PNNL-37298

RemPlex Workshop: Vertical Delineation of Contamination in Aquifers

Hosted by Pacific Northwest National Laboratory and UK Nuclear Decommissioning Authority on October 10 and 29, 2024

January 2025

Karen P. Smith[1], Frederick D. Day-Lewis[1], John P. Heneghan[2], Nikolla P. Qafoku[1]

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REMPLEX
CENTER FOR THE REMEDIATION OF COMPLEX SITES
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Figure 1. As illustrated in this image, a long-screened well connects multiple aquifer layers with different concentrations of a contaminant, indicated by color. Variations in permeability and hydraulic gradients control the exchange of water between the well and surrounding aquifer and drive vertical flow within the well; hence concentration measured in samples collected in the well may not reflect conditions within the aquifer at adjacent depths. 3

1.0 Introduction

The Center for Remediation of Complex Sites (RemPlex) is an international forum hosted at Pacific Northwest National Laboratory (PNNL) to support knowledge transfer, collaboration, and professional development in the realm of environmental remediation. To help meet these objectives, RemPlex organizes quarterly web-based seminars and a biennial Global Summit to share insights on key challenges, lessons learned, relevant research and development, and innovative solutions for a range of remediation topics.

In 2024, in collaboration with the UK Nuclear Decommissioning Authority (NDA), PNNL organized a small-group workshop as a new approach to support discussion on a specific and seemingly intractable issue: vertical delineation of contamination in aquifers underlying and/or impacted by complex sites with extensive radiological contamination, a challenge experienced at Hanford (USA), Sellafield (UK), and other remediation sites. The workshop was convened over two days and involved an international group of participants, including researchers, site operators, government agency staff, practitioners, and regulators.

The goal of the workshop was to identify and discuss issues related to vertical delineation of contamination in aquifers, identify expertise that could be brought to bear on the issue, and explore ways to transition practical experience and recent research to broader field application, enabling the design and optimization of targeted remedies and groundwater monitoring programs. The workshop focused primarily on characterization through monitoring and sampling of the saturated zone, although the discussion and recommendations are relevant to vadose zone monitoring and sampling. Similarly, although the workshop organizers have a particular interest in resolving challenges specific to complex sites with radiological contamination, discussions and recommendations are relevant to other contaminants.

This report documents the workshop discussion, including summaries of the issue (i.e., the problem statement), discussion of impediments to resolving the issue, and ideas for future collaborations to address the issue.

2.0 The Issue

Groundwater wells installed to characterize and/or monitor the hydraulic head and spatial distribution of contamination in aquifers can be grossly divided into two types: (1) wells that are open to the entire aquifer sequence or a significant portion of it, including long-screened wells or, in bedrock aquifers, open boreholes, and (2) wells that use multilevel sampling or completion technologies (e.g., packer systems, well liners, and/or multi-level well completions) to vertically isolate targeted portions of the aquifer including aquitard layers, if appropriate. These options present tradeoffs in terms of cost, data resolution, and technical constraints, and the benefits of each approach will need to be considered in terms of the site geology, monitoring objectives, and site conceptualization.

As illustrated in Figure 1, long-screened wells or open boreholes allow for sampling and detection of contamination over multiple aquifer layers (or fracture zones). These conventional monitoring wells potentially are less costly and more straightforward to install than multi-level systems and can more easily provide long-term access for geophysical logging, hydraulic testing, and remedial activities such as amendment injection and/or pumping for pump-and-treat. However, conventional wells provide limited information to determine direction and magnitude of groundwater (and contamination) flow and vertical distribution of contamination or to evaluate the effectiveness of a remedy. Furthermore, sampling from long-screened wells is affected by dilution and bias arising from intra-borehole flow and aquifer heterogeneity.

The implications of intra-borehole flow for sampling are well recognized in the literature, and experimental and modeling approaches have been developed to address the issue. Borehole flowmeter logging, fluid replacement logging, dilution logging, active thermal logging, fluid electrical conductivity logging, and single-well tracer tests have been used to infer intra-borehole flow and provide a hydraulic context for estimation of the vertical concentration profile in the aquifer based on concentrations measured in samples collected from long-screened wells. However, these methods provide limited information about conditions in low-permeability zones, which transmit relatively little water to wells; hence, long-screened wells may provide misleading or incomplete information for development of conceptual site models (CSMs). This may ultimately result in implementation of ineffectual groundwater remediation approaches. Another concern with long-screened wells is the prospect of cross-contamination between different aquifer intervals connected by the well.

In comparison, multi-level well systems that enable discrete-zone characterization and monitoring allow for targeted-depth sampling and accurate measurements of hydraulic head across saturated aquifer and aquitard layers and higher-resolution vertical delineation of contaminant concentrations. These systems hydraulically isolate intervals of a well, preventing intraborehole flow and eliminating the potential for cross contamination between aquifer layers. Information derived from these systems can result in improved CSMs and, potentially, better remedy design and evaluation.

Designing multi-level well systems may require a more complete understanding of the site geohydrologic setting; inadequately informed multi-level well designs lacking pre-characterization data may miss contaminant mass in unsampled intervals of the borehole/aquifer. In addition, multi-level well systems may prevent use of the well for other purposes, such as geophysical logging or pumping. While these systems also may be more expensive and technically challenging to install and decommission and, depending on the technology, more expensive to sample, costs should be evaluated in the context of the benefits of obtaining additional zone-specific data per well.

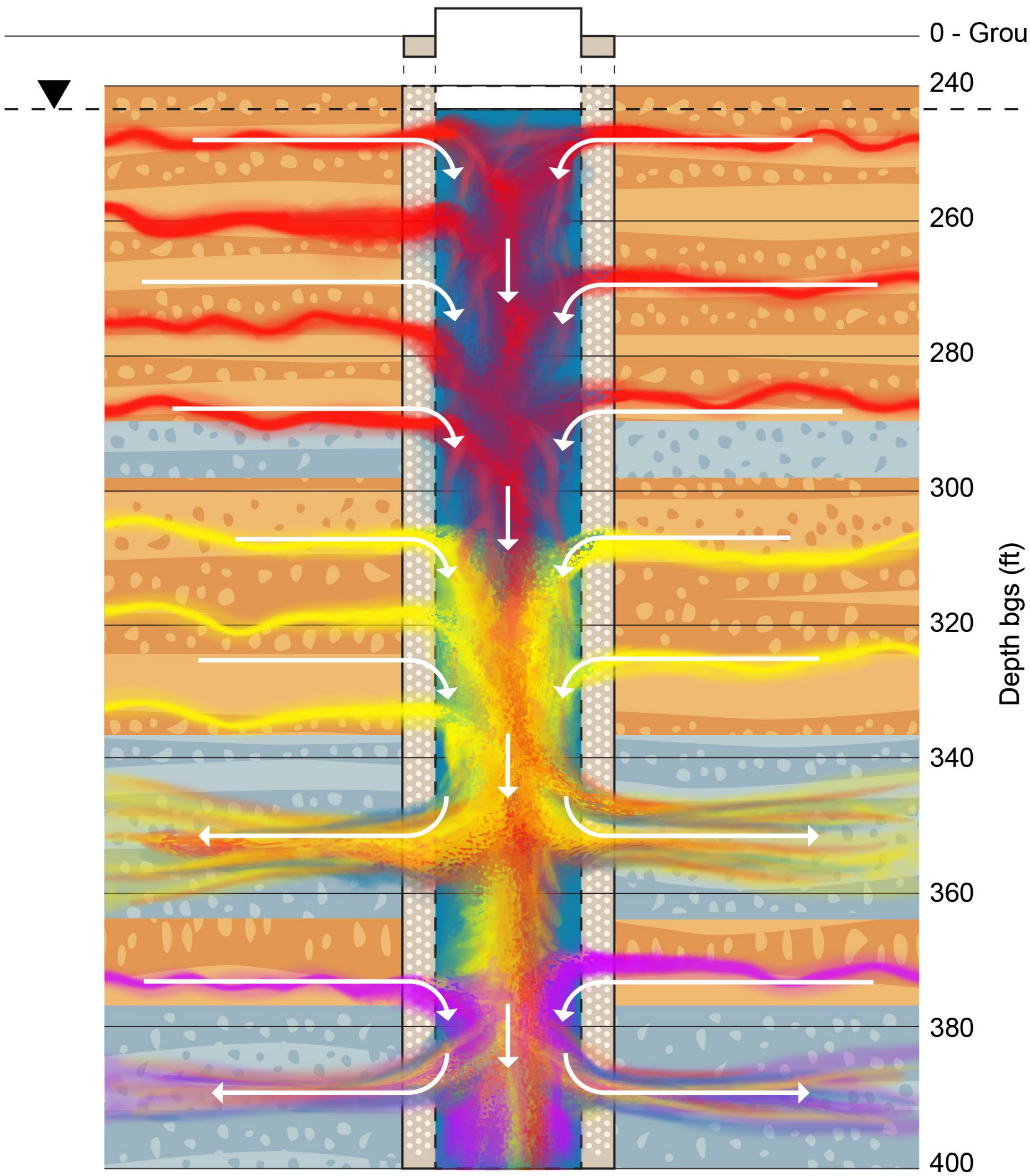

Figure 1. A long-screened well connects multiple aquifer layers with different concentrations of a contaminant, indicated by color. Variations in permeability and hydraulic gradients control the exchange of water between the well and surrounding aquifer and drive vertical flow within the well; hence concentration measured in samples collected in the well may not reflect conditions within the aquifer at adjacent depths.

The adoption of multi-level sampling techniques has the potential to offer a number of technical, cost, and program benefits in the characterization of nuclear-contaminated sites, encompassing benefits in risk-based decision-making; estimation of contaminated land volumes; end-state options development; and supporting the design, operation, close-out, and ultimate validation of *in situ* groundwater remediation. When installed in transects across the contaminant plume, data from multi-level monitoring wells facilitate the calculation of contaminant mass discharge, an important emerging metric on contaminated sites. Numerous technologies have been developed and are being deployed in diverse geologic and hydrologic settings. As documented in Appendix A and Appendix B, with more widespread use and continuing research, an improved understanding of the applicability and limitations of each technology is emerging.

Although multi-level well systems can provide a more refined understanding of aquifers by discretely characterizing hydraulic properties, hydraulic head, water chemistries, and contaminant concentrations, these systems have not been widely deployed in the nuclear industry. A failure to develop this understanding can lead to poorly designed or ineffective remedies, which can lead to prolonged remediation programs with increased costs or, potentially worse, incomplete remediation that fails to appropriately reduce risk to humans and the environment.

Multi-level systems are not without their own challenges, and may not be necessary at all remediation sites, but they are likely to be critical to effective remediation of complex sites. Understanding the impediments to adoption of these systems on nuclear sites, defining where such systems are appropriate, and articulating the value proposition for their use are key to more widespread adoption.

3.0 The Discussion

Building on a discussion of the potential advantages of using multi-level well systems, participants turned their attention to common stakeholder, legal, and logistical issues that can be encountered in moving toward this approach. It was recognized that impediments can range from those related to human factors (e.g., unfamiliarity with the technology, preference for perceived "proven" approaches) to technical factors, (e.g., understanding heterogeneity sufficiently to inform system design, selecting an appropriate system based on site or borehole conditions and study goals, developing suitable sampling methodologies, developing appropriate data interpretation methodologies) to economic factors (e.g., investing more in characterization efforts before remediation, adopting potentially more expensive well completion technologies).

It was recognized that resolving these concerns, in part, requires overcoming the impediments to adoption of multi-level well systems and clearly articulating the benefits of such systems. Participants identified the following as potential impediments:

- ***Lack of understanding of the value of data*** derived from multi-level well systems in terms of (1) increased understanding of site hydrology and (2) improved design of both the remedy and long-term monitoring program
- ***Perception that outcomes do not justify increased costs*** and lack of case studies providing cost/benefit analyses
- ***Perception of greater complexity*** of locating, designing, and sampling in multi-level characterization and monitoring wells
- Considered to be ***more in the realm of research*** than essential to improving site remediation outcomes
- ***Limited familiarity with technologies*** on the part of operators and their contractors with potential for increased cost, improper use of technologies (including the potential for any system to present an operational liability), and/or inaccurate data interpretation
- ***Lack of expertise required to integrate data*** to support remedy decisions and/or regulatory requirements, including using the data to assess contaminant concentration versus flux
- Hesitancy or concern regarding the ***implications of more detailed aquifer characterizations*** in terms of remediation requirements and costs (e.g., will higher concentrations be discovered once mixing of groundwater is eliminated?)
- ***Absence of regulatory drivers*** in some jurisdictions and little justification to exceed requirements
- ***Perception of increased complexity and cost of decommissioning*** of multi-level well systems compared to conventional wells

4.0 The Ideas

Workshop participants brainstormed about possible actions to overcome some of the impediments listed in the previous section. Priority was placed on (1) helping proponents develop appropriate business cases for implementing a multi-level system approach and (2) promoting greater collaboration to build widespread expertise. Participants agreed that the outputs would ideally be easily accessible and, where appropriate, supported by a trusted organization such as the Interstate Technology and Regulatory Council, Contaminated Land: Applications in Real Environments (CL:AIRE), or the International Atomic Energy Agency (IAEA). After brainstorming, participants recommended the following actions. (These are listed in no particular order and may be implemented in combination with each other.)

- Develop guidance and/or case studies providing:
  - Examples of applying multi-level well systems in a variety of geologic settings and contamination scenarios, including experience at specific sites plus modeled scenarios
  - Discussion of the types of sites/conditions that require or benefit most from discrete-zone characterization and monitoring
  - Discussion of the data needed to design multi-level well systems
  - Descriptions of contaminant-specific considerations for application of multi-level well systems
  - Information about design life and/or chemical resistance of construction materials to substances that may be present in the subsurface environment
  - A guide to technology selection and design according to site conditions and remediation needs
- Compile information to help support a business case for deploying multi-level well systems, including discussion of the following:
  - How more complete and higher resolution data may optimize end state solutions, reduce uncertainty, increase remedy effectiveness, and enable operators to better satisfy permit and closure requirements
  - Cost/benefit analyses comparing multi-level well systems versus long-screened wells/open boreholes, including installation, sampling, and maintenance costs and considering benefits in terms of outcomes that improve remedy effectiveness and/or reduce long-term remediation costs
  - Safety considerations
  - Decommissioning needs and/or feasibility of re-using the wells
  - Infrastructure needs and logistics
  - Sustainability considerations
- Develop publications (e.g., journal articles, position pieces, technical bulletins, Enviro Wiki content, StoryMaps, conference papers) and/or organize conference sessions to disseminate the guidance, case study experiences, and cost/benefit analyses across a full set of stakeholders (e.g., site owners and operators, remediation contractors, technology developers, regulators)
- Collaborate with other groups that have relevant technical expertise and/or platforms for disseminating information regarding multi-level well systems

5.0 Next Steps

The workshop organizers will develop a strategy to advance ideas presented in the previous section that will offer the most value to practitioners, operators, regulators, and other interested stakeholders. Expressions of interest to participate in the production of this output(s) are welcome from workshop participants. It is proposed that progress on this work will be presented at the 2025 RemPlex Global Summit.

6.0 Workshop Participants

- Delphine Appriou, PNNL
- David Becker, U.S. Army Corps of Engineers
- Tom Brouns, PNNL
- Elliot Broze, Central Plateau Cleanup Company (CPCCo)
- Mark Byrnes, DOE Hanford Field Office
- Steven Chapman, Morwick G360 / University of Guelph
- Fred Day-Lewis, PNNL
- Inci Demirkanli, PNNL
- Murray Einarson, Haley Aldrich
- Vicky Freedman, Sealaska Technical Services
- Ellwood Glossbrenner, DOE Hanford Field Office
- Chris Harvey, Nuclear Restoration Services – Magnox
- John Heneghan, Sellafield LTD
- Rebecka Iveson, PNNL
- Christian Johnson, PNNL
- Jenifer Linville, DOE Hanford Field Office
- Juliet Long, NDA
- Rob Mackley, PNNL
- Horst Monken Fernandes, IAEA
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- Celia Onishi, DOE Hanford Field Office
- Beth Parker, Morwick G360 / University of Guelph
- Nik Qafoku, PNNL
- Mike Rivett, GroundH2O plus LTD
- Judy Robinson, PNNL
- Beth Rowan, U.S. Army Corps of Engineers
- Karen P. Smith, PNNL
- Kyle Stiles, CPCCo
- Sally Thompson, UK Environment Agency
- Tollef Winslow, CPCCo

Appendix A – Overview of Commercially Available Multi-Level Monitoring Systems

The following table was advanced with Morwick G360[1] support and is derived from Table D-6d in *Integrated DNAPL Site Characterization and Tools Selection,* a 2015 guidance document by the Interstate Technology and Regulatory Council (ITRC).[2] It has been updated for this workshop report by Dr. Beth Parker and Steven Chapman of the Morwick Groundwater Research Institute of the University of Guelph, Ontario, Canada, to reflect more recent advancements in multi-level system technology.

Per these authors, a multi-level monitoring system (MLS) is a single device assembled on surface and then installed in an open borehole or a casing with multiple screens, each isolated at a different depth to divide the hole into many depth-discrete segments for data acquisition. These systems can be used in overburden or bedrock. An MLS is used to obtain vertical profiles of hydraulic head, dissolved contaminants, or natural geochemistry in the saturated zone. It can also be used in the unsaturated zone for soil gas profiling. An MLS can be equipped for single use (fluid sampling or head measurements) or dual use (both fluid sampling and head measurements).

[1] See https://g360group.org/ for information about the Morwick G360 Groundwater Research Institute.

[2] ITRC (Interstate Technology and Regulatory Council). 2015. *Integrated DNAPL Site Characterization and Tools Selection (ISC-1)*. DNAPL Site Characterization Team. Washington, D.C. 361 pp. Available at https://projects.itrcweb.org/DNAPL-ISC_tools-selection/Content/Resources/DNAPLPDF.pdf.

Overview of Commercially Available Multi-Level Monitoring Systems (MLS) (updated from ITRC 2015)

Multilevel System Description	Applicability / Advantages	Limitations / Difficulties	References
Westbay Systems[a] (Westbay Instruments) First used in groundwater applications in 1978. It is a modular system using PVC or stainless-steel casing with valves at the sampling point. Ports are most commonly isolated using packers that can be installed in 3.0-6.3 in. (7.6-16 cm) diameter boreholes and for holes ≥ 5 in. (≥ 13 cm) it can be installed with backfilling option.[b] To date, the maximum installation depth achieved is 4035 ft (1235 m) with the PVC version, and 7128 ft (2173 m) with the stainless-steel version. Deeper installations are feasible with the stainless-steel version.[c]	• Least chemically reactive[d] • Can be easily installed through temporary drill casing in weak rock or soils to prevent borehole collapse interfering with installation • Can monitor largest number of zones in deep boreholes • Can QA/QC individual packer seals from installation data and/or testing after MLS installation • Some design modifications can be made in the field • Can conduct hydraulic tests with the fewest restrictions when using the pumping port[e] • Discrete sampling without repeated purging[f] • No fixed downhole (dedicated) instruments avoids irreplaceable instrument failure	• Can only monitor head in one port at a time with a single MOSDAX probe; however, a string of MOSDAX probes can be used to monitor continuously in multiple ports at the same time • When sampling using a measurement port, the maximum amount of water that can be obtained in a single trip is 1 L; if greater volume is required, more trips down the hole are needed • The current version of the pumping port is not intended for repeated use; however, an improved version is under development	https://www.westbay.com/ Black et al. (1986), Patton and Smith (1988)
Waterloo Systems[a] (Solinst) First used in groundwater applications in 1984. It is a permanent, modular system using PVC casing. Ports are isolated in 3-4.5 in. (7.6-11.4 cm) diameter boreholes using packers and in boreholes ≥ 5 in. (≥ 13 cm) by backfilling option.[b] To date, the maximum installation depth achieved is 1000 ft (305 m).[c]	• Minimally reactive option available • Largest number of monitoring zones in shallow holes (< 100 ft) • Self-inflating permanent packers • Two options are available: (1) dedicated double-valve pumps and transducers or (2) removable peristaltic pump and manual water level measurements with small-diameter water level meters • Wide selection of tubing materials available • Can be installed through casing using all drilling techniques • More monitoring points can be used if only measuring hydraulic head • Some design modifications can be made in the field	• Most difficult to decommission due to stainless steel ports • Packer option restricts the hole diameter to ≤ 5 in. (13 cm) • Cannot identify if self-inflating packers rupture, but chemical self-sealing effect minimizes leakage	https://www.solinst.com/products/multilevel-systems-and-remediation/401-waterloo-multilevel-system/ Cherry and Johnson (1982), Parker et al. (2006)

Multilevel System Description	Applicability / Advantages	Limitations / Difficulties	References
FLUTe Systems (Flexible Liner Underground Technologies)[g] **Water FLUTe** First used in groundwater applications in 1994. This system uses a continuous flexible urethane-coated nylon fabric tube (liner) to seal the borehole with spacers between the liner and the borehole wall to create monitoring zones. The entire system is pressed against the borehole wall with water or grout and can be used in 3-20 in. (7.6-50 cm) diameter boreholes. To date, the maximum Water FLUTe installation depth achieved is 1700 ft (518 m); however, deeper installations are feasible.[c]	• Most easily removable for repair/replacement or reuse of borehole[h] • Smallest sampling reservoir volume • Seals entire borehole except for monitoring intervals; general overall seal is confirmed by water level measurement inside the liner, except for zones with head larger than excess head in liner • Design is not restricted by individual component lengths • Simultaneous, rapid high-volume purging of all monitoring intervals possible • More monitoring points can be used if only measuring head • Most easily installed in artesian holes • Most convenient for angled holes and holes in karst (use heavier fabric)	• Requires lead time for fabrication and shipping to site and no field design modifications possible • Most chemically reactive[d]; however, the high-volume rapid purging system minimizes contact time for reactions to occur • A zone with significantly higher head than the blended head may result in a weak seal for this zone • Extremely low head at depth may cause liner rupture	https://www.flut.com/water-flute Cherry et al. (2007), Keller (2009), Keller (2023)
Shallow Water FLUTe (SWF) Lower cost version introduced ~2015 that uses smaller diameter open tubes running to each port within the liner that seals intervals between ports.	• Lower cost version with open tubes running to each port suited to sites with shallow water table (<25 ft) • Requires separate pumping system for sampling (e.g., peristaltic pump) • Water levels can be measured with small-diameter water level meters or FLUTe vacuum water level meter • Otherwise similar to Water FLUTe (above)	• Small-diameter tubes running to each port limit head monitoring and purging / sampling options • Otherwise similar to Water FLUTe (above)	https://www.flut.com/shallow-water-flute Keller 2023 (Section 10.5.2) MG360 experience: 10-port SWF installed at NAWC (NJ) site (2016) in a 150-ft (46-m) HQ-borehole.
FLUTe Cased Hole Sampler (CHS) Lower cost version introduced ~2018 that allows direct insertion into boreholes (no eversion) in cased holes or smooth bedrock boreholes. Uses smaller diameter open tubes running to each port within the liner that seals intervals between ports.	• Lower cost direct insertion option for installation in cased multi-screen holes or smooth open bedrock boreholes with diameters 2-4-in (5-10 cm) and shallow water table (<25 ft) • Open tubes running to each port so requires separate pumping system for sampling (e.g., peristaltic pump) • Water levels can be measured with small diameter water level meters or FLUTe vacuum water level meter • Otherwise similar to Water FLUTe (above)	• Small-diameter tubes running to each port limit head monitoring and purging / sampling options • Requires cased multi-screen holes or stable, relatively smooth open bedrock boreholes for direct-insertion method • Can be difficult to insert system downhole, especially in rougher walled boreholes • Otherwise similar to Water FLUTe (above)	https://www.flut.com/casedholesampler Keller 2023 (Section 10.5.3) MG360 experience: two 6-port CHS installed at Sweden site in HQ-cored boreholes in granite (2019) to 80-90 ft (24-27 m) depth.

Multilevel System Description	Applicability / Advantages	Limitations / Difficulties	References
CMT Systems (Solinst) First used in groundwater applications in 1999. Polyethylene tubing with 3 or 7 chambers is used, and each chamber is converted into a depth-discrete monitoring tube in 4-8 in. (10-20 cm) diameter boreholes using backfilling option.[(b)] Bentonite packers can be used for 3-channel systems in boreholes from 2.5-3.5 in. (6.1-9.0 cm). Removable version possible using lightweight rubber packers on 7-CH system, using one of the channels for packer inflation (reducing the number of usable ports to 6) for insertion into small-diameter stable bedrock boreholes (2.5-3.5-in., 6.1-9.0 cm). To date, the maximum installation depth achieved is 300 ft (91 m) for 7-CH and 500 ft (152 m) for 3-CH.	• Lowest capital cost • Simple installation procedure does not require advanced training • Can be installed through casing using all drilling techniques • Most versatile system for design modifications in the field • Continuous tube; no joints minimize potential leaking • Heads measured using narrower diameter water level tape, or option for dedicated pumps/transducers. • Several methods for water sampling (double valve pump, peristaltic pump, inertial lift, etc.) • Simple surface completion with minimally intrusive infrastructure • Option for lightweight rubber packers on 7-CH system using one channel for packer inflation (so 6 usable ports) for use in stable, smaller diameter bedrock boreholes	• Moderately chemically reactive[(d)] • Maximum number of monitoring zones limited to 7 • Bentonite and sand cartridges only available for 3-CH systems; however, additional CMT packer options are being developed • A removable version using lightweight rubber packers on 7-CH system (using one channel for packer inflation, so 6 ports) has been developed and field-tested	https://www.solinst.com/instruments/multilevel-systems/403-cmt-multilevel-systems/ Einarson and Cherry (2002), Fernandes et al. (2019) MG360 experience: lightweight packer version tested at Guelph site in dolostone bedrock in 51-mm backpack drilled boreholes.
G360 MPS (Multiport System)[(i)] (Solinst, in progress) Adapted version of Waterloo System with increased flexibility using open-tube system (no dedicated equipment). Allows larger diameter system casing (currently 2.5-, 3.0- and 4.0-in. ID) with versatility in the number and/or diameter of internal tubes running to each port. Two versions are available: 1. Threaded version using off-the-shelf threaded Sch. 40 casing in backfilled type systems in overburden or bedrock boreholes. 2. Push-fit version using double O-ring sealed push-fit Sch. 80 casing with lightweight rubber packers, with packer inflation using pressurized system casing and sealed manifold at surface.	• Flexibility in number of ports and/or diameters of tubes running to each port • Larger tubes provide more options for hydraulic head monitoring, for example, using self-contained (and removable) pressure transducers • Larger diameter tubes provide more options for groundwater purging and sampling, including use of inertial pumps, and larger double valve pumps or bladder pumps for deeper water level conditions • Avoids use of any dedicated / non-removable equipment, providing the most flexibility and long-term robustness	• Backfilled systems require sufficiently large diameter borehole for adequate annular space for backfilling (typically 2-in. or 5 cm annulus, although backfilled systems have been installed in boreholes with less annular space (e.g., 1.5-in. or 3.8 cm) • Packer systems using sealed-casing method rely on entire system casing (i.e., all downhole joints and at surface where tubes exit via a sealed manifold) to hold adequate pressure for packer inflation to suitable pressures; some research systems have required removal for troubleshooting for leaks and/or periodic pressure checks and adjustments • Only the threaded (backfilled) system is currently available commercially through Solinst (official release pending)	Cherry et al. (2015), Cherry et al. (2017), Parker et al. (2020, 2022, 2024)

Notes:

(a) Westbay and Waterloo systems have three options: (1) using packers to isolate multiple screens in a cased well, (2) using packers to isolate borehole sections in an open hole in bedrock, and (3) using sand backfill in monitored sections with bentonite seals between sections in an open hole.
(b) The backfilling option is not attractive for karstic rock with large zones that will require too much sand and/or bentonite.
(c) Installation to the greatest depths can be achieved for the Westbay and Waterloo systems using packers, and for Water FLUTe systems in holes greater than 6-in. diameter.
(d) Chemical reactivity refers to the system components being prone to sorption and/or diffusion of organic contaminants. Purging is more important for systems with greater reactivity to avoid adsorption/diffusion effects.

Multilevel System Description	Applicability / Advantages	Limitations / Difficulties	References

(e) Hydraulic tests can be conducted with all MLS but there is a maximum permeability that can be measured depending on the tubing size or other flow restrictions.
(f) The Westbay system does not include any components that isolate water from the sampling point (e.g., tubing to the surface) and therefore does not need to be purged to remove stagnant water from tubing before obtaining a relatively undisturbed sample.
(g) FLUTe systems have two options: (1) install in hole that has multi-screened casing and (2) install in open borehole. There are two lower cost open-tube options, the SWF and CHS, for use in specific applications where water levels are shallower.
(h) Waterloo and CMT systems can be removed by over-drilling, or the CMT system can be decommissioned by grouting in place.
(i) G360MPS offer flexibility with different external casing diameters and internal tubing diameters and numbers running to each port. These can be installed as backfilled systems in overburden and bedrock boreholes and with removable options with packers in bedrock boreholes. These allow use of non-dedicated transducers with on-board memory and batteries and different pump types for purging and groundwater sampling.

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Appendix B – Overview of High-Resolution Sampling and Profiling Tools

The following table is based on the direct sensing summary table included in Section 3 (p. 257) of *Implementing Advanced Site Characterization Tools*, a 2019 guidance document by the Interstate Technology and Regulatory Council (ITRC).[1]

[1] ITRC (Interstate Technology and Regulatory Council). 2019. *Implementing Advanced Site Characterization Tools*. Implementing Advanced Site Characterization Tools Team. Washington, D.C. 328 pp. Available at https://asct-1.itrcweb.org/asct_full_pdf_12_15_19.pdf.

Tool	Primary Parameter	Parameter Resolution	Drilling Methods	Typical Productivity per Day	Vertical Parameter Resolution	Limitations	Potential Tool Combinations
High-Resolution Sampling and Profiling							
Screen Point GW Sampler	Aqueous samples	Aqueous samples, parameter based on analytical method used	Percussion or static driven DPT	Varies based on objectives	inches – 1 ft	Low-permeability formations	Pneumatic slug testing, mobile lab
Direct-Push Temporary Well Point Systems	Aqueous samples	Aqueous samples, parameter based on analytical method used	Percussion or static driven DPT	Varies based on objectives	1 ft	Limited to lithologies that can be pushed, refusal in bedrock and rocky formations	MIP, LIF, OIP XRF, injection flow logging, electrical conductivity, mobile lab
Soil/ Bedrock Cores	Soil and/or rock samples	Lithologic descriptions, solid media samples with parameters based on analytical method used	Percussion or static driven DPT, hollow stem auger with sampler, sonic, bedrock coring methods	Varies based on objectives and drilling method	As needed	Limited recovery in some lithologies	Mobile lab, DFN, PID, FID, XRF
HPT – GWS	Estimated hydraulic conductivity, aqueous samples	Aqueous samples, parameter based on analytical method used	Percussion or static driven DPT	Varies based on frequency of sample collection	cm on hydraulic profiling, depth-discrete over 3- to 4-inch interval for groundwater samples	Not effective in lower permeability formations, potential fouling in finer grained formations	Electrical conductivity
Waterloo APS	Estimated hydraulic conductivity, aqueous samples	Aqueous samples, parameter based on analytical method used	Percussion or static driven DPT	Varies based on frequency of sample collection	cm on hydraulic profiling, depth-discrete over 3- to 4-inch interval for groundwater samples	Not effective in lower permeability formations, potential fouling in finer grained formations	Electrical conductivity
FLUTe (FACT)	Vertical profile of VOCs	Limited to analytes that adsorb to carbon Results reported in mass of VOC per mass of carbon	Needs open borehole for deployment Unconsolidated and bedrock applications	Deployed in hours, wait time 1-2 weeks	Continuous carbon profile, resolution based on sampling	Not applicable for constituents that do not adsorb to carbon	FLUTe T-Profiler, blank liner, NAPL FLUTe
FLUTe (NAPL)	Presence and depth of NAPL	LNAPL and DNAPL	Needs open borehole for deployment Unconsolidated and bedrock applications	Deployed in hours, wait time 1+ hours	Continuous profile, NAPL detection based on visual inspection of liner	Can't specify NAPL type	FLUTe T-Profiler, blank liner, FACT System
DFN	Distribution of VOCs in bedrock (fractures and matrix)	VOCs, physical rock properties	Bedrock coring	Varies based on rock type and frequency of sampling	Inches to feet, depth-discrete sampling, interval based on objectives and geology	Data representative of mass diffused in the matrix, not a direct measure of dissolved concentrations	Mobile lab
Multi-Level Well Systems	Vertical profile of contaminants	Aqueous samples, parameter based on analytical method used	Any, depends on lithology	Varies	Depth interval determined based on objectives	Depends on system, e.g., FLUTe only in consolidated and direct-push only in unconsolidated or soft consolidated	FLUTe T-Profiler, downhole physical and analytical tools

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