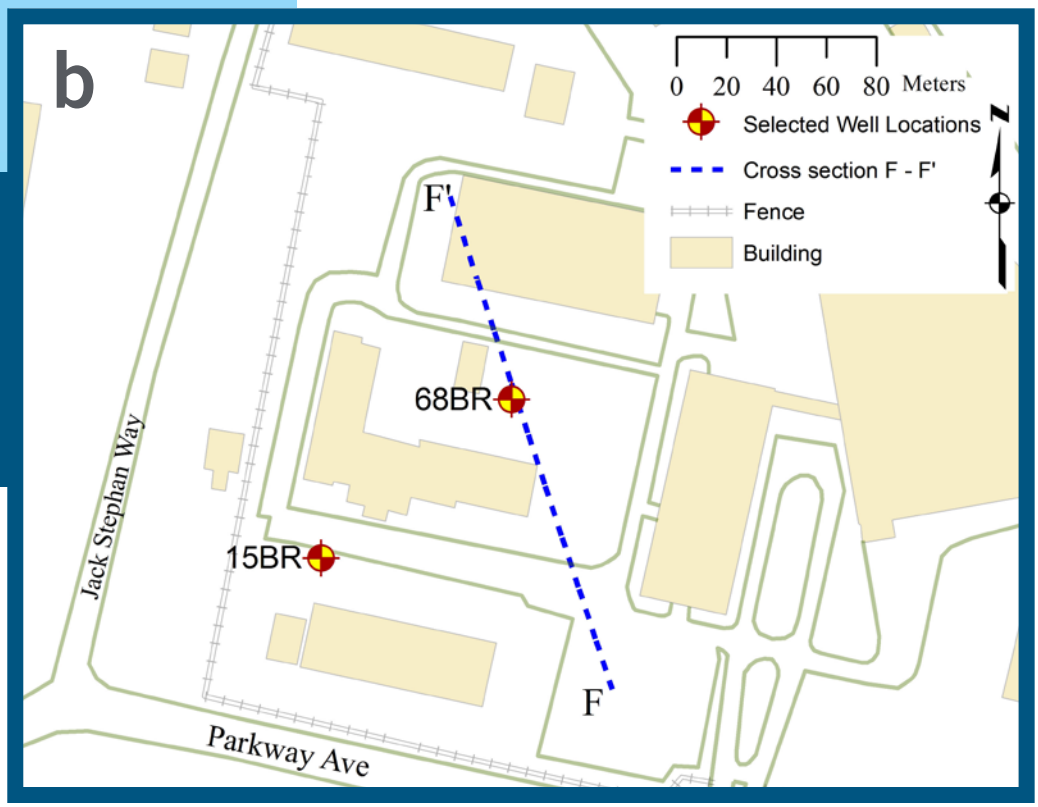


Figure 1-2. Location maps.

(a) Former Naval Air Warfare Center (NAWC).

(b) Pumping well 15BR, test well 68BR, and cross section F-F' location.

1.5 Test well selection and site hydrogeology

1.5.1 Test well selection

The former Naval Air Warfare Center (NAWC) is a 24 hectare (60 acre) facility located in West Trenton, New Jersey (Figure 1-2a). The NAWC served as a naval testing facility for aircraft jet engines from 1953 to 1994. During its operation, trichloroethene (TCE) was used as a heat exchange medium in testing aircraft engines under various environmental conditions. The handling and disposal of TCE at the site resulted in extensive groundwater contamination (Lacombe, 2000).

The U.S. Geological Survey (USGS) operates the NAWC Research Site as part of the USGS Toxic Substances Hydrology Program and scientists and engineers from the USGS and other institutions conduct research on the characterization and remediation of chlorinated solvents in fractured sedimentary rock (Lacombe and Burton, 2010). At the NAWC site these rocks include undifferentiated mudstones, massive mudstones, laminated mudstones, and fissile mudstones.

Well 68BR at the NAWC Research Site (Figure 1-2b) was selected by the project team as the test borehole for this project because:

- It is a 0.2 m (6 inch [in]) borehole cased with 6-inch diameter steel to 4.0 m (13 feet [ft]) below ground surface (bgs) with a 0.2 m (6 in) nominal diameter borehole extending to 52 m (170 ft) bgs. This borehole size is optimum for the use of the current FRPFM system. The steel casing extends 0.43 m (1.4 ft) above land surface.

- Historically, groundwater samples from this well show high levels of TCE and cis-1,2-dichloroethene (cis-1,2-DCE). In May 2009 TCE was detected in packer sampling interval "D" in well 68BR at a concentration of 20,800 micrograms per liter (µg/L) while cis-1,2-DCE was detected at a concentration of 7,470 µg/L (Geosyntec, 2010). Interval D extends from 27.7 to 30.5 m (90.8 to 100.1 ft) bgs and includes the interval tested during this study.

- Various open-hole and closed-hole investigative methods typically deployed at EPA Superfund sites to characterize fractured bedrock hydrogeology have been used in the borehole and the data sets are available for comparison. These include: borehole geophysical data, a FLUTe™ transmissivity profile, rock matrix sample results for TCE and other VOCs, and packer testing.

When well 68BR is not in use, a blank FLUTe™ liner is maintained in the borehole by the USGS to prevent vertical movement of groundwater and contaminants in the borehole.

Presently, the U.S. Navy, under oversight by the State of New Jersey, operates a groundwater pump and treat system at the NAWC site. Under typical pumping conditions, well 68BR is hydraulically influenced by the nearby pumping well 15BR (Figure 1-2b), located approximately 100 m (300 ft) SW of 68BR. Before, during, and after the BHD, the MSPFM deployment, and the FRPRM deployment conducted under this project, extraction well 15BR was not operating. During the time when 15BR was out of service, the total system pumping rate was maintained at the permitted level by increasing the pumping rate of other extraction wells.

1.5.2 Site hydrogeology

The NAWC site is underlain by sedimentary rocks in the Newark Basin (Figure 1-3). Soil and weathered rock cover the site to a depth of approximately 4.6 m (15 ft). The water table varies from 1.5 to 4.6 m (5 to 15 ft) bgs over the site (Lacombe, 2002). Well 68BR is completed in the Lockatong Formation which is bounded to the south by a fault separating the Lockatong from the Stockton Formation. A conceptual depiction of the site geology is shown in Figure 1-4.

Muds of the Lockatong Formation were deposited in Van Houten cycles during the Triassic Period, approximately 200 million years ago, lithified to form the bedrock that is typical of much of the Newark Basin. The four lithotypes include a basal red massive mudstone, black carbon-rich laminated mudstone, dark-gray laminated mudstone, and an upper light-gray massive mudstone. Diagenesis, tectonic compression, off-loading, and weathering have altered the rocks to give some strata greater hydraulic conductivity than other strata (Lacombe and Burton, 2010).

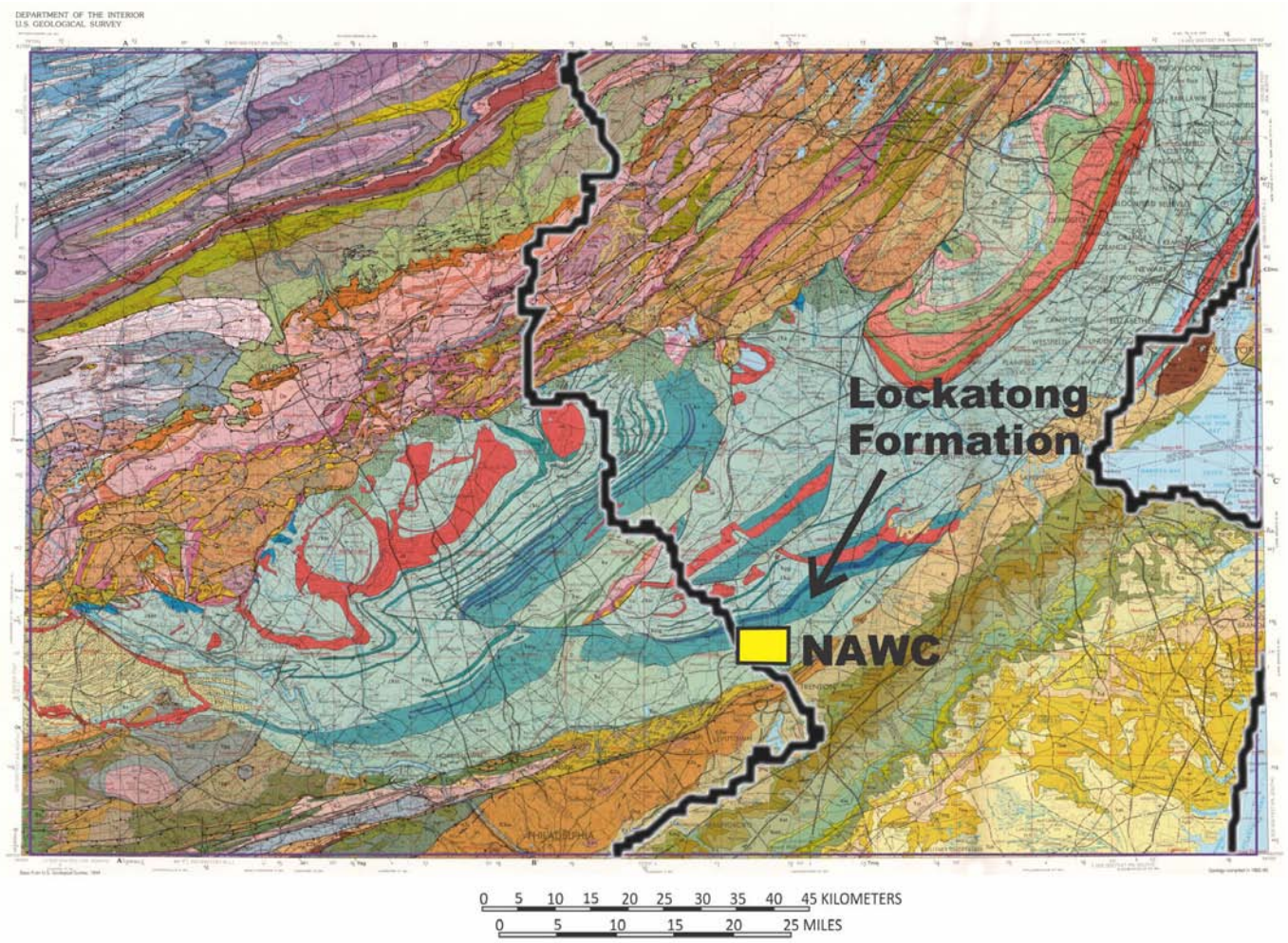


Figure 1-3. Site location relative to Lockatong Formation.

Map courtesy of U.S. Department of the Interior | USGS

Each stratum in the Lockatong Formation is 0.3 to 8 m (1 to 26 ft) thick, strikes N65°E, and dips 25° to 70°NW. The black, carbon-rich laminated mudstone is the more extensively fractured strata, has a relatively high hydraulic conductivity, and is associated with high natural gamma-ray count rates. The dark-gray laminated mudstone is less fractured and has a lower hydraulic conductivity than the black carbon-rich laminated mudstone. The light-gray and the red massive mudstones are highly indurated and tend to have the least fractures and a low hydraulic conductivity (Lacombe and Burton, 2010).

The detailed hydrogeologic framework developed for the site shows that black carbon-rich laminated mudstones are the most hydraulically conductive. Water-quality and aquifer-test data indicate that groundwater flow is greatest and TCE contamination is highest in the black, carbon- and clay-rich laminated mudstones. Large-scale groundwater flow at the NAWC research site can be modeled as highly anisotropic with the highest component of hydraulic conductivity occurring along bedding planes (Lacombe and Burton, 2010; Tiedeman et al., 2010).

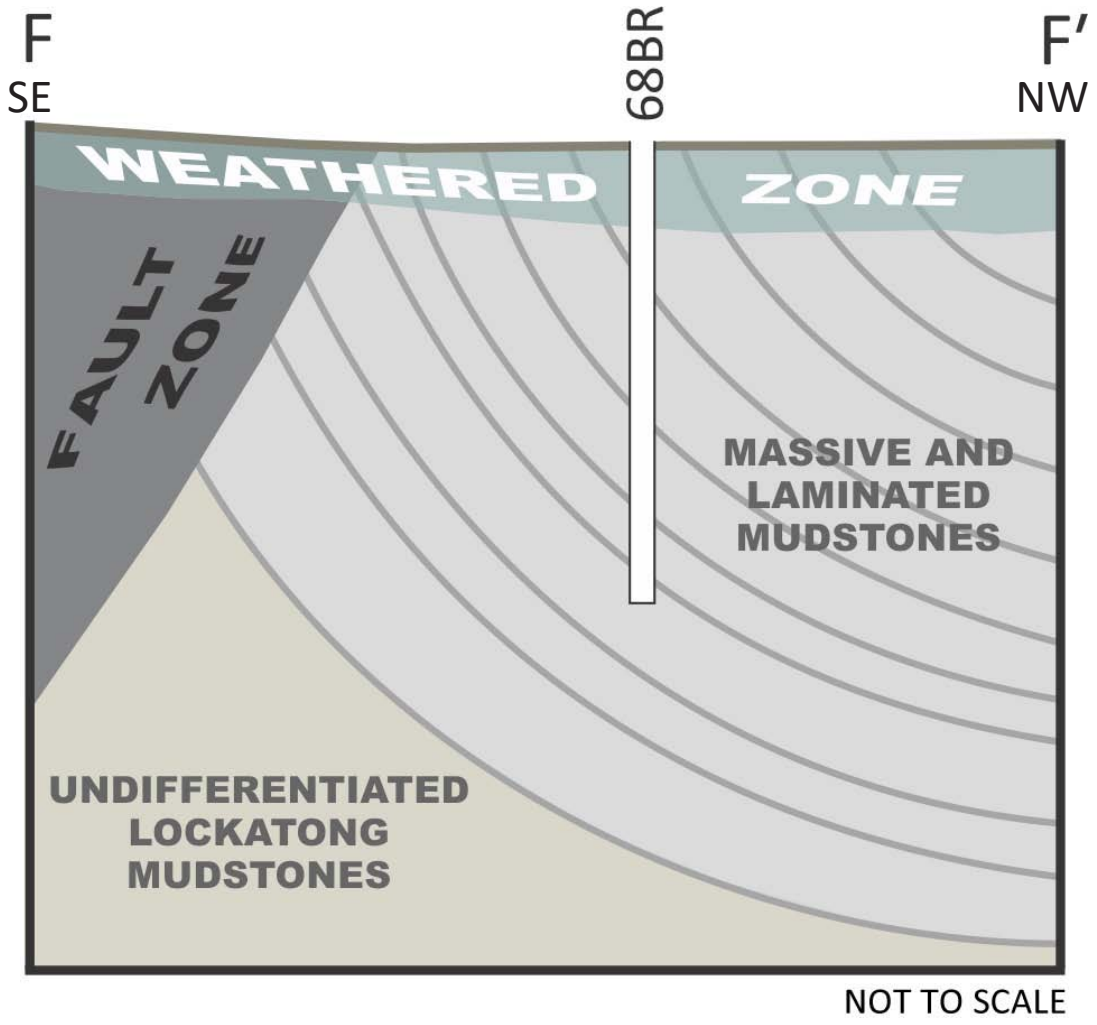


Figure 1-4. Conceptual depiction of geologic stratigraphy near well 68BR.
Adapted from Tiedeman et al., 2010, and Lacombe and Burton, 2010.

SECTION 2
Methods

Deployment of MSPFM

2.1 Overview

The BHD test, along with deployment, retrieval and sampling of the MSPFM and FRPFM, were conducted in accordance with the QAPP prepared by EPA (EPA, 2015) and procedures developed by UF (Hatfield, 2015). Each of these methods is illustrated in Figure 2-1. The BHD test, MSPFM, and FRPFM deployments were centered on a target depth of 29.0 m (95.1 ft) bgs. This depth was selected to be consistent with previous work conducted using the FRPFM in this borehole (Hatfield, 2015) and is 0.3 m (1 ft) below the transmissive fracture identified at 28.7 m (94 ft) bgs in previous geophysical logging of the borehole (see Section 3.1). The fracture is in a fissile black shale approximately 0.3 m (1 ft) thick which extends from 28.7 to 29.0 m (94 to 95 ft) bgs. Analysis of the acoustic televiewer (ATV) log by CDM Smith shows that the dip azimuth is 1.7 degrees, and the dip angle is 32 degrees.

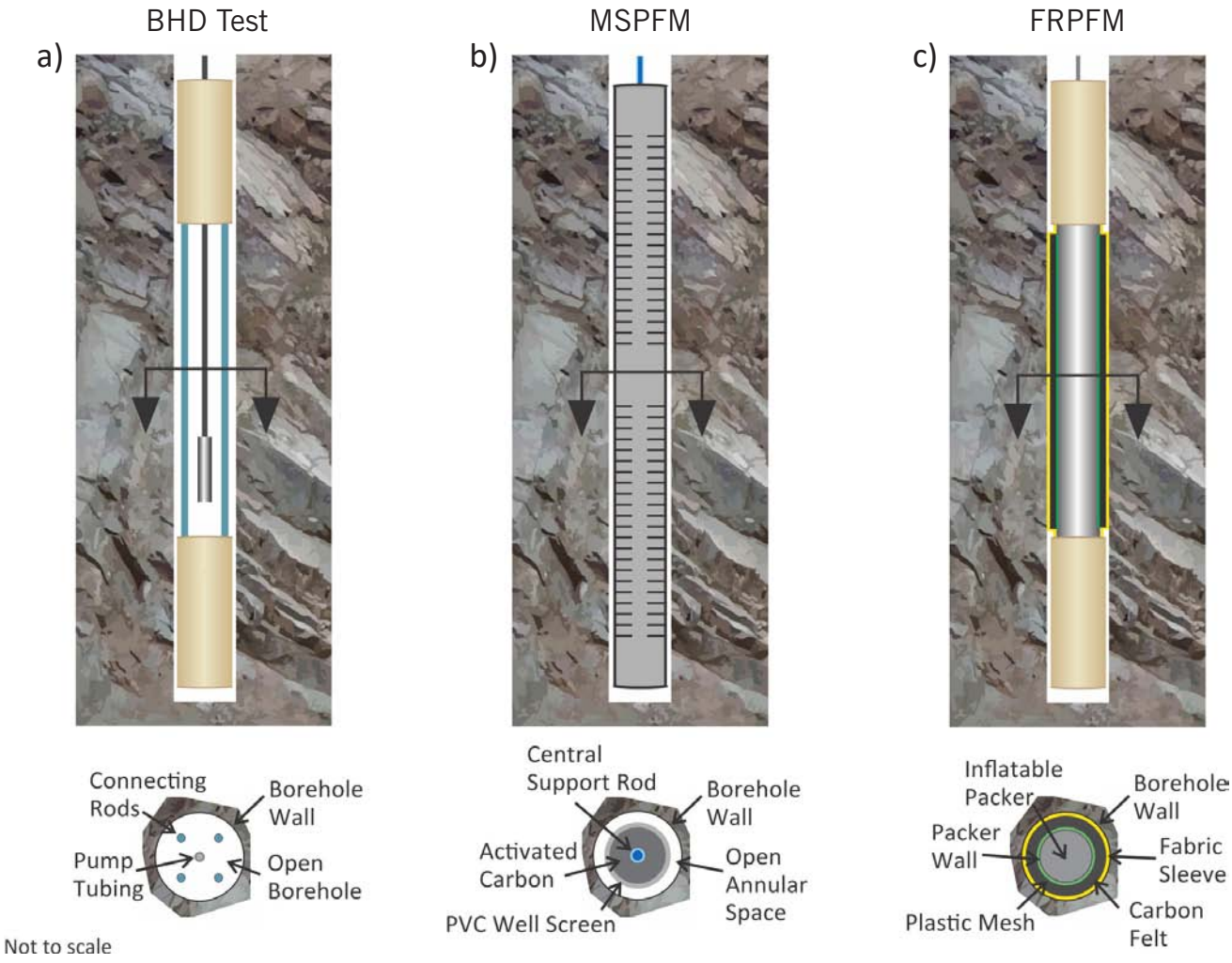


Figure 2-1. Schematic depiction of test methods: a) BHD, b) MSPFM, and c) FRPFM.

Table 2-1 lists the start and finish date of each element of field work conducted during this project.

Table 2-1 Summary of activities

Date	Activities and comments
6/1/15	Install borehole dilution rig in 68BR. Pump does not work. Retrieve rig, check and fix pump, probably clogged with sediment.
6/2/15	Install borehole dilution rig and start BHD. Test interval 28.4 to 29.5 m (93.3 to 96.9 ft) bgs.
6/3/15	Monitor BHD and collect groundwater samples for VOC analysis.
6/4/15	Complete BHD, remove BHD rig from well, conduct insertion/retrieval test using MSPFM.
6/5/15	Deploy MSPFM from 27.4 to 30.7 m (89.9 to 100.6 ft) bgs.
6/5/15 - 6/23/15	MSPFM deployed.
6/23/15	MSPFM retrieved and sampled.
6/24/15	FRPFM assembled and deployed. Test interval 28.6 to 29.5 m (93.7 to 96.7 ft) bgs.
6/24/15 – 7/1/15	FRPFM deployed.
7/1/15	FRPFM retrieved and sampled.

A specialized tripod provided by UF was used to install and remove equipment from the well. Prior to starting the test the blank FLUTe™ liner installed in 68BR was removed (Figure 2-2).

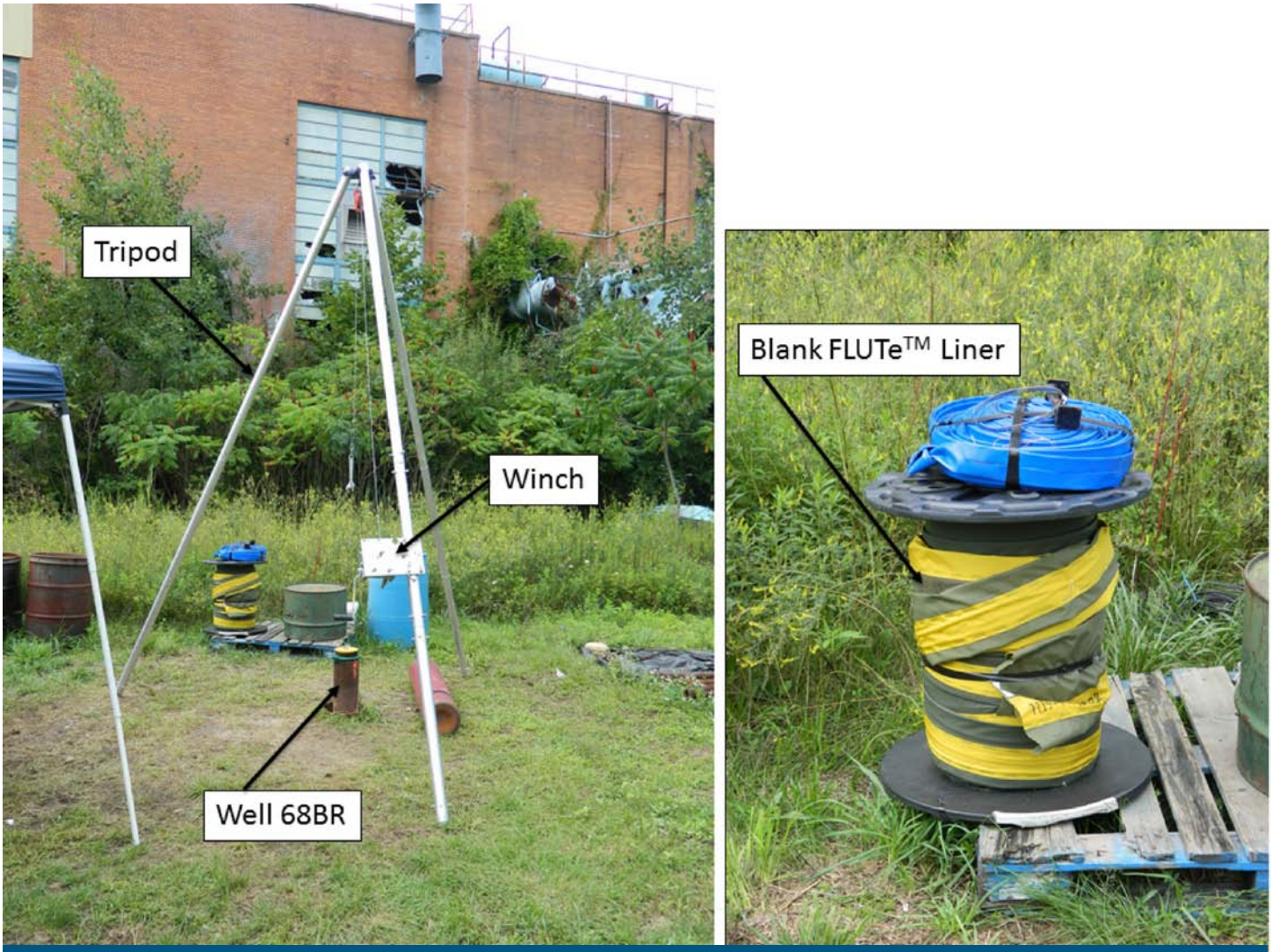


Figure 2-2. Tripod used to install and remove equipment from well 68BR and blank FLUTe™ liner.

2.2 Borehole Dilution Test

A BHD test was conducted to estimate the specific discharge and concentration of cis-1,2-DCE and TCE in the test interval. These target compounds were chosen because TCE was used extensively at the site and because cis-1,2-DCE is a degradation product of TCE. To conduct the BHD test, UF deployed a custom built rig in the borehole (Figure 2-3). The rig includes packers at the top and bottom which isolate a 1.1 m (3.6 ft) long test interval.

After correcting a problem with the pump on 6/1/2015, the rig was deployed on 6/2/2015. The rig was installed so that the test interval extended from 28.4 to 29.5 m (93.3 to 96.9 ft) bgs with the center of the test interval at 29.0 m (95.1 ft) bgs. The packers were then inflated to isolate the test zone and the submersible pump was used to pump water from the test interval at a low flow rate of 0.5 to 1 liters per minute (LPM). The flow rate was regulated using the variable speed motor on the pump and a flow meter. The water was pumped from the well, through two conductivity meters in series and then discharged to a drum for disposal in the on-site treatment plant. Over the course of the next two hours a series of groundwater samples were collected for VOC analysis to assess the pre-dilution test VOC concentrations in the test zone. At the end of this period, the ambient electrical conductivity of 0.491 milliSiemens per centimeter (mS/cm) was measured. Then valves were used to recirculate water pumped to the surface, and through the conductivity meters, back down the tubing and into the test zone. One liter of potassium chloride (KCl) tracer solution, prepared using groundwater pumped from the well, was injected into the recirculating water, a peak specific conductance of 9.44 mS/cm was observed and the BHD was started at 12:44 EDT on 6/2/2015.

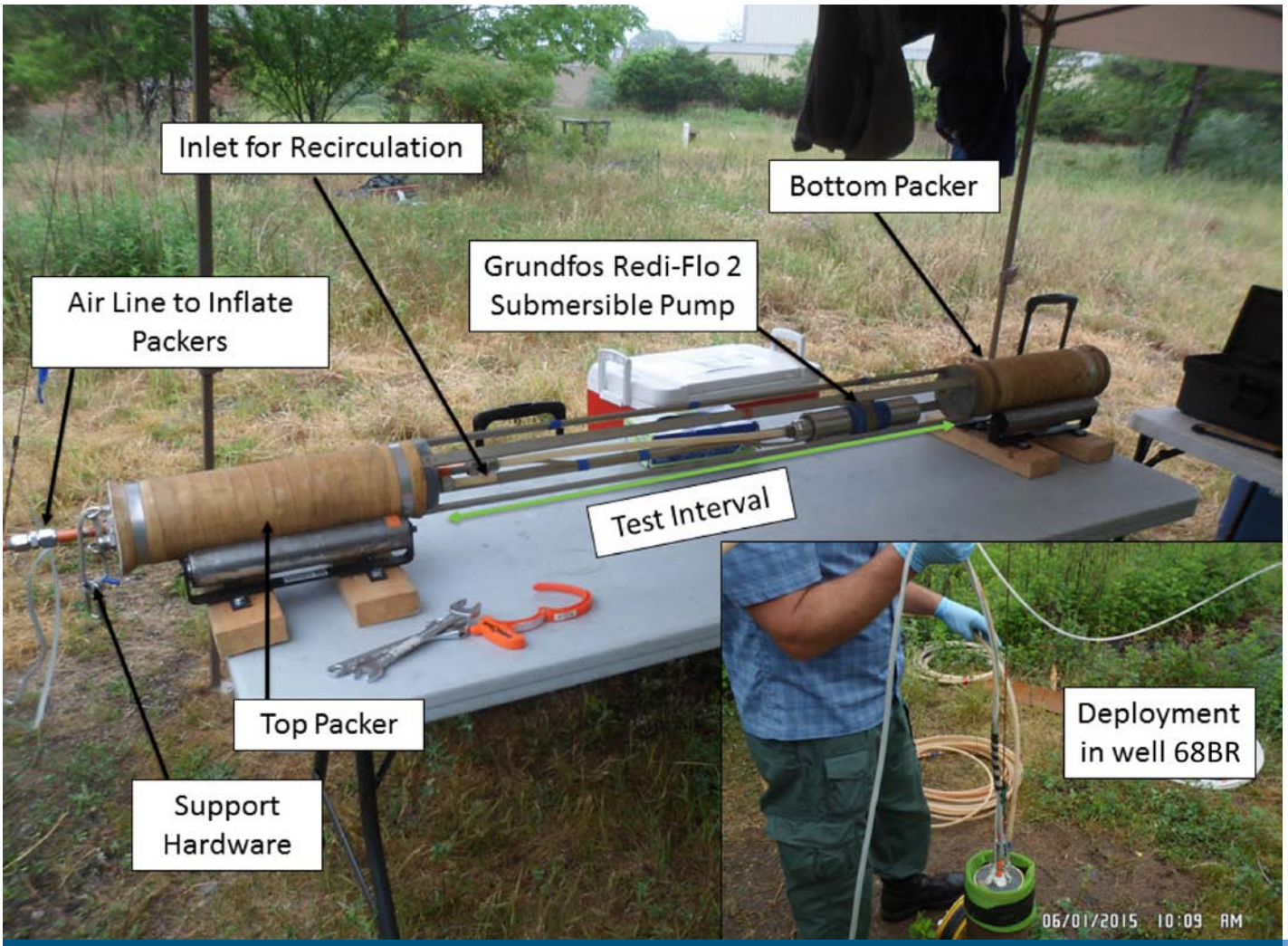


Figure 2-3. BHD test apparatus and deployment in well 68BR.

During the test, groundwater samples were collected at regular intervals for VOC analysis and the conductivity of the water was monitored, and the data logged continuously, using two meters to provide redundancy. After 42.5 hours from the start of the BHD, the conductivity had dropped to 6.72 mS/cm, and the test was stopped as sufficient data had been collected to define a log-linear trend in the conductivity-time series data. Table 2-2 lists the BHD sequence of events. The data were then analyzed using the procedure described in Pitrak et al. (2007) to calculate q_0. The results of the BHD are discussed in Section 3.1. The calculated q_0 was used to estimate an appropriate deployment time for the MSPFM and FRPFM.

Table 2-2 BHD test sequence of events

Date	Time (EDT)	Elapsed Time (hours)	Activity	Sample Numbers (See note)
6/2/15	08:55		Static Water Level: 2.46 m (8.08 ft) below top of casing (TOC)	
6/2/15	08:57		Begin Installation BHD rig, target depth 29.4 m (96.5 ft) below TOC	
6/2/15	09:48	-	Packers Inflated	
6/2/15	10:05	-	Start purging test zone, flow rate 0.5 LPM	
6/2/15	10:10	0	Low Flow Sampling, flow rate 0.73 LPM	1, 2, 3
6/2/15	10:46	0.6	Low Flow Sampling	4, 5, 6
6/2/15	11:36	1.43	Low Flow Sampling	7, 8, 9
6/2/15	11:43	1.55	Prepare 1 L of saturated KCl solution using water purged from well	
6/2/15	12:12	2.03	Low Flow Sampling, 80 L pumped from test zone	10, 11, 12
6/2/15	12:14	2.07	Stop pumping from and start recirculating water in the test zone	
6/2/15	12:19	2.15	Baseline conductivity established at 0.491 mS/cm	
6/2/15	12:39	2.48	Add concentrated KCl solution to test interval start BHD	
6/2/15	12:44	2.57	Start BHD, conductivity 9.44 mS/cm	
6/2/15	19:00	8.83	BHD Sampling	1, 2, 3
6/3/15	07:00	20.83	BHD Sampling	4, 5, 6
6/3/15	13:00	26.83	BHD Sampling	7, 8, 9
6/3/15	14:44	28.57	Depth to water: 2.26 m (7.40 ft) below TOC (see note)	
6/3/15	19:00	32.83	BHD Sampling	10, 11, 12
6/4/15	07:00	44.83	BHD Sampling	13
6/4/15	07:15	45.08	BHD stopped, total duration 2,550 minutes (42.5 hours)	

Samples were analyzed for VOCs. The observed decrease in depth to water between 6/2/15, before the test, and 6/3/15, during the test, was probably due to the inflation of the packers which isolated the fracture at 28.7 m (94 ft) bgs. This fracture has a lower head than the fractures in the shallow zone (see Section 3.1). Blocking the lower head fracture increased the head in the borehole and therefore decreased the depth to water.

2.3 Modified Standard Passive Flux Meter

2.3.1 Description

The MSPFM consists of a standard PFM placed inside a 0.1 m (4 in) diameter factory slotted poly-vinyl chloride (PVC) pipe to protect it from the abrasive borehole wall. A standard PFM, designed for unconsolidated sediments, consists of a central PVC pipe, norprene divider rings, and sorbent material packed inside a mesh sock. In the case of organic contaminants, the sorbent material is typically activated carbon, as it was in this study. The sorbent material retains dissolved contaminants present in the groundwater flowing passively through the meter. The contaminant mass intercepted and retained on the sorbent is used to quantify cumulative contaminant mass flux. The sorbent material is also impregnated with known amounts of water soluble alcohol tracers. These tracers are displaced from the sorbent at rates proportional to the specific discharge; hence, the amount of tracer remaining after deployment can be compared to the original amount and the results used to estimate the groundwater flux (Hatfield et al., 2004).

An important difference between applications of the MSPFM in fractured rock formations compared to either applications of the standard PFM in unconsolidated sediments or the FRPFM in fractured rock formations, is that the sorbent of the MSPFM does not actually come in contact with the borehole wall. The design of the MSPFM which protects it from the abrasive borehole wall results is an annular space between the device and the borehole wall (see Figure 2-1). This annular space allows water to preferentially flow around the device, and this may impact measurements. Another noteworthy difference between the MSPFM and the FRPFM is the deployment time. Deployment times were estimated prior to deployment based on site specific estimates of groundwater flux, and were 18 days for the MSPFM and 7 days for the FRPFM.

2.3.2 Insertion/Retrieval test

An “insertion/retrieval” test was conducted to determine how much VOC mass might be added and how much tracer mass might be lost simply by lowering the MSPFM into position in the test interval, from 27.4 to 30.7 m (89.9 to 100.6 ft) bgs, and then immediately removing it from well 68BR. In other words the effective deployment time of the MSPFM was zero. This test was conducted on 6/4/15. The MSPFM was shipped to the site in a PVC tube and was stored in the tube on-site until ready for use. Figure 2-4 shows the MSPFM used for this test, which was about 1.2 m (4 ft) long, and the process of sample collection. Note the norprene divider rings (Figure 2-4d) used to isolate sample intervals within the MSPFM and induce horizontal flow while limiting vertical flow. As shown in Figure 2-4a, the work table used during MSPFM sampling was covered with plastic sheeting, which was changed after use, to prevent cross-contamination. Samples were collected directly from the MSPFM into clean stainless steel bowls and homogenized with clean stainless steel spatulas. Pre-cleaned wide mouth clear glass jars were filled to the top with sample, labeled, and stored on ice for shipment to the laboratory at UF. After use, the bowls and spatulas were wiped clean with paper towels, rinsed with distilled water as needed, and air dried.

Figure 2-4. MSPFM insertion/retrieval test.

a) MSPFM used in "insertion/retrieval" test. b) Removing the standard PFM from the PVC screen. c) Collecting activated carbon from the PFM sample interval into a stainless steel bowl. d) Note gray norprene dividers used to sub-divide the PFM into sample intervals and to limit vertical fluid movement. e) Sample of activated carbon from the PFM ready to ship to the lab.

2.3.3 MSPFM deployment, retrieval, and sampling

The MSPFM was assembled and deployed on 6/5/15. The test interval was from 27.4 to 30.7 m (89.9 to 100.6 ft) bgs. The MSPFM was deployed and retrieved at the same speed as the MSPFM used during the insertion/retrieval test so that the loss and/or gain of mass data from the insertion/retrieval test could be applied to the data from the MSPFM. The MSPFM consisted of three 1.2 m (4 ft) long segments. The three MSPFM segments were shipped to the site in PVC tubes and were stored in the tubes on-site until ready for use. Figure 2-5 shows the sequence of MSPFM assembly and deployment.

After MSPFM retrieval on 6/23/15 a total of 20 samples, labeled S1 through S20, were collected from the MSPFM by homogenizing sorbent over fixed intervals, and then collecting a sub-sample for analysis. The samples spanned a 3.3 m (10.7 ft) interval from 27.4 to 30.7 m (89.9 to 100.6 ft) bgs. A total of 5 samples, S1 through S5, were collected from the bottom MSPFM segment at intervals of 0.2 m (0.6 ft). The distance from sample S5, the last sample in the bottom MSPFM segment and the first sample in the middle MSPFM segment, S6, was 0.49 m (1.6 ft). A total of 10 samples, S6 through

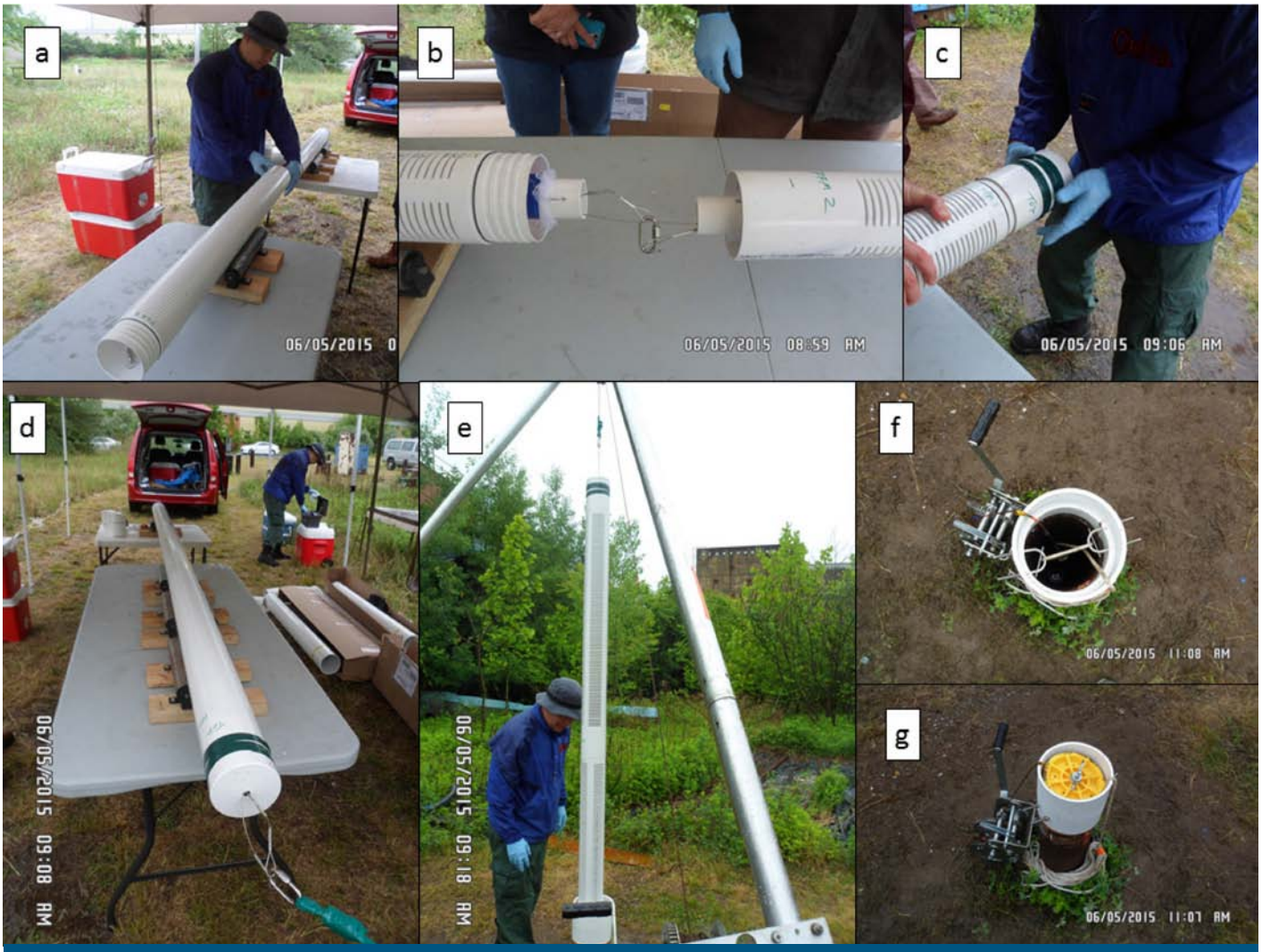


Figure 2-5. MSPFM assembly and deployment.

a) Lower and middle MSPFM segments being assembled. b) Redundant wire cable connection between two MSPFM segments. c) Attaching the top cap to the MSPFM. d) MSPFM assembled and ready to deploy, total length about 3.7 m (12 ft). e) Deploying the MSPFM in well 68BR. f) MSPFM suspended from PVC coupling. g) Well cap in place, MSPFM deployed.

S15, were collected from the middle MSPFM segment. These samples came from homogenizing the sorbent over intervals of 0.1 m (0.3 ft). This MSPFM segment was centered on a point 29.0 m (95.1 ft) bgs just below the fracture at 28.7 m (94 ft) bgs, and a finer sampling interval was used in an attempt to capture details of the flowing fracture. The distance from sample S15, the last sample in the middle MSPFM segment and the first sample in the top MSPFM segment was 0.49 m (1.6 ft). A total of 5 samples, S16 through S20, were collected from the top MSPFM segment based on homogenizing sorbent over intervals of 0.2 m (0.6 ft).

Figure 2-6 shows the process of MSPFM sample collection. Note the norprene divider rings used in the MSPFM, Figure 2-6e, to help channel flow through the MSPFM and limit vertical flow. The sampling process was identical to that described in Section 2.3.2 for the insertion/retrieval test.

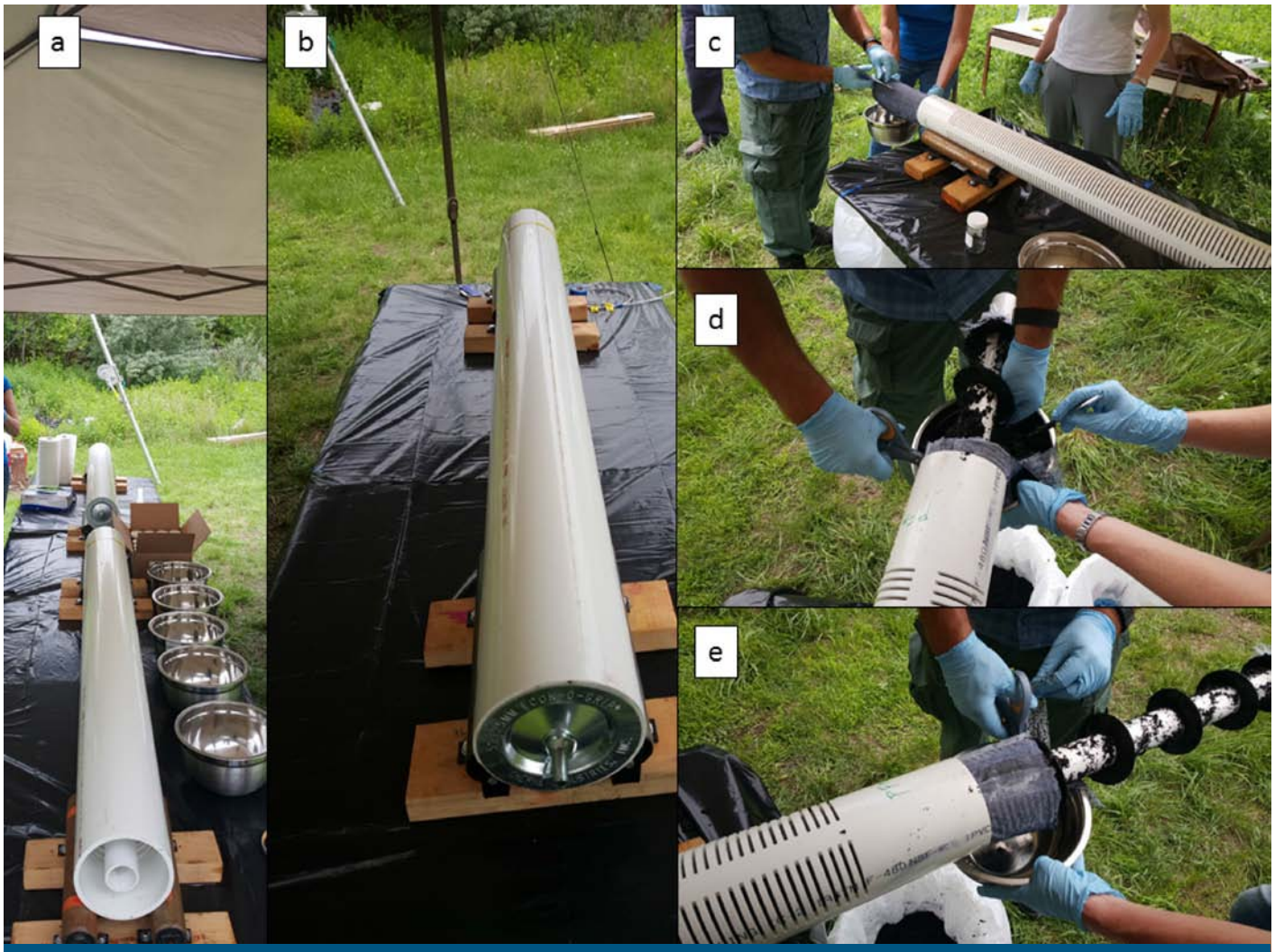


Figure 2-6. MSPFM retrieval sampling.

a) MSPFM segment ready for sampling. b) MSPFM segment stored in PVC shipping tube to reduce VOC loss before sampling. c) Cutting the PFM mesh sock to collect sorbent material in segment. d) Collecting sample into stainless steel mixing bowl. e) Note dividers between segments to limit vertical flow and to define sample intervals.

2.4 Fractured Rock Passive Flux Meter

2.4.1 Description of the FRPFM

The FRPFM is an experimental system designed for deployment in a borehole completed in rock. The FRPFM system consists of the following elements as shown in Figure 2-7.

- Three packers. The top and bottom packers are used to isolate the test zone occupied by a middle packer in the borehole. The test zone is about 1 m (3 ft) long. The middle packer is wrapped first in a green plastic mesh, then in sheets of activated carbon felt, and finally an outer elastic fabric (nylon/spandex blend) sleeve dyed with turmeric (hereafter referred to as the fabric sleeve). The mesh is used to induce a uniform permeability through the activated carbon felt and fabric sleeve when compressed against the borehole wall. Like the activated carbon in the MSPFM, the carbon felt is impregnated with alcohols which elute at different rates. The carbon felt also absorbs VOCs. The fabric sleeve is impregnated with turmeric dye, which fluoresces when exposed to UV light. It is used to create an image of the flowing fractures on the borehole wall.
- A weight and accelerometer are attached at the bottom of the packers. The weight helps to deploy the FRPFM from the shield packer. The accelerometer is used to determine the position of the FRPFM in the borehole relative to magnetic north during deployment.
- The shield consists of a stainless steel pipe, larger in diameter than the FRPFM, with a packer at the top. The assembled FRPFM is placed inside the shield and is then held in place by inflating the top and bottom FRPFM packers. The shield isolates the activated carbon felt and fabric sleeve during deployment and retrieval. The FRPFM is also stored and transported in the shield when not in use.

The diameter of this FRPFM system is constructed for deployment in a 0.2 m (6 in) diameter borehole such as 68BR, but prototypes also exist for 0.1 m (4 in) boreholes.

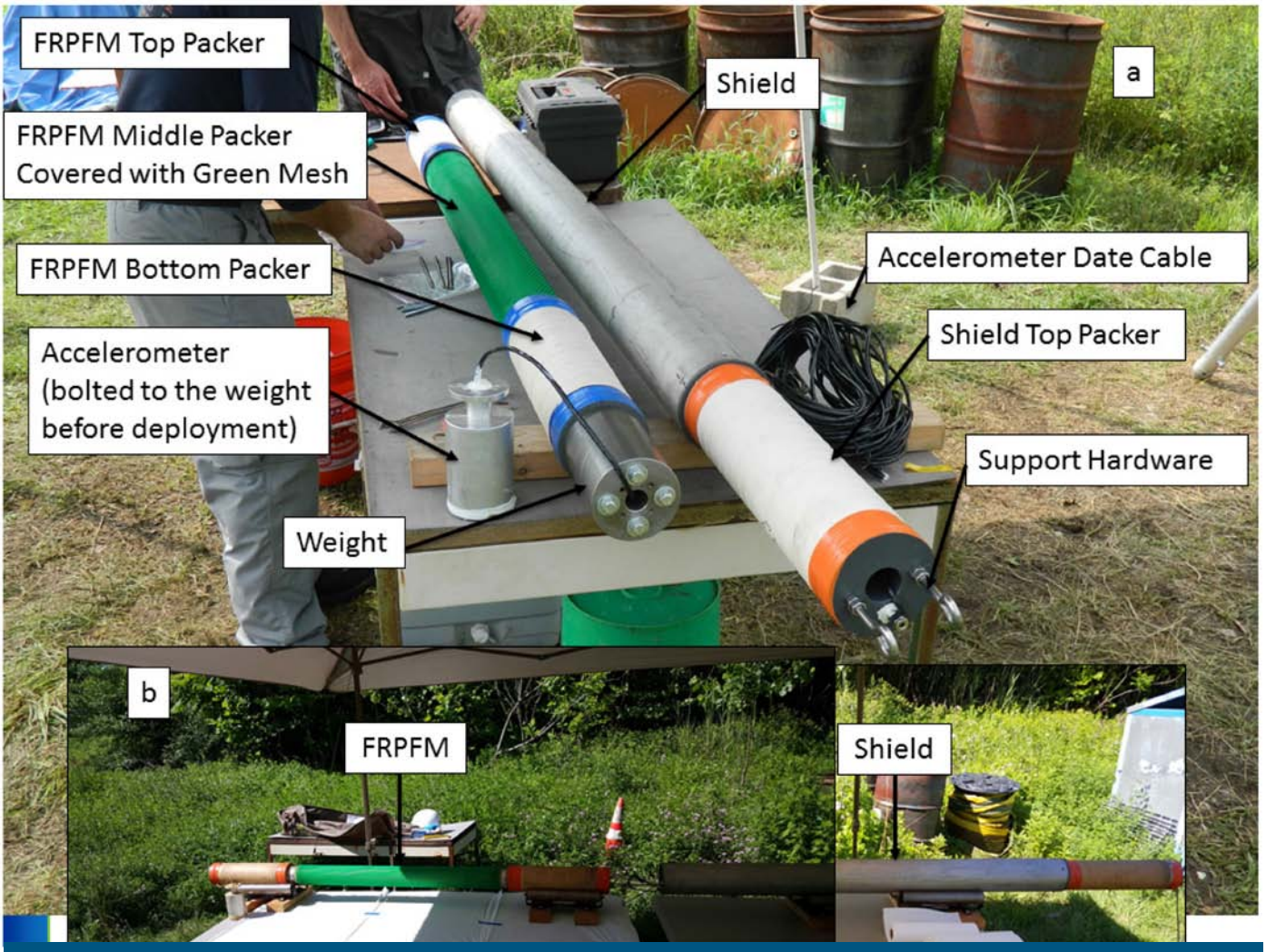


Figure 2-7. FRPFM components.

a) FRPFM and shield components. b) FRPFM ready for attachment of activated carbon felt and fabric sleeve prior to stowing in the shield for deployment.

2.4.2 FRPFM deployment, retrieval, and sampling

The FRPFM was prepared and deployed on 6/24/15 using the process illustrated in Figure 2-8, and consisted of the following steps.

- The middle packer in the FRPFM was wrapped in green plastic mesh, four activated carbon felt sheets, and then covered with the fabric sleeve. The activated carbon felt sheets were prepared at UF by impregnating them with a suite of alcohol tracers, and were sealed in plastic bags and shipped to the site in plastic containers. Likewise the fabric sleeve was also prepared at UF and transported to the site in a sealed container.

- Immediately before installation of the FRPFM the activated carbon felt sheets were soaked in distilled water in a plastic container for about 3 minutes to saturate them prior to deployment. Pre-saturating them flushes trapped air from the pore space and promotes uniform permeability.

- A sample of the activated carbon felt was cut from each of the sheets before it was wrapped around the FRPFM and placed in sample containers. These samples were analyzed to determine the initial, or C_0, concentrations of VOCs and alcohols in the activated carbon felt. The value of C_0 is used in calculations to determine J_c and q_0 .

- The carbon felt sheets were wrapped around the green plastic mesh, overlapped in the middle to allow for expansion of the packer when it is inflated, and held in place temporarily with rubber bands. The fabric sleeve was then installed over the carbon felt, rolled back to remove the rubber bands from the felt, and then secured at either end using rubber bands.

- The assembled FRPFM was then slid inside the shield and the FRPFM packers were inflated to hold the FRPFM in place and to isolate it from water in the borehole until it was in position and ready to be deployed. In this way, the FRPFM is prevented from either losing alcohols or gaining VOC mass while it is lowered into position.

- The shield/FRPFM was then lowered into position using the tripod. The shield was positioned above the test zone so that when deployed the middle packer of the FRPFM was centered on the point 29.0 m (95.1 ft) bgs and the test interval was from 28.6 to 29.5 m (93.7 to 96.7 ft) bgs. Once in position for deployment the top packer on the shield was inflated to hold it in position.

- The top and bottom packers on the FRPFM were then deflated to allow the FRPFM to be lowered out of the shield and into position. In practice how quickly this process proceeds depends on the transmissivity of the borehole below the shield packer. Based on previous experience deploying the FRPFM in 68BR in 2012 (Hatfield, 2015), it was anticipated that the FRPFM deployment would be very slow due to the time it takes for water displaced by the FRPFM to move into the fractures. To speed up deployment, pressure on the shield packer was reduced temporarily to allow water below the shield to bypass the shield as the FRPFM was deployed.

- Once in position the FRPFM core packer was inflated sealing the activated carbon felt and fabric sleeve against the borehole wall. Then the FRPFM top and bottom packers were inflated to isolate the interrogation zone from vertical flow. The shield was left in place with the shield packer inflated.

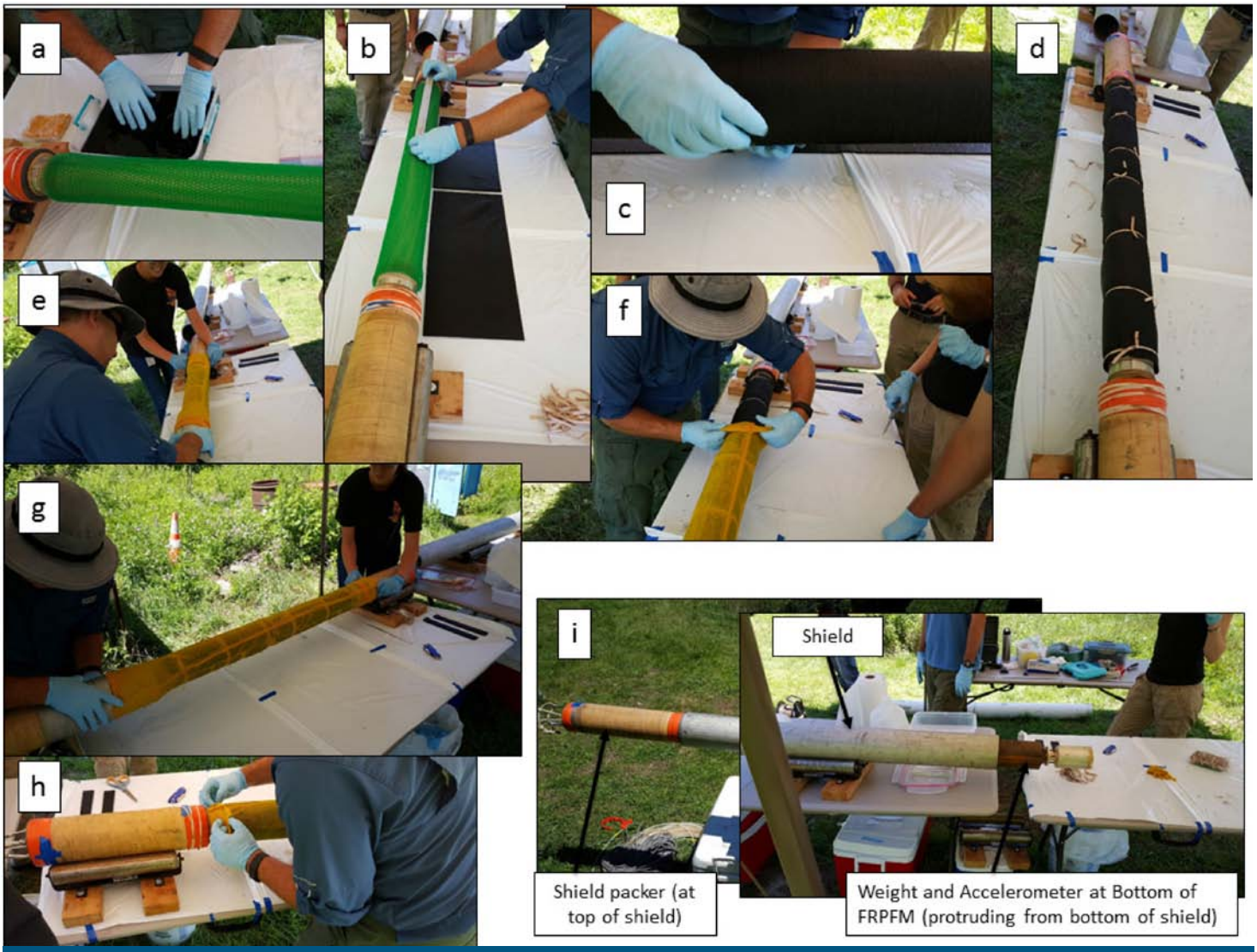


Figure 2-8. FRPFM assembly and deployment.

a) Soaking activated carbon felt in distilled water. b) Preparing to attach activated carbon felt to the middle packer in the FRPFM. c) Wrapping the activated carbon felt around the middle packer. d) Activated carbon felt temporarily held in place with rubber bands. e) Placing the fabric sleeve over the felt. f) Pulling back the fabric sleeve to remove the rubber bands holding the felt in place. g) Fabric sleeve in place. h) Securing the fabric sleeve with rubber bands. i) FRPFM stowed in the shield for deployment.

The FRPFM was retrieved and sampled on 7/1/15 using the process illustrated in Figure 2-9, which consisted of the following steps.

- All FRPFM packers were deflated and the unit was pulled up, using a line from the surface, into the shield. The top and bottom packers were then re-inflated to hold the FRPFM in the shield and the shield/FRPFM was raised to the surface. In this way, the FRPFM is prevented from either losing alcohols or gaining VOC mass while it is raised to the surface.
- As the FRPFM was raised from the borehole several people were needed to manage the various cables and tubing running to the FRPFM.
- The FRPFM was then removed from the shield and placed on a work table. The fabric sleeve was removed and then the carbon felt sheets were removed and samples were collected.

In practice it was difficult to determine if the FRPFM was fully retrieved into the shield before it was removed from the well. As shown in Figure 2-9a and 2-9b, a rock fragment was dislodged during deflation of the core and wedged between the FRPFM and shield, which caused the fabric sleeve and felt to be dragged down and bunch up at the bottom of the middle packer as the FRPFM was raised into the shield. Both the fabric sleeve and felt were torn in places (Figure 2-9c and 2-9d) due to contact with the rock fragment and borehole wall. Despite this problem the fabric sleeve was removed from the FRPFM and inspected under UV light in a truck provided by the USGS. (See Figure 2-10.) The results of this inspection were inconclusive with respect to evidence of flowing fractures. The fabric sleeve was analyzed by UF for visual evidence of fracture flow under controlled conditions in their laboratory at the university and the results are discussed in Section 3.

The carbon felt was removed from the FRPFM and laid out on the work table, covered with plastic sheeting to prevent cross-contamination, and cut into sample strips (Figure 2-9e and 2-9f). The strips were then placed into sample containers and stored on ice for transport and analysis at UF. A total of 19 samples were collected spanning the 0.9 m (3 ft) interval from 28.6 to 29.5 m (93.7 to 96.7 ft) bgs at a spacing of approximately 6 cm (0.2 ft).

Figure 2-9. FRPFM retrieval and sampling.

a) Shield and FRPFM at the surface. The FRPFM activated carbon felt and fabric sleeve are bunched up between the stainless steel shield (above) and light brown FRPFM bottom packer (below). A rock jammed between the shield and FRPFM, consequently the fabric sleeve and felt were pulled down by the shield while the FRPFM was pulled up into the shield. b) FRPFM removed from the shield, the felt and fabric sleeve have been pulled down off of the FRPFM middle packer. c) Felt and fabric sleeve pulled back up into position before removing them from the FRPFM. d) Felt laid out after removal from the FRPFM, note the tears in the felt. e) Measuring the felt prior to cutting into strips for sample collection. f) Cutting felt into strips and placing them into sample containers.

Figure 2-10. Image of FRPFM under the black light shown in purple. The yellow color represents fluorescence of the turmeric dye on the fabric sleeve, which was damaged during FRPFM retrieval.

SECTION 3
Results and Synthesis

3.1 Existing borehole geophysical data review

Before reviewing the results of the BHD, MSPFM, and FRPFM the existing borehole data from 68BR were reviewed to evaluate how the MSPFM or FRPFM would be deployed within the 68BR borehole. The rock core collected by the USGS for this location is shown in Figure 3-1. Existing data from the 68BR borehole, which are also typically collected at Superfund sites to characterize fractured bedrock hydrogeology, include the following.

- Caliper
- Natural Gamma
- Optical televiewer (OTV)
- Acoustic televiewer (ATV)
- Stratigraphy
- Rock matrix sample results for TCE and cis-1,2-DCE
- Heat pulse flow meter data (ambient and pumped conditions)
- Head data from packer testing and calculated from the heat pulse flow meter (HPFM) data
- Transmissivity data from packer testing, calculated from HPFM, and a FLUTe™ transmissivity profile
- Borehole fluid temperature and resistivity logs under both pumped and ambient conditions
- VOC sampling results from packer sampling and long-term monitoring

The borehole geophysical logs were collected by the USGS in 2005 (Williams et al., 2007), the transmissivity profile was collected by Flexible Liner Underground Technologies, LLC in June 2012 for the University of Guelph (Parker, 2015), and the stratigraphy was developed by the USGS (Lacombe, 2000; Lacombe and Burton, 2010). The rock matrix VOC sample results were reported in Goode et al. (2014) and provided by the lead author. Note that because these data were collected by different investigators at different times using different equipment the vertical resolution is assumed to be ± 0.3 m (± 1 ft).

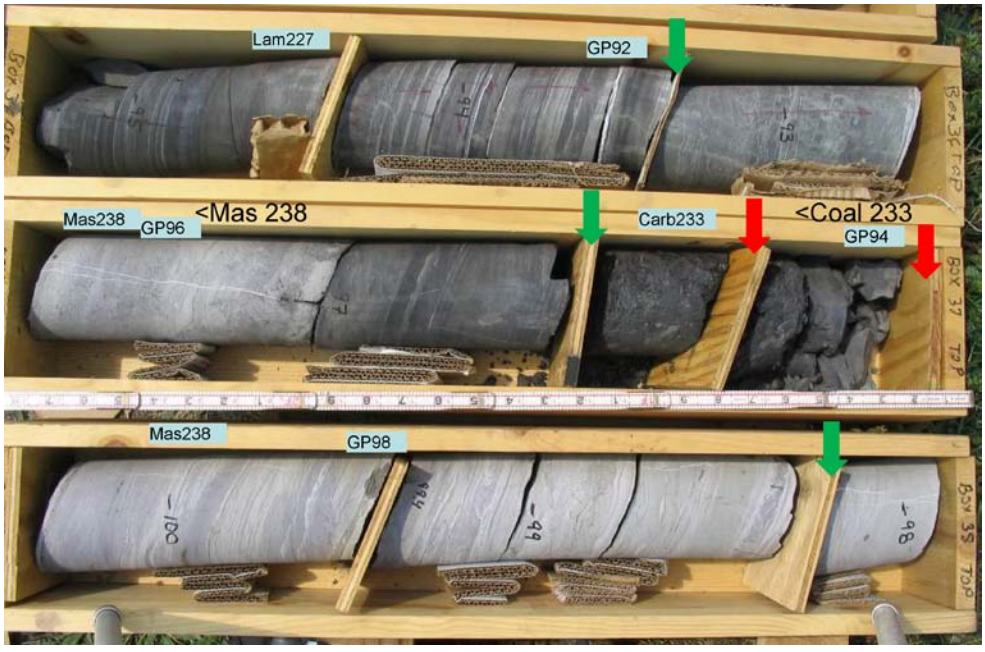


Figure 3-1. Rock core from location 68BR collected by the USGS.

The numbers on the core indicate the depth below grade, and the cores in this image correspond to the depth interval from 28 to 30 m (93 to 100 ft) below grade. Ruler is calibrated in decimal feet.

Image courtesy of Pierre Lacombe, USGS.

These logs and other data sets are presented in Figure 3-2 and are typical of the investigative methods deployed at EPA Superfund sites to characterize fractured bedrock hydrogeology. As detailed in Figure 3-2, these data provide multiple lines of evidence which indicate that the fracture at 28.7 m (94 ft) bgs is transmissive, that significant concentrations of TCE and cis-1,2-DCE are present in the rock matrix adjacent to the fracture (indicating exposure to contaminated groundwater and possibly dense non-aqueous phase liquid (DNAPL) over time), and that the hydraulic head in this fracture is lower than the head in the overlying shallow zone extending from the bottom of the casing to about 12 m (40 ft) bgs. While the open borehole is an unnatural condition, the rock matrix VOC data indicate that there is a vertical pathway for contaminated groundwater to reach this fracture. In a hypothetical site conceptual model the fracture at 28.7 m (94 ft) bgs could be a pathway for offsite migration of contaminants. In this context, the MSPFM or FRPFM would be deployed during the remedial investigation to evaluate the mass flux in this fracture so that this information could be used in the remedial design.

3.2 Borehole Dilution Test

The groundwater conductivity data collected during the BHD are shown in Figure 3-3a, and were analyzed using the method described in Pitrak et al., (2007). Along with the test zone dimensions, the data was used to estimate q_0 for the test zone at 1.46 centimeters/day (cm/day). The test zone is 1.1 m (3.6 ft) long and centered on a point 29.0 m (95.1 ft) bgs just below the fracture at 28.7 m (94 ft) bgs. This estimate of q_0 was used to finalize the calculation of the duration of deployment of the MSPFM, 18 days, and the FRPFM, 7 days.

The BHD low flow sample results from the isolated test zone showed the concentrations of TCE and cis-1,2-DCE increased from 0.34 mg/L and 0.88 mg/L, respectively, at the start of the purging to 1.16 mg/L and 4.59 mg/L, respectively after 2 hours of purging. After recirculation began and the BHD started, the concentration of TCE dropped to 1.29 mg/L after 45 hours. In contrast, the cis-1,2-DCE concentration leveled off and stayed at 1 mg/L for the duration of the test. Table 3-1 lists the results which are plotted in Figure 3-3b.

Table 3-1 Low flow and BHD test sample results

Method	Sample	Elapsed Time (hours)	cis-1,2-DCE (mg/L)	TCE (mg/L)
Low Flow	1	0	0.3	0.9
Low Flow	4	0.6	0.8	2.8
Low Flow	7	1.4	1.0	4.0
Low Flow	10	2.0	1.2	4.6
Borehole Dilution	1	8.8	1.0	2.7
Borehole Dilution	4	20.8	1.0	1.8
Borehole Dilution	7	26.8	1.0	1.6
Borehole Dilution	10	32.8	1.0	1.5
Borehole Dilution	13	44.8	1.0	1.3

mg/L = milligrams per liter

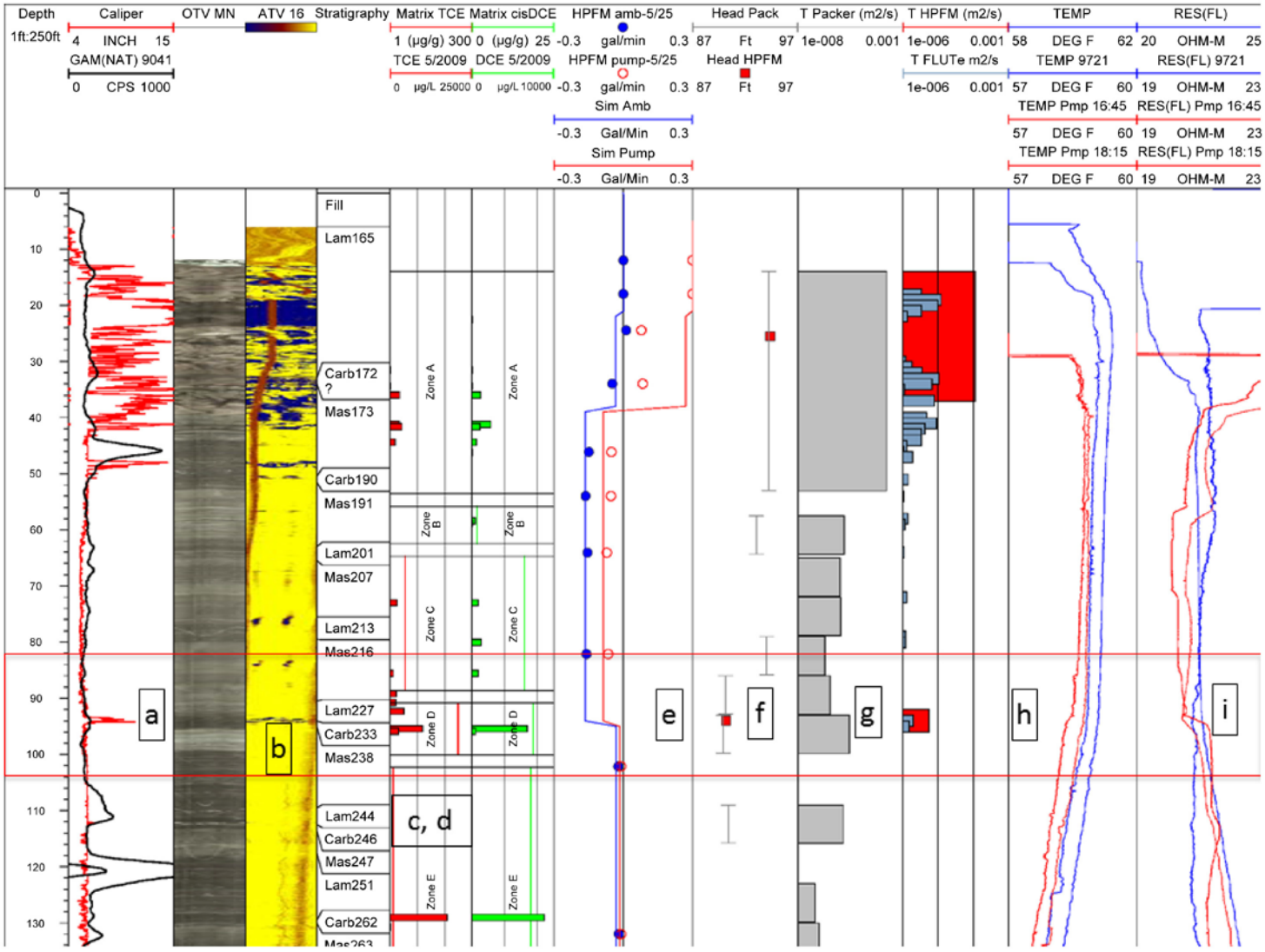


Figure 3-2. Well 68BR borehole geophysical data and rock matrix VOC results.

a) Caliper log (red trace) showing fracture at 94 feet bgs. b) Fracture, dark sinusoidal band, shown on ATV. c) Rock matrix sample results indicated by horizontal bars for TCE (red) and cis-1,2-DCE (green) showing significant concentrations. d) Groundwater sample results indicated by the vertical lines, the length of which indicates the sampling interval, May 2009. e) Heat pulse flow meter (HPFM) data showing vertical flow of groundwater down, from the zone at 40 feet, and exiting the borehole at the fracture at 94 feet bgs, note that below 94 feet the HPFM data indicate essentially no vertical flow. f) Head data showing a downward gradient from the shallow to deep zones. g) Packer test, HPFM, and FLUTe™ transmissivity data showing the fracture at 94 feet is transmissive. h,i) Inflections at 94 feet in the fluid temperature and fluid resistivity logs indicating that fracture at 94 feet is transmissive. Borehole geophysical data from Williams et al. (2007), and packer test data from Shapiro and Tiedeman (2005). Rock matrix VOC data from Goode et al. (2014). FLUTe™ transmissivity profile data provided by Parker (2015). Groundwater sample results from Geosyntec (2010).

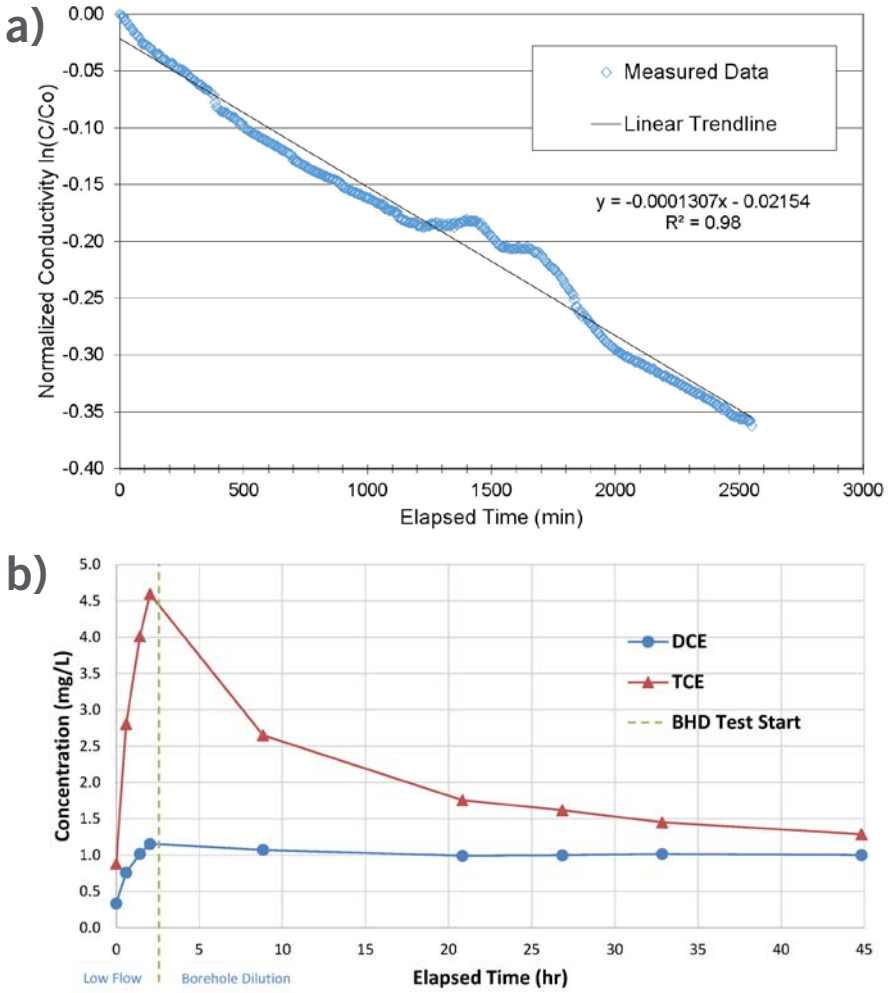


Figure 3-3. BHD test results.

a) Measured conductivity data, normalized to the initial conductivity measurement (blue diamonds), as a function of elapsed time from the start of the BHD test. Also shown is the trendline based on a linear regression.

b) Aqueous contaminant concentrations from low flow sampling and BHD as a function of elapsed time from the start of pumping the test zone prior to the start of the BHD test. The green dashed line denotes the start of the BHD.

The observed increase in TCE and cis-1,2-DCE concentrations during low-flow sampling indicates contaminated groundwater was being drawn into the pump from the test zone. Because the borehole was open before the start of the BHD, groundwater from shallower depths flowed down and exited the borehole at 28.7 m (94 ft) bgs. Therefore, the sample results probably reflect a mixture of groundwater. During recirculation the TCE concentration dropped and cis-1,2-DCE concentration stabilized probably reflecting ambient conditions in the zone.

Using Equation 1-2, J_c for TCE in the BHD test interval was calculated as 18.8 milligrams/square meter/day (mg/m^2/day), based on q_0 = 1.46 cm/day and C_F = 1.29 mg/L. Likewise J_c for cis-1,2-DCE in the same interval was calculated as 14.6 mg/m^2/day, based on q_0 = 1.46 cm/day and C_F = 1.00 mg/L. These values will be compared to the results from the MSPFM and FRPFM.

3.3 Insertion/Retrieval test

Results from the MSPFM insertion/retrieval test were used to evaluate potential tracer loss and mass sorption during insertion and retrieval of the device to the target depth. It should be noted that larger deployment depths lead to larger potential tracer loss, while shorter depths (3 m/10 ft or less) lead to minimal if any effect on observed values. For the measurements conducted in this study, it is estimated that in the absence of results from the insertion/retrieval test, Darcy flux and contaminant flux from the MSPFM test may have been overestimated by up to 8% and 3%, respectively. The results of the insertion/retrieval test were used to estimate the MSPFM quantification limits as outlined below.

3.4 Modified Standard Passive Flux Meter

3.4.1 Quantification limit

Quantification limits for the MSPFM are limits below which measurements take on significant uncertainty relative to higher measurements, and which take into account the effects of deployment duration, water column depth, and the annular space between the MSPFM and borehole wall. The limits for MSPFM will typically be lower for longer duration deployments, shallower water column depth, and smaller annular water space. For the conditions of the test performed in 68BR (with duration of 18 days, water column depth of 27 m (90 ft), and annular space of approximately 3 cm [1 in]), it was estimated that the quantification limit for groundwater flux was approximately 0.5 cm/day, and the quantification limit for contaminant flux was approximately 0.4 mg/m^2/day.

3.4.2 Sample results

When evaluating the results of the MSPFM one must bear in mind the geophysical data discussed in Section 3.1. In particular, the HPFM data, Figure 3-2e, and the head data, Figure 3-2f, show that under open hole conditions, groundwater flows into the borehole in the interval above 12 m (40 ft) bgs, flows downward at a rate of about 0.57 LPM (0.15 gallons per minute [gpm]) and exits the borehole at the fracture at 28.7 m (94 ft) bgs. With the MSPFM deployed, the rate of downward water flow may be less, due to blockage of the open borehole space by the MSPFM. Nonetheless, there is still the potential for downward flow, and this means that a significant amount of contaminant mass may not be moving through the MSPFM because ambient flow is into the fracture and away from the MSPFM. Likewise the vertical flow component may dampen the groundwater flux measured by the MSPFM, which is designed to measure horizontal groundwater flow. Lastly, the orientation of the MSPFM in the borehole is unknown which means that it may be closer to the borehole wall in some places than others, which will probably affect the tracer mass lost and the VOC mass absorbed.

A total of 20 samples were collected from the MSPFM spanning a 3.26 m (10.7 ft) interval from 27.4 to 30.7 m (89.9 to 100.6 ft) bgs. Sample spacing was 0.1 m (0.3 ft) in the middle interval centered on the point 29.0 m (95.1 ft) bgs, which is comparable to the 6 cm (0.2 ft) spacing of the samples from the FRPFM, and 0.2 m (0.6 ft) in the upper and lower MSPFM intervals. The results of the MSPFM sample analysis are shown in Figure 3-4.

The groundwater flux averaged 2.14 cm/day over the interval sampled by the MSPFM. Values ranged from 0.2 cm/day, at 30.3 m (99.4 ft) bgs, to 5.8 cm/day at 29.4 m (96.6 ft) bgs. The median value was 2 cm/day. Over the interval sampled by the FRPFM, from 28.6 to 29.5 m (93.7 to 96.7 ft) bgs, the MSPFM average groundwater flux was 2.9 cm/day and ranged from 1.5 cm/day to 5.8 cm/day.

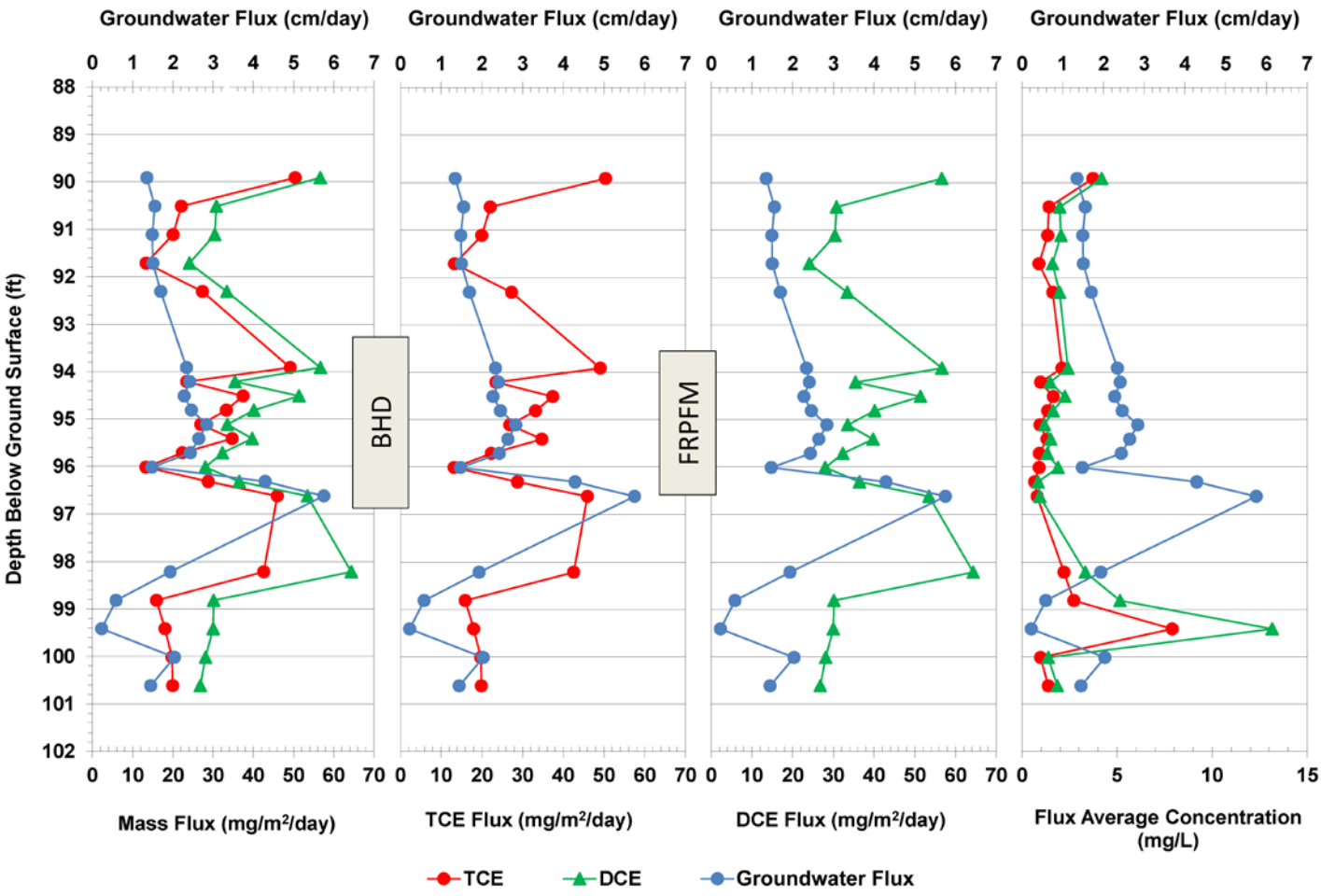


Figure 3-4. MSPFM results. BHD interval, 93.3 to 96.9 feet bgs; FRPFM interval, 93.7 to 96.7 feet bgs.

The TCE mass flux averaged 28.23 mg/m^2/day over the interval sampled by the MSPFM. The minimum TCE mass flux was 13.3 mg/m^2/day at 29.3 m (96 ft) bgs. The maximum TCE mass flux was 50.4 mg/m^2/day at 27.4 m (89.9 ft) bgs. Over the interval sampled by the FRPFM, TCE mass flux from the MSPFM ranged from 13.2 mg/m^2/day to 49.1 mg/m^2/day and the average was 31.5 mg/m^2/day. The highest TCE mass flux in this interval, 49.1 mg/m^2/day, was observed in the sample from 28.6 m (93.9 ft) bgs which is adjacent to the transmissive fracture observed at 28.7 m (94 ft) bgs. It could also reflect contaminated groundwater flowing down the borehole, partially through the MSPFM, and exiting the borehole at this fracture. However, the groundwater flux profile is not consistent with either of these explanations because the groundwater flux gradually increases from a depth of 27.4 to 29.0 m (90 to 95 ft) bgs, without reflecting a peak groundwater flux near the transmissive fracture at 28.7 m (94 ft) bgs. The cis-1,2-DCE and TCE mass flux follow a similar pattern but the cis-1,2-DCE values were higher and the average was 38.1 mg/m^2/day. The maximum cis-1,2-DCE mass flux, 64.4 mg/m^2/day, was observed at 29.9 m (98.2 ft) bgs. The minimum cis-1,2-DCE mass flux, 24.1 mg/m^2/day, was observed at 28.0 m (91.7 ft) bgs. Over the interval sampled by the FRPFM, cis-1,2-DCE mass flux from the MSPFM ranged from 28 to 56.7 mg/m^2/day and the average was 40.7 mg/m^2/day. On the right side of Figure 3-4 the flux average contaminant concentrations are shown graphically. The flux average contaminant concentration is an estimate of the groundwater concentration calculated from the groundwater flux and mass flux. These data show that the highest flux average contaminant concentration was present between 30.2 to 30.5 m (99.0 to 100.0 ft) bgs but that mass flux was low in this zone because of the low groundwater flux. In fact, the groundwater flux was 0.2 cm/day at this location, which is below the estimated quantification limit.

3.5 Fractured Rock Passive Flux Meter

3.5.1 Quantification limit

Quantification limits for FRPFM are limits below which measurements take on significant uncertainty relative to higher measurements, and which take into account deployment duration. Use of the FRPFM shield avoids insertion and retrieval effects, therefore these effects do not impact the quantification limits as they do for the MSPFM. For the conditions of the test performed in 68BR (duration of 7 days), it was estimated that the technology quantification limit for groundwater flux was approximately 0.3 cm/day, and that the quantification limit for contaminant flux was approximately 0.2 mg/m^2/day.

3.5.2 Sample Results

When evaluating the results of the FRPFM one must bear in mind the geophysical data discussed in Section 3.1. In particular, the HPFM data, Figure 3-2e, and the hydraulic head data, Figure 3-2f, show that under open-hole conditions, like those present before the FRPFM was fully deployed, groundwater flows into the borehole in the interval above 12 m (40 ft) bgs, flows downward at a rate of about 0.57 LPM (0.15 gpm) and exits the borehole at the fracture at 28.7 m (94 ft) bgs. However, unlike the MSPFM, the FRPFM is equipped with packers to isolate the test interval from vertical groundwater movement in the borehole. In particular, the top packer on the FRPFM should block the vertical flow in the borehole from above the FRPFM. Together the top and bottom packers should isolate the test interval and maintain conditions that minimize if not eliminate the influence of the open borehole. Moreover, one must also bear in mind when evaluating the FRPFM results from this study that the FRPFM was damaged during retrieval.

A total of 19 samples were collected spanning the 1 m (3 ft) interval from 28.6 to 29.5 m (93.7 to 96.7 ft) bgs at a spacing of 4.6 cm (0.15 ft), compared to 0.1 m (0.3 ft) sample spacing in the MSPFM over the same interval. The results of the FRPFM sample analysis are represented graphically in Figure 3-5.

The groundwater flux averaged 2.7 cm/day over the interval sampled by the FRPFM. Values ranged from 1.3 cm/day, at 28.6 m (93.7 ft) bgs, to 3.5 cm/day at 29.5 m (96.7 ft) bgs. The median value was 2.9 cm/day. Over the same FRPFM sampling interval, the average groundwater flux measured by the MSPFM was 2.9 cm/day and ranged from 1.5 to 5.8 cm/day.

The TCE mass flux averaged 116 mg/m^2/day over the interval sampled by the FRPFM. The minimum TCE mass flux was 66.3 mg/m^2/day at 28.6 m (93.7 ft) bgs. The maximum TCE mass flux was 215 mg/m^2/day at 28.7 m (94 ft) bgs. Over the interval sampled by the FRPFM, TCE mass flux from the MSPFM ranged from 13.2 mg/m^2/day to 49.1 mg/m^2/day and the average was 31.5 mg/m^2/day. The FRPFM cis-1,2-DCE and TCE mass flux follow a similar pattern but the cis-1,2-DCE values were lower and the average was 68.2 mg/m^2/day. The maximum cis-1,2-DCE mass flux, 104 mg/m^2/day, was observed at 29.0 m (95.2 ft) bgs. The minimum cis-1,2-DCE mass flux, 35.1 mg/m^2/day, was observed at 28.6 m (93.7 ft) bgs. Over the interval sampled by the FRPFM, cis-1,2-DCE mass flux from the MSPFM ranged from 28 mg/m^2/day to 56.7 mg/m^2/day and the average was 40.7 mg/m^2/day.

On the right side of Figure 3-5 the flux average contaminant concentrations are shown graphically. These data follow the same pattern as the mass flux data due to the fact that groundwater flux is relatively constant, averaging 2.7 cm/day, over the test interval. The highest flux average contaminant concentration for TCE was 7.8 mg/L, detected at 28.7 m (94 ft) bgs, adjacent to the transmissive fracture at this depth. The flux average contaminant concentration of cis-1,2-DCE was less variable than the TCE concentration and peaked at 4.8 mg/L at 29.0 m (95.2 ft) bgs.

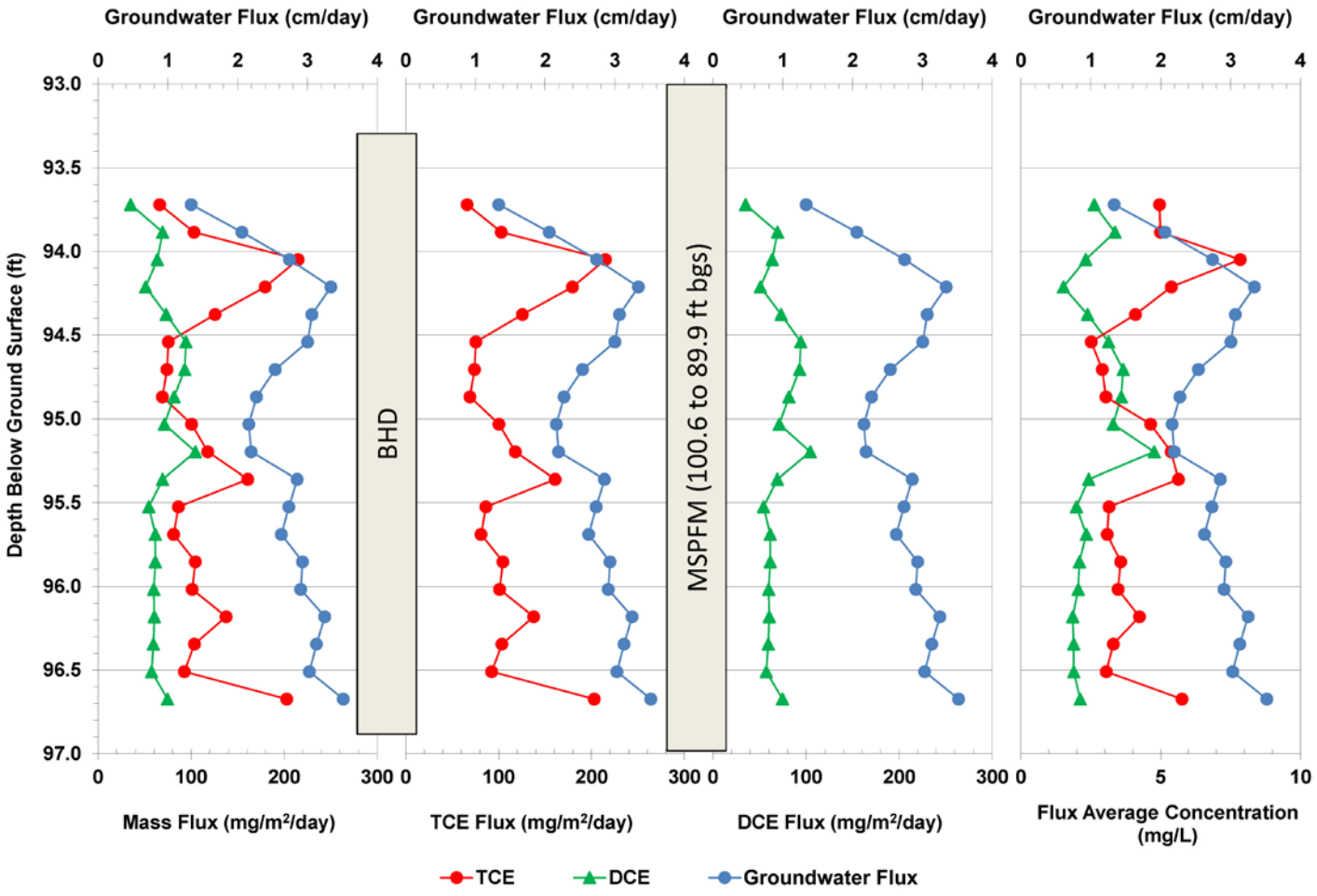


Figure 3-5. FRPFM Results.
BHD interval, 93.3 to 96.9 feet bgs; MSPFM interval, 89.9 to 100.6 feet bgs.

3.5.3 Results of Analysis of Fabric Sleeve for Fracture Flow Information

The fabric sleeve from the FRPFM was analyzed at the UF lab to try to gather data from it to determine fracture frequency, to identify flowing fractures, and to determine groundwater flow direction. Because the fabric sleeve was damaged during retrieval, it was not possible to evaluate fracture frequency, flow, or flow direction. Figure 3-6a shows the image of the damaged fabric sleeve. UF deployed the FRPFM in the same zone in 2013 as part of another project (Hatfield, 2015). The visual results of that test are shown in Figure 3-6b and can be compared to the FRPFM sample results from the current test (Figure 3-6a). The visual results from 2013 show flow, indicated by the dark green traces on the light green background, at the fracture at 28.7 m (94 ft) bgs as well as at smaller fractures, which are less apparent on the ATV and OTV, distributed in the test interval below 28.7 m (94 ft). This is consistent with the current sample results which showed mass flux over the test interval. The results from 2013 demonstrate one of the unique capabilities of the FRPFM which is to identify flowing fractures. The results from 2013 indicated a groundwater flow direction of 199 degrees (south-southwest).

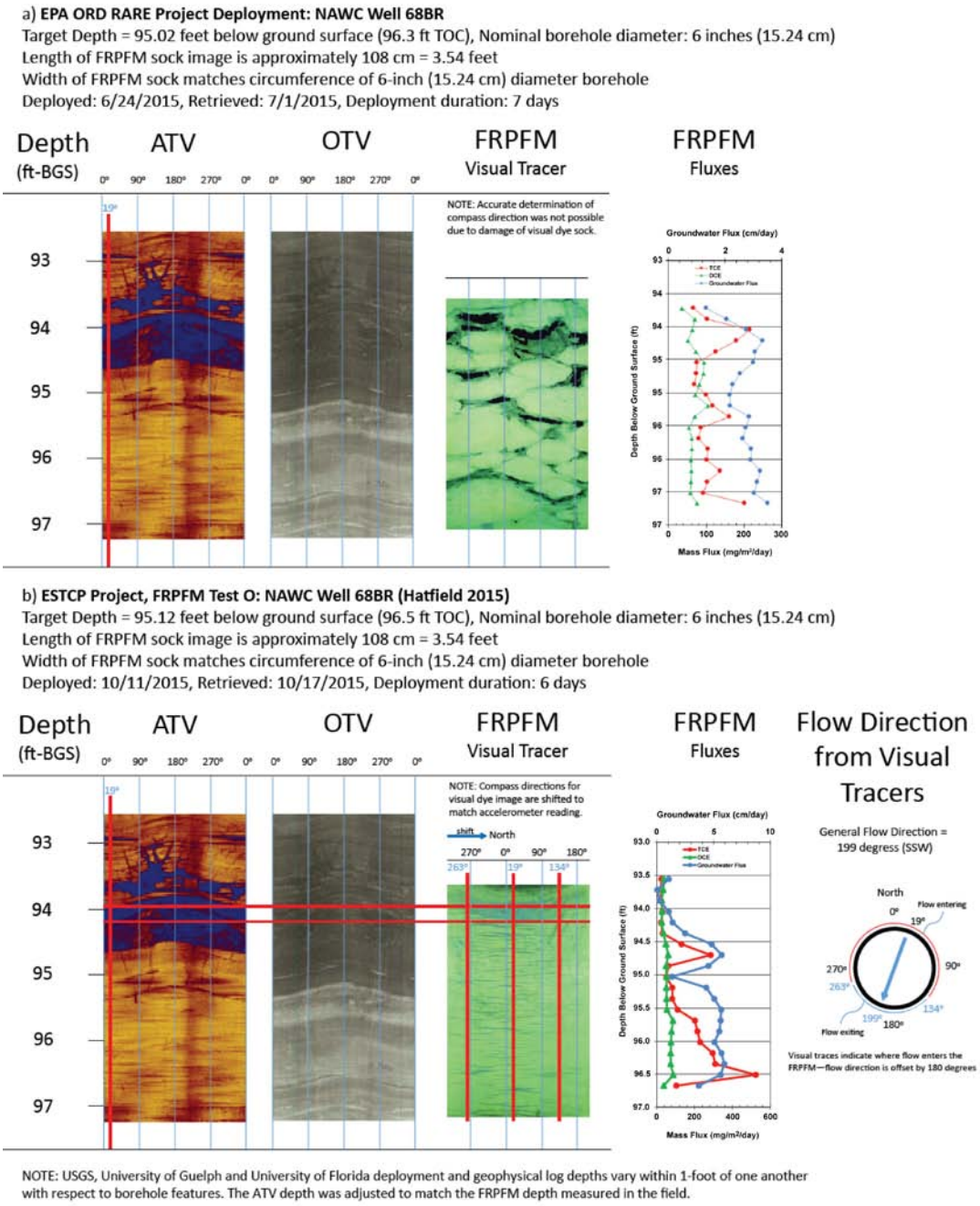


Figure 3-6. FRPFM groundwater flux comparison.

3.6 Comparisons between methods

In comparing the results from the BHD, MSPFM, and FRPFM it is important to note that the three methods all operate under different boundary conditions within the test zone. For all three approaches used to estimate Darcy and contaminant fluxes, a flow convergence factor was used to account for the modified flow field through the borehole devices (Klammler et al., 2007). The convergence factor for the BHD was 2.0, for the FRPFM 1.9 and for the MSPFM 0.5, all calculated using estimated hydraulic conductivities for the aquifer and components of each device. Borehole dilution testing, including low flow sampling, is performed in a vertically isolated open-hole, the MSPFM is deployed in an open-hole, and the FRPFM is deployed under vertically isolated closed-hole conditions. Therefore, no one technique is "right" as they each represent different measures of groundwater flux and mass flux under different conditions that hopefully provide comparable information. Previous work has shown good correlation between groundwater flux and mass flux results between the BHD and FRPFM methods (Hatfield, 2015). In this previous study, the average relative percent difference (RPD) of groundwater flux for 6 trials involving BHD and FRPFM tests in well 68BR was -8%, while the average RPD of TCE mass flux in the same trials was -9%. However, comparisons made here of the BHD and MSPFM results to the FRPFM results should be viewed bearing in mind that the FRPFM was damaged during retrieval.

In addition, it is important to keep in mind that the instruments were deployed in series, for different durations, and either under open-hole conditions or after the borehole had been open. Therefore natural fluctuations in groundwater flux and VOC concentrations, and vertical movement of contaminated groundwater from shallower parts of the borehole and exiting via the fracture at 28.7 m (94 ft) bgs may also contribute to the observed differences in results. At the start of the BHD and FRPFM deployment, groundwater quality in the test interval represented a mixture of groundwater from shallower zones and test zone. In contrast, the borehole was open during the entire MSPFM deployment.

The results from the BHD, MSPFM, and FRPFM are compared in Table 3-2 and presented graphically in Figure 3-7. Table 3-2 compares the results from these three methods and lists the RPDs calculated between the results using the BHD results as the baseline, because this is the method most easily employed at the present time at Superfund sites to measure groundwater flux and mass flux. In addition, the data from the MSPFM is reported over the entire MSPFM interval, 27.4 to 30.7 m (89.9 to 100.6 ft) bgs, and also for the interval sampled by the FRPFM (28.6 to 29.5 m [93.7 to 96.7 ft] bgs). This discussion will focus on the interval sampled by the BHD (28.6 to 29.4 m [93.9 to 96.6 ft] bgs), the FRPFM, which are almost identical, and the data for this same interval from the MSPFM.

The results show that the RPD between the groundwater flux measured with the BHD test, 1.5 cm/day, and the average MSPFM (FRPFM interval), 2.6 cm/day, and average FRPFM, 2.7 cm/day, are 78% and 86% respectively. These RPDs are larger than the average RPD of -8% based on six trials comparing BHD and FRPFM results in well 68BR as reported in Hatfield (2015) from the previous study. It could be expected that the BHD and the average FRPFM results would be more similar because both are closed-hole methods isolating the same interval, while more difference is expected between these results and the average MSPFM result because it is an open-hole method, and therefore subject to interference from vertical groundwater flow. However, the average groundwater flux values from the MSPFM (FRPFM interval) and the FRPFM are close at 2.6 cm/day and 2.7 cm/day, which suggests the MSPFM results were not significantly impacted by vertical flow. Yet, the spatial patterns of groundwater flux as measured with the MSPFM and FRPFM are not comparable, and the MSPFM results do not reflect the fracture at 28.7 m (94 ft) bgs. A detailed diagnostic explanation for the differences in results cannot be offered at this time, in large part because the true groundwater flux distribution during each test is unknown. Differences between the estimates of groundwater flux may reflect differences between test methods, but actual changes in hydrologic conditions between and during the tests cannot be ruled out.

Table 3-2 Comparison of the BHD, MSPFM, and FRPFM results

Method	Sample Interval (feet)	Groundwater Flux (cm/day)	cis-1,2-DCE Concentration (mg/L)[a]	TCE Concentration (mg/L)[a]	cis-1,2-DCE Mass Flux (mg/m²/day)[b]	TCE Mass Flux (mg/m²/day)[b]
BHD	93.3 to 96.9	1.5	1.0	1.3	14.6	18.8
MSPFM	89.9 to 100.6	2.1	2.6	1.8	38.1	28.2
MSPFM (FRPFM Interval)	93.9 to 96.6	2.6	1.5	1.2	40.7	31.5
FRPFM	93.7 to 96.7	2.7	2.6	4.3	68.2	115.7
Relative percent difference using BHD as the reference						
BHD and MSPFM	N/A[c]	47%	161%	39%	161%	50%
BHD and MSPFM (FRPFM Interval)	N/A	78%	50%	-7%	179%	67%
BHD and FRPFM	N/A	86%	160%	231%	367%	515%

[a]The concentration reported for the MSPFM and FRPFM are the average flux average contaminant concentration calculated from the mass flux.

[b]The mass flux values reported are the values calculated for the BHD and the average of the values calculated for the indicated MSPFM and FRPFM test intervals.

[c]N/A - not applicable.

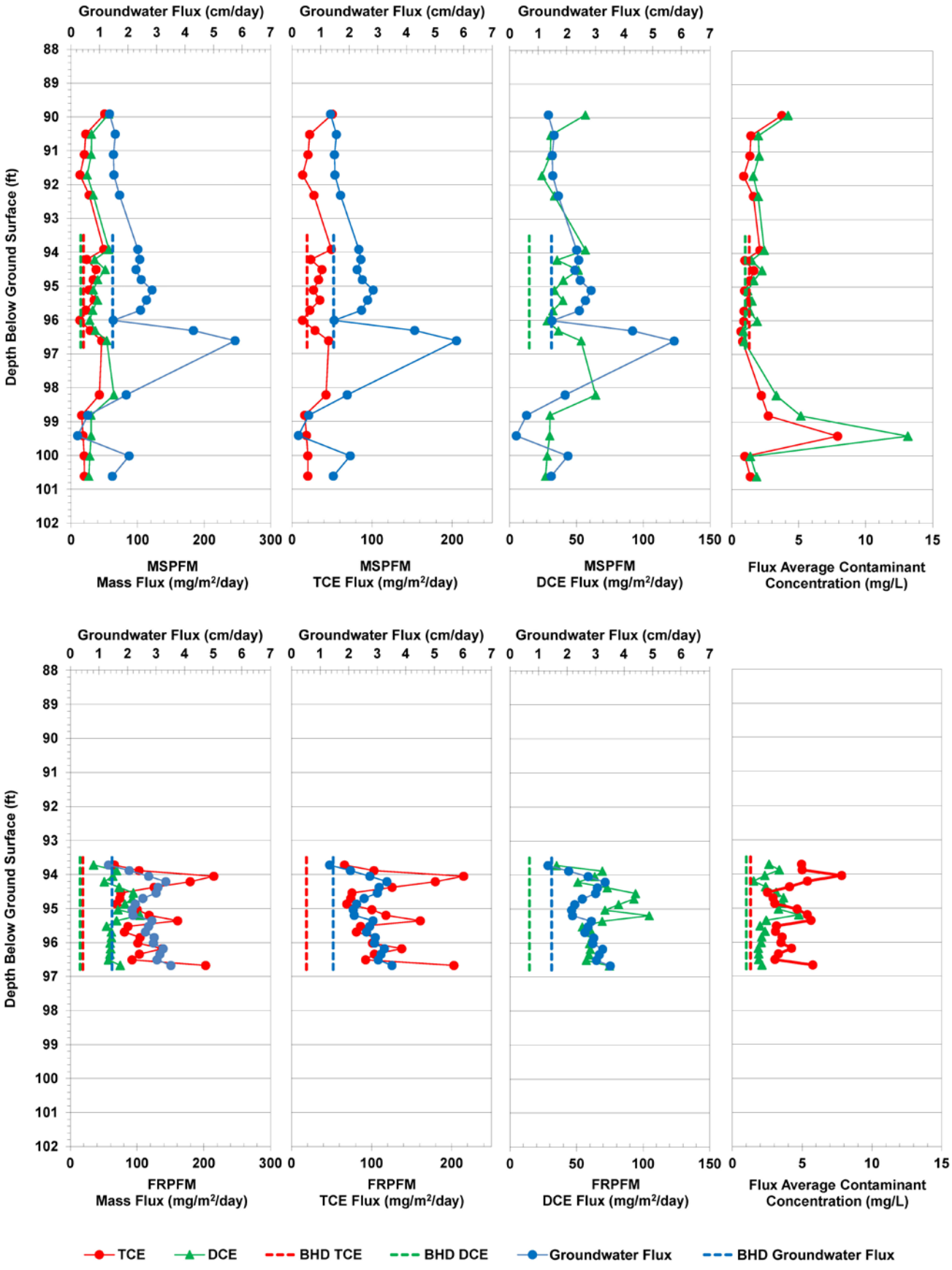


Figure 3-7. Comparison of BHD, MSPFM and FRPFM results.

The RPD between the cis-1,2-DCE concentration measured during the BHD, 1 mg/L, and the average concentration calculated from the MSPFM (FRPFM interval), 1.5 mg/L, and FRPFM, 2.6 mg/L, are 50% and 160% respectively. The values from the BHD and the MSPFM (FRPFM interval) are closer to one another relative to the FRPFM result. As noted for the groundwater flux results, one would expect more difference between the BHD and FRPFM results relative to the MSPFM result because the former two are closed-hole methods while the latter is an open-hole method and therefore subject to interference from vertical groundwater flow. Evidence for this was observed during low flow sampling before the BHD test when the cis-1,2-DCE concentration rose from 0.34 mg/L at the start of sampling to 1.16 mg/L just before the start of the BHD (Section 3.2). Likewise, greater similarity could be expected between the BHD and the FRPFM results because both are closed-hole methods isolating the same interval. Instead the RPD is 160% and the FRPFM result is more than twice the BHD value.

The RPD between the TCE concentration measured during the BHD, 1.3 mg/L, and the average calculated from the MSPFM (FRPFM interval) flux average concentration, 1.2 mg/L, and FRPFM flux average concentration, 4.3 mg/L, are -7% and 231% respectively. Again, the values from the BHD and the MSPFM (FRPFM interval) are close, respectively, at 1.3 mg/L and 1.2 mg/L, while the FRPFM result indicates a greater difference. Evidence for potential impacts on the MSPFM test due to vertical flow was observed during low flow sampling before the BHD when the TCE concentration rose from 0.88 mg/L at the start of sampling to 4.59 mg/L just before the start of the BHD (Section 3.2). But this does not explain the similarity between the BHD and MSPFM results, as well as the relative difference compared to these in the FRPFM result.

The RPD between the cis-1,2-DCE mass flux based on the BHD, 14.6 mg/m^2/day, and the calculated averages from the MSPFM (FRPFM interval), 40.7 mg/m^2/day, and FRPFM, 68.2 mg/m^2/day, are 179% and 367% respectively. Similarly, the RPD between the TCE mass flux based on the BHD test, 18.8 mg/m^2/day, and the calculated averages from the MSPFM (FRPFM interval), 31.5 mg/m^2/day, and FRPFM, 116 mg/m^2/day, are 67% and 515% respectively. In both cases, the BHD gave the lowest estimates and the FRPFM gave the highest estimates of contaminant flux. Moreover, the spatial distributions of cis-1,2-DCE and TCE contaminant flux estimates based on the MSPFM and FRPFM measurements are not very similar. Across the board the RPD of the FRPFM is greater than that of the MSPFM. In the MSPFM the sorbent media is never in contact with the borehole wall and is probably only exposed to VOCs in the dissolved phase. In contrast, the design of the FRPFM results in more direct contact of the sorbent media and the borehole wall, exposing it not only to dissolved phase VOCs in the fracture, but also possibly to DNAPLs or dissolved phase VOCs in the rock matrix, and sorbed VOCs on the rock matrix. The rock matrix sample results, see Figure 3-2c, show the cis-1,2-DCE and TCE were both detected in the rock matrix in the FRPFM sampling interval. However, comparable differences between the BHD and FRPFM results were not observed during the previous study (Hatfield, 2015) that involved comparisons of these methods in well 68BR. As noted before, the groundwater flux calculated with the MSPFM (FRPFM interval) and the FRPFM are similar suggesting that contact with the borehole wall, if it is a factor, may not make a significant difference in the loss of tracers.

As noted in the case of groundwater flux discussed above, the exact reason for the differences in estimates of flux-average concentration and contaminant flux are unknown at this time. Most likely, the differences stem from differences in measurement methods between the three techniques, but natural variability in conditions during the tests may also be a factor. Moreover, damage to the FRPFM during retrieval may also play a factor in the results obtained. Additional research is needed to better evaluate method accuracy, such as laboratory tests in which the true contaminant flux distribution is known.

3.7 Comparisons to common borehole geophysical methods

For comparison, the BHD, MSPFM, and FRPFM groundwater flux and mass flux data are posted with the geophysical logs from well 68BR on Figure 3-8. The range of borehole geophysical tools discussed in Section 3.1 provide useful, necessary, and high quality data on the physical characteristics of the borehole but do not provide groundwater flux or mass flux data. Currently, borehole dilution testing, as conducted during this project, is the most common method for estimating groundwater flux and mass flux in fractured rock boreholes. The MSPFM and FRPFM can also be used to estimate groundwater flux and mass flux, but like the BHD, the geophysical logging tools described in Section 3.1 must first be used to characterize the borehole and provide the data needed to select targets for deployment of the MSPFM or FRPFM. Therefore, the MSPFM and FRPFM complement rather than replace existing tools.

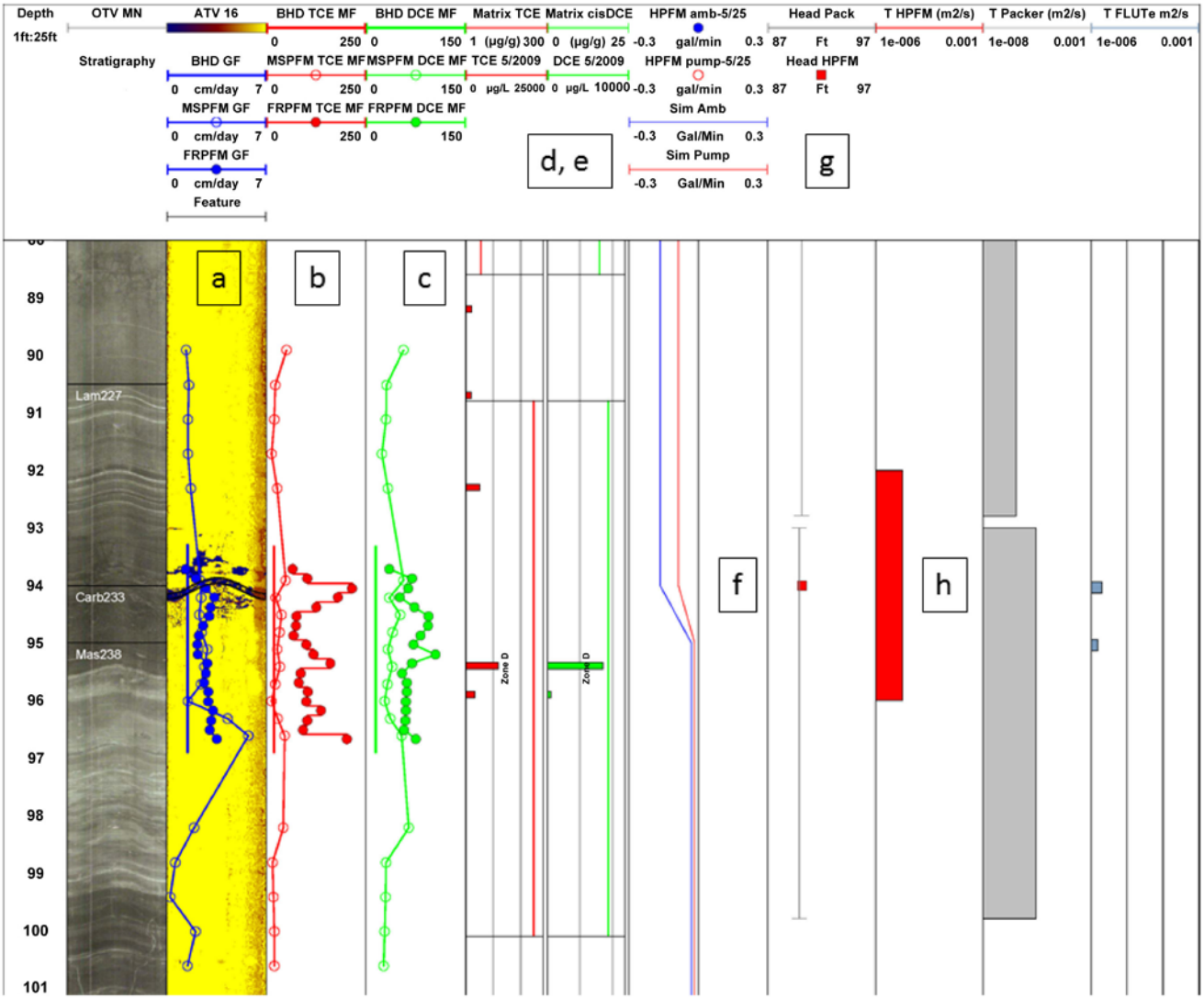
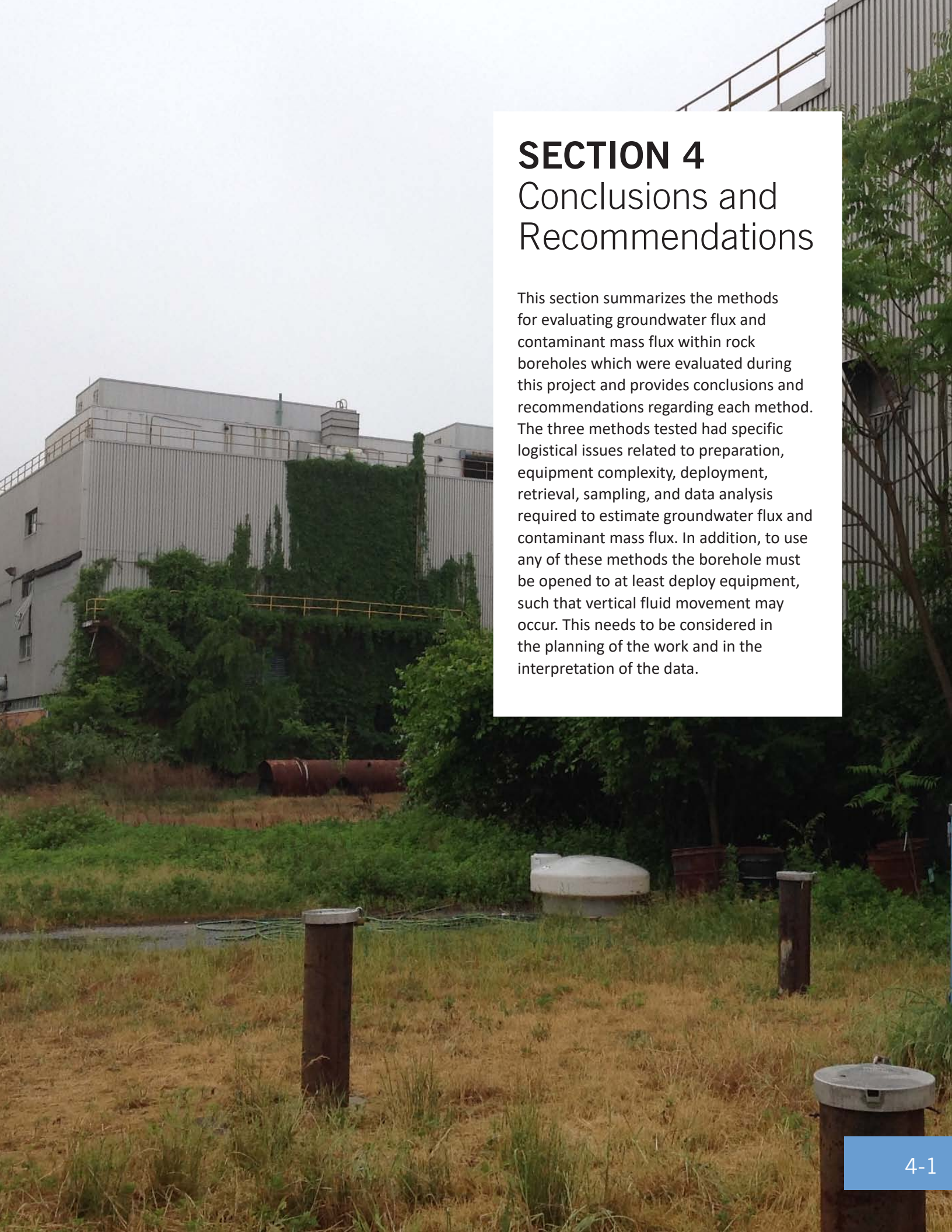


Figure 3-8. Comparison of borehole geophysical and sample data and BHD, MSPFM, and FRPFM results.

a) FRPFM and MSPFM groundwater flux (GF) data, cm/day, overlaid on the ATV log. b) FRPFM and MSPFM TCE mass flux (MF)data, mg/m^2/day. c) FRPFM and MSPFM cis-1,2-DCE mass flux data, mg/m^2/day. d) Rock matrix sample results for TCE and cis-1,2-DCE. e) Groundwater sample results, May 2009. f) HPFM data showing vertical down flow exiting the borehole at the fracture at 94 feet bgs. g) Head data showing a downward gradient from the shallow to deep zones (see Figure 3-2). h) Packer test, HPFM, and FLUTe™ transmissivity data showing the fracture at 94 feet is transmissive. Borehole geophysical data from Williams et al. (2007), and packer test data from Shapiro and Tiedeman (2005). Rock matrix VOC data from Goode et al. 2014. FLUTe™ transmissivity profile data provided by Parker (2015). Groundwater sample results, Geosyntec, 2010.

As pointed out by Hatfield (2015), due to the high resolution nature of the FRPFM technology, its optimum application is characterizing targeted borehole depth intervals and not screening conditions over an entire borehole. The FRPFM used in this study is designed to investigate a 1 m (3.28 ft) interval. Changing the sample interval would require rebuilding the tool or designing a new tool with the ability to vary the sampling interval. As a practical matter the existing FRPFM is an experimental tool designed to test the concept, materials, and procedures and collect data to validate the technology. Due to the complexity of preparing, deploying, retrieving, and sampling the FRPFM it would not be practical to employ it, in its present form, at a large number of Superfund sites. In contrast, the length of the MSPFM can be adjusted relatively easily and is easier to deploy, retrieve and sample. The MSPFM is also less vulnerable to damage than the FRPFM, and is much more similar to the commercially available, standard PFM technology. However, because the MSPFM is not equipped with packers it must be deployed in an open borehole where vertical fluid movement during deployment could complicate data interpretation and potentially allow cross-contamination between different zones in the borehole. Therefore, the performance of the MSPFM could be improved if a way can be found to limit vertical fluid movement in the annular space while the MSPFM is deployed. One way this might be accomplished would be by adapting the flexible petal technology used to channel flow through a heat pulse flow meter to the MSPFM (Figure 3-9).

Figure 3-9. Flexible petal used to channel flow through a heat pulse flow meter.



SECTION 4
Conclusions and Recommendations

This section summarizes the methods for evaluating groundwater flux and contaminant mass flux within rock boreholes which were evaluated during this project and provides conclusions and recommendations regarding each method. The three methods tested had specific logistical issues related to preparation, equipment complexity, deployment, retrieval, sampling, and data analysis required to estimate groundwater flux and contaminant mass flux. In addition, to use any of these methods the borehole must be opened to at least deploy equipment, such that vertical fluid movement may occur. This needs to be considered in the planning of the work and in the interpretation of the data.

4.1 Borehole Dilution Test

During this project a BHD test was successfully used to estimate groundwater flux and mass flux. Results from the BHD test served as a basis of comparison to the MSPFM and FRPFM results, because the former is currently the more commonly applied method relative to the latter two. Moreover, BHD results were used to calculate the deployment time for the MSPFM and FRPFM. It may be possible in other applications to estimate deployment duration for the MSPFM and FRPFM technologies from other site-specific characterization data, thus eliminating the need to conduct a BHD test in conjunction with MSPFM or FRPFM tests. However, this option currently remains untested and should be explored in future work.

Executing a BHD test requires a straddle packer system set up to recirculate groundwater in the borehole. For the configuration used in this project, it also required above ground plumbing and instrumentation, which necessitates security and weather protection considerations. Conducting a BHD test can be completed by personnel experienced with the procedure and with access to the appropriate equipment. Such personnel should also be familiar with typical field sampling techniques and protocols to ensure, for example, that water specific conductivity data and VOC sampling are completed properly. Other methods for conducting borehole dilution tests, such as those discussed in Section 1.3, are available but are typically done in open boreholes and so are subject to inaccuracies when significant vertical flow is observed.

The BHD method provides an integrated measure of groundwater flux across the entire test interval. The data resolution is a function of the length of the interval between the packers. It does not provide information at higher resolution in and around transmissive fractures within the interrogated interval. In order to calculate mass flux, the groundwater flux is multiplied by the contaminant concentrations. As shown during this test however, contaminant concentrations varied significantly during the low-flow sampling. It is important that the concentrations used in the calculation of contaminant mass flux are representative of the concentrations associated with the transmissive zone or fracture(s) in the interrogated interval. In the case when concentrations vary, judgement may be needed in the interpretation of the data. On the other hand, concentration-time series information both before and after the start of the BHD provide data that can be used to make qualitative assessments about the relative proximity of the sampling location to sources of higher concentration.

Towards this end, one limitation of the system used during this test is that it was not equipped with pressure transducers above, between, and below the packers. It is recommended that pressure transducers be used to collect water level data for use in determining the quality of the seal between the packer and borehole wall. One problem with packers is that flow may simply “short circuit” around the packer via the formation. Water level data can be used to help assess if this is occurring. Knowing whether or not the test interval is isolated from the interval above and below is necessary for a complete interpretation of the VOC sample and borehole dilution data. In this case, the decrease in depth to water observed during the BHD test (Table 2-2) suggests that the test interval was isolated.

4.2 MSPFM

The MSPFM, compared to the FRPFM, was easier to prepare, deploy, retrieve, and sample. For example, the MSPFM is contained inside a well screen so it is protected from the borehole wall and less likely to be damaged during retrieval than the FRPFM. However, at the present time, an initial insertion/retrieval test is required to correct the tracer-based groundwater flux and mass flux estimates to account for tracer losses and contaminant mass loading onto the sorbent during deployment and retrieval. An insertion/retrieval test is not required for the FRPFM because it is deployed and retrieved inside a shield. The main advantage of the MSPFM is that it is a modified version of the commercially available PFM that is already in use. The main disadvantage of the MSPFM is that it may underestimate groundwater flux and contaminant mass flux when deployed in an open borehole subject to influence from vertical flow. Moreover, deployment in an open borehole may not be acceptable at sites because vertical fluid movement in the open borehole could cross-contaminate different zones. It is also a patented technology owned by UF. An improvement to the existing MSPFM design is a modification that would prevent vertical fluid flow in the annular space between the MSPFM and borehole wall during deployment. An example of a baffle used in a borehole geophysical logging tool for this purpose is discussed in Section 3.7. In addition, unlike the FRPFM, the MSPFM does not provide information on groundwater flow direction or flow in specific fractures. Furthermore, like the BHD and FRPFM, a borehole logging program needs to be undertaken in a borehole before deciding where to deploy the MSPFM. Comparisons of the spatial distributions of groundwater flux and contaminant mass flux between the MSPFM and FRPFM as measured in this project indicate more research is needed to further assess the accuracy of and confidence in measurements of spatial distributions. Controlled experiments in which the true distribution is known would be helpful in this regard.

4.3 FRPFM

The FRPFM offers a unique combination of capabilities including the following for active or flowing fractures: (1) location along the borehole; (2) number; (3) individual fracture orientations in terms of strike, dip, and orientation of dip (direction of falling dip, e.g., SW); (4) cumulative groundwater flux; and (5) groundwater flow direction. Fracture characteristics (1) through (3) can be obtained through existing borehole imaging technologies (as long as those fractures can be resolved); however, these commercially available technologies cannot measure the magnitude or direction of fracture flow. Further analytical analysis of the FRPFM internal sorbent layer at indicated locations of active fractures yields: (1) additional estimates of cumulative groundwater flux in fractures; and (2) cumulative contaminant flux in those fractures. Thus, the in situ measurements of direction and magnitude of water and contaminant fluxes in active fractures are given by the FRPFM alone.

However, the FRPFM, compared to the MSPFM and BHD, was the most complex method to prepare, deploy, retrieve, and sample. Due to the complexity of preparing, deploying, and sampling the FRPFM and due to the fact the patent holder (UF) currently needs to provide these services, it is not practical to use the FRPFM at a large number of sites at this time. At present, its best use would be those applications where high resolution data is needed over short intervals. The FRPFM does not require an insertion/retrieval test because it is deployed and retrieved inside a shield. However, the FRPFM is fragile and if there are problems retracting it into the shield, as happened during this study due to rock falling in from the borehole wall, then valuable data may be lost and data interpretation complicated. Furthermore, as with the BHD and MSPFM, a borehole logging program needs to be undertaken in a borehole before deciding where to deploy the FRPFM. Further development of the FRPFM technology may result in a more widely applicable technology. For example, combining this technology with flexible underground liner technology may simplify deployment and retrieval.

SECTION 5
References

Acar, Ö., H. Klammler, K. Hatfield, M.A. Newman, M.D. Annable, J. Cho, B.L. Parker, J.A. Cherry, P. Pehme, P. Quinn, and R. Kroecker. 2013. A stochastic model for estimating groundwater and contaminant discharges from fractured rock passive flux meter measurements. Water Resources Research, 49, 1277-1291, doi: 10.1002/wrcr.20109.

Cherry, J.A., B.L. Parker and C. Keller. 2007. A new depth-discrete multilevel monitoring approach for fractured rock. Ground Water Monitoring & Remediation, 27(2): 57-70.

EPA 2015. Quality Assurance Project Plan: Measuring contaminant mass flux and groundwater velocity in a fractured rock aquifer using passive flux meters. EPA Region 2, Emergency and Remedial Response Division, New York.

Geosyntec 2010. Final Draft Report Bioaugmentation Pilot Study Former NAWC Trenton Site West Trenton, NJ. Project Number JR0021. Prepared for ECOR Solutions, Inc., 1075 Andrew Drive, Suite 1, West Chester, PA. May.

Goode, D.J., T.E. Imbrigiotta, and P. J. Lacombe. 2014. High-resolution delineation of chlorinated volatile organic compounds in a dipping, fractured mudstone: Depth- and strata-dependent spatial variability from rock-core sampling. Journal of Contaminant Hydrology, v. 171, p. 1-11, doi:10.1016/j.jconhyd.2014.10.005.

Hatfield, Kirk; Rao, P. Suresh C.; Annable, Michael D.; Campbell, Timothy J., Device and method for measuring fluid and solute fluxes in flow systems. US Patent (6,401,547). 2002.

Hatfield, K., M. Annable, J. Cho, P.S.C. Rao, and H. Klammler. 2004. A direct passive method for measuring water and contaminant fluxes in porous media. Journal of Contaminant Hydrology 75, p. 155– 181.

Hatfield, K., 2015. Final Report: Demonstration and Validation of a Fractured Rock Passive Flux Meter (FRPFM). ESTCP Project Number: ER-200831.

ITRC (Interstate Technology & Regulatory Council). 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 Resour. Res., 43, W04407, doi:10.1029/2005WR004718.

Klammler, Harald Rene; Hatfield, Kirk; Annable, Michael D.; Cherry, John Anthony; Parker. Beth Louise., Device and method for measuring fluid fluxes, solute fluxes and fracture parameters in fracture flow systems. US Patent (7,334,486). 2008.

Kolditz, O., 2002. Computational Methods in Environmental Fluid Mechanics, Springer-Verlag, Berlin, 378 pgs.

Lacombe, P.J., 2000. Hydrogeologic framework, water levels and trichloroethylene contamination, Naval Air Warfare Center, West Trenton, New Jersey, 1993-97: U.S. Geological Survey Water-Resources Investigations Report 98-4167, 139 pgs.

Lacombe, P.J., 2002. Ground-water levels and potentiometric surfaces, Naval Air Warfare Center, West Trenton, New Jersey, 2000: U.S. Geological Survey Water-Resources Investigations Report 01-4197, 38 pgs.

Lacombe, P. J. and W. C. Burton. 2010. Hydrogeologic framework of fractured sedimentary rock, Newark Basin, New Jersey. Groundwater Monitoring and Remediation. Vol. 30, No. 2. p. 35–45. doi: 10.1111/j1745–6592.2010.001275.x.

Michalski, A. and G. M. Klepp. 1990. Characterization of transmissive fractures by simple tracing of in-well flow. Ground Water. Vol. 28, No. 2. March-April, p. 191-198.

Parker, B. L., 2015. Personal communication. FLUTe™ transmissivity profile collected on June 21, 2012 from well 68BR at the former Naval Air Warfare Center in West Trenton, NJ by Flexible Underground Liner Technology for the University of Guelph.

Pehme, P.E., B. L. Parker, J. A. Cherry, D. Blohm. 2014. Detailed measurement of the magnitude and orientation of thermal gradients in lined boreholes for characterizing groundwater flow in fractured rock. J. Hydrology (484), 1–15. http://dx.doi.org/10.1016/j.jhydrol.2014.03.015.

Pitrak, M. S. Mares, and M. Kobr. 2007. A simple borehole dilution technique in measuring horizontal ground water flow. Ground Water, Vol. 45, No. 1, January–February, p. 89–92.

Shapiro, Allen, and Tiedeman, Claire, USGS, written communication. 2005.

Tiedeman, C., P. J. Lacombe, D. J. Goode. 2010. Multiple well-shutdown tests and site-scale flow simulation in fractured rocks. Ground Water. Vol. 48, No. 3. May-June, p. 401-415.

Williams, J.H., P.J. Lacombe, C. D. Johnson, and F. L. Paillet. 2007. Cross-borehole flow tests and insights into hydraulic connections in fractured mudstone and sandstone, in Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2007), Denver, Colorado, April 1-5, 2007: Denver, Colo., Environmental and Engineering Geophysical Society, p. 1,140-1,152 (CD-ROM).

Wilson, J.T., W.A. Mandell, F.L. Paillet, E. R. Bayless, R.T. Hanson, P.M. Kearl, W.B. Kerfoot, M.W. Newhouse, and W.H. Pedler. 2001. An evaluation of borehole flowmeters used to measure horizontal ground-water flow in limestones of Indiana, Kentucky, and Tennessee, 1999: U.S. Geological Survey Water-Resources Investigations Report 01-4139, 129 pgs.

APPENDIX
Data Quality Assurance and Quality Control

As required by EPA's quality assurance policy, a QAPP was prepared and approved for this project prior to collection of data and implemented without significant deviations. A QAPP describes the technical and quality assurance/quality control (QA/QC) activities of an environmental research project that is implemented to ensure that the results will satisfy the intended use of the data.

Secondary data (i.e., data taken from other published reports) used in this project was collected as part of Environmental Security Technology Certification Program (ESTCP) funded research projects. These projects require written quality assurance procedures in their demonstration plans, and these procedures were deemed appropriate and acceptable for the research goals of this project.

Groundwater samples collected during the borehole dilution test were analyzed at a UF laboratory for cis-1,2-DCE and TCE concentrations using a Shimadzu single quadrupole gas chromatography/mass spectrometer (GCMS-QP2010 SE) with an Evolution Purge and Trap Concentrator. Analytical quality control included positive controls (calibration checks and matrix spikes), negative controls (blanks), and duplicates. Data quality acceptance was determined by the UF principle investigators for the project using their laboratory's documented acceptance criteria. Analytical data used in this report satisfied those QA/QC requirements.

Extracts from MSPFM and FRPFM sorbent samples were analyzed at a UF laboratory for alcohol (methanol, ethanol, isopropyl alcohol, tert-butyl alcohol, and 2,4-dimethyl-3-pentanol) and volatile organic compound (cis-1,2-DCE and TCE) concentrations. The analytical method used a Perkin Elmer Autosystem gas chromatography with a flame-ionization detector. Analytical quality control included positive controls (calibration checks and matrix spikes), negative controls (blanks), and duplicates. Data quality acceptance was determined by the UF principle investigators for the project using their laboratory's documented acceptance criteria. Analytical data used in this report satisfied those QA/QC requirements.

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