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Direct-push profiling technologies for sustainable investigation of contaminated sites

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ABSTRACT

Most contaminated site investigations still rely on conventional characterisation approaches based on collecting a limited number of soil samples and installing long-screened wells. However, it is widely recognised that these methods cannot adequately capture the subsurface heterogeneity largely governing the fate and transport of contaminants. Following the example of cone penetration testing (CPT), multiple direct-push profiling tools have been developed over the years to investigate and manage contaminated sites in a more efficient and sustainable way. The objective of this work is to present well-established and emerging direct sensing technologies for contaminated site investigation and demonstrate how their application does not just result in a reduction of uncertainties but also in improved sustainability outcomes. The assessed technologies included the Hydraulic Profiling Tool (HPT), laser-induced fluorescence (LIF), Membrane-Interface Probe (MIP), and nuclear magnetic resonance (NMR). Direct-push profiling techniques were found to be valuable throughout the project lifecycle, from initial site screening phases to remedial design and closure. The high-density data collected helped to delineate contaminant source zones, preferential migration pathways and low-permeability zones. This information complemented the analysis of a reduced number of physical samples to optimise remedial designs and monitoring networks. Additional benefits related to sustainability concepts included the production of minimal investigation-derived waste, the need for less field campaigns and the little impact caused to site owners and their activities. High-resolution site characterisation approaches are paramount to conduct informed risk assessments and effectively achieve remediation goals.

Keywords: contaminated site characterization; direct-push logging; subsurface heterogeneity; sustainability.

1. Introduction

In general, contaminated site investigations based on collecting a limited number of soil samples and installing long-screened wells cannot adequately capture the subsurface heterogeneity largely controlling contaminant fate and transport processes. Following the example of cone penetration testing (CPT), multiple direct-push profiling tools have been developed to overcome this issue. Some early examples of direct-push sensors for contaminated site investigation consisted of modules incorporated into CPT systems. Over time, many of these hydrogeological and contaminated land direct sensing probes evolved to robust, standalone designs that could be hammered into the ground to expand their applicability range. These direct sensing probes are often advanced using multi-purpose rigs capable of physical sampling and drilling through a variety of methods.

Limitations associated to conventional contaminated site investigations include: (i) relatively low productivity, (ii) incomplete core recovery and contaminant loss or redistribution during sampling, (iii) significant waiting time involved in obtaining laboratory results, and (iv) production of potentially contaminated waste.

On the contrary, many direct sensing probes can record quasi-continuous measurements of subsurface parameters in situ, have real-time visualisation capabilities, offer higher productivity rates (increasing the number of locations that can be investigated per day compared to conventional approaches), and produce minimal investigation-derived waste (ITRC 2019). Despite these advantages and the fact that most contaminated sites present suitable ground conditions for the application of direct sensing tools, they remain underutilised by the contaminated land industry internationally (García-Rincón et al. 2024). This is in part due to the absence of incentive structures supporting the reduction of site investigation uncertainties to better protect exposed populations and the environment.

The objective of this work is to present some popular direct sensing technologies for contaminated site assessment and demonstrate how their application can improve conceptual site models, remedial designs, and sustainability outcomes. This is illustrated through a comparison with conventional methods and case studies.

2. Sustainability in contaminated site investigation: conventional methods versus direct sensing

Conventional investigation and remediation methods are often found to underperform due to the complex subsurface conditions typically encountered at contaminated sites (Alden et al. 2023). From a sustainability perspective, this poses many challenges. Multiple mobilisations and field campaigns are frequently needed, contamination source zones and hotspots are often missed, and costly remediation systems result ineffective. The application of direct sensing tools contributes to more rapid, efficient, and sustainable site investigations by collecting higher resolution data and by having the ability to analyse it on real time. This enables the development of adaptive investigation strategies and the optimisation of resources and site management plans, which generally translate into cost savings (Dyment and Kady 2018).

Furthermore, there are other sustainability concerns that can be eliminated or mitigated by using direct sensing technology, including:

1. drilling-derived waste: Conventional drilling and sampling methods produce large quantities of potentially contaminated soil and water requiring costly storage and transport to licensed waste management facilities. Direct-push profiling does not produce any waste besides the tooling decontamination (which also applies to conventional drilling) and, depending on the tool, relatively small quantities of water used as part of quality assurance/quality control measures or during logging;
2. well construction materials: Sand is the second most extracted natural resource globally after water. Sand extraction is largely ungoverned in many regions of the world and it is increasing at unsustainable rates, being the current production equivalent to approximately 18 kg of sand and gravel per person per day. Furthermore, desert sand is commonly not suitable for engineering applications and active sand bodies (e.g., fluvial or coastal environments) need to be mined causing environmental impacts like coastal and river erosion, deltas shrinkage and loss of biodiversity, saltwater intrusion, and increase of flooding and drought risks (UNEP 2022). Consequently, there is a need to find sand replacements, being crushed waste glass a promising alternative (Kazmi et al. 2021). Additionally, other well construction materials also represent an environmental concern, including polyvinyl chloride (PVC) pipes, whose production is energy demanding and involves a toxic precursor like vinyl chloride (a carcinogenic organochloride);
3. sampling consumables: Soil and groundwater sampling heavily relies on single-use items such as nitrile gloves, plastic bags, disposable bailers, tubing made of polytetrafluoroethylene (PTFE; popularly known as Teflon, which belongs to the group of per- and polyfluoroalkyl substances or PFAS), soil jars, packaging, and so on;
4. borehole sealing: As discussed by Purdy et al. (2022) for the case of geotechnical investigations, the small borehole diameter typically associated with direct-push profiling tools like CPT results in higher efficiencies during grouting when this is required. Additionally, the ability to visualise direct sensing data in real time enhances improved identification of aquitards and reduces the risk of creating contaminant migration pathways between separate aquifers.

3. Direct-push profiling methods for contaminated site characterisation

3.1. Hydraulic Profiling Tool (HPT) and other direct-push injection loggers

Different direct-push injection loggers exist, being the Hydraulic Profiling Tool (HPT) commercialised by Geoprobe Systems® (Salina, KS, USA) the most popular design (Liu et al. 2023). Direct-push injection loggers are used for hydrostratigraphic characterisation. They provide information on the distribution of preferential flow pathways and low-permeability zones, and can be used to estimate hydraulic conductivity values.

The HPT consists of a probe with an injection port and a downhole pressure transducer. The probe is connected to a field instrument and HPT flow controller using a trunkline threaded through the direct-push rods.

As the probe is pushed into the ground, water is injected into the formation at a rate typically set between 200 and 300 mL/min. The system quasi-continuously records flow rate and downhole pressure, which represents the sum of pressure induced by injecting water, atmospheric pressure, hydrostatic pressure in the saturated zone, and pressure caused by the probe advancement.

Increases in induced pressure (and possible drops in flow rate) are observed when passing through less permeable intervals while a decrease in pressure is generally an indication of more permeable materials. The ratio between flow rate and induced pressure is often used to estimate water-saturated hydraulic conductivity using empirical correlations or physically based approaches, primarily within the 0.03–25 m/day range (Liu et al. 2023).

The HPT also incorporates an electrical conductivity sensor (dipole or Wenner array). Electrical conductivity often works as an indicator of clay-rich sediments, although it may also be influenced by other factors such as hydrocarbon biodegradation processes (Atekwana et al. 2023) seawater intrusion, and presence of remedial fluids or other anthropogenic materials.

3.2. Membrane-Interface Probe (MIP)

The Membrane-Interface Probe (MIP), also manufactured by Geoprobe Systems® (Salina, KS, USA), is used for delineation of volatile organic compounds (VOCs) such as petroleum hydrocarbons and chlorinated solvents. As depicted in Fig. 1 (a), the MIP is nowadays combined with the HPT in a system called Membrane-Interface & Hydraulic Profiling Tool (MiHPT) enabling simultaneous logging of parameters related to the hydrostratigraphic profile and the contaminant distribution.

The MIP probe consists of a heater block and a semi-permeable membrane impeding water ingress. The heater block is typically set at 120 °C to enhance volatilisation and diffusion through the semi-permeable membrane of VOCs present in the formation (in any phase: aqueous, gaseous, sorbed, or non-aqueous phase liquid—NAPL). Using a carrier gas (normally nitrogen), VOCs are transported to the surface where the gas lines are

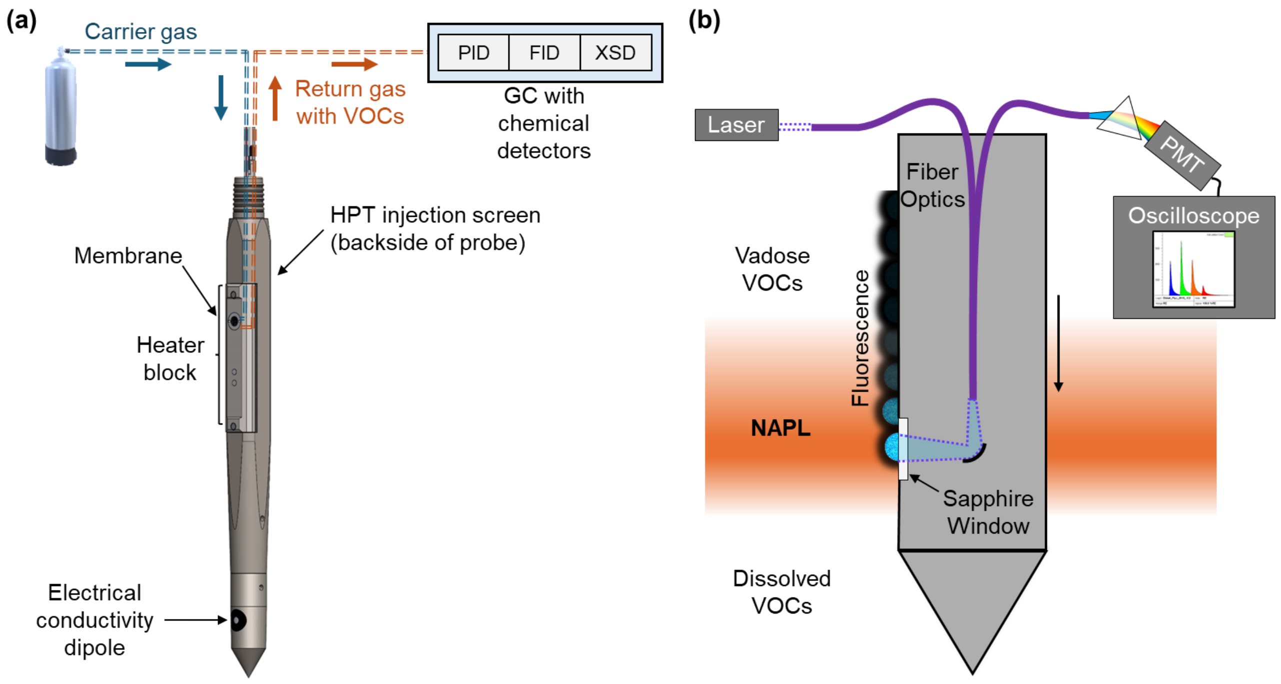

Figure 1. (a) MiHPT and (b) LIF probe concepts (after St. Germain 2023). PMT stands for photomultiplier tube.

connected to a gas chromatograph (GC) housing multiple chemical detectors, commonly a photo-ionisation detector (PID), a flame ionisation detector (FID), and a halogen specific detector (XSD). The probe advancement is frequently paused (typically every 0.3 m for 30–45 s) to ensure adequate heating of the ground at these points and collect more representative VOC measurements.

The recorded PID, FID, and XSD logs provide information on the types of chemicals being encountered. The XSD will only respond to halogenated compounds (e.g., chlorinated or brominated substances) while the PID using a 10.6 eV lamp will respond to aromatic hydrocarbons and double-bonded halogenated compounds (not alkanes). If natural gas or methane is found, only the FID will yield a positive signal (ITRC 2019). The responses from the chemical detectors correspond not just to the contaminant concentration in the formation but they also likely influenced by other factors like sediment type (St. Germain 2023) Contaminants like PFAS are too large molecules and have too high boiling points to be sampled with MIP. Alternative approaches like combining HPT and targeted physical sampling must be adopted for their delineation.

The MIP system and operation procedure can be adjusted to investigate a wide range of VOC concentrations, from sub-ppm levels to intervals impacted with NAPL. High concentration levels may pose certain risks to the system, impact the production performance by increasing the baseline levels in the chemical detectors, and cause carryover effects (St. Germain 2023). Because of these reasons, it is common practice to investigate the presumably less contaminated areas first (outside-in approach) and use other tools like laser-induced fluorescence (LIF) probes in areas where petroleum NAPL may exist.

3.3. Laser-induced fluorescence (LIF)

Among the optical screening systems available, those based on LIF technology offer additional capabilities for the rapid delineation of subsurface NAPL bodies, which is paramount for the characterisation of sites contaminated with petroleum hydrocarbons or chlorinated solvents because NAPLs can persist in the subsurface for decades and contribute to the continued contamination of soil and groundwater. Depending on the NAPL type, different LIF tools are employed, with the Ultra-Violet Optical Screening Tool (UVOST), manufactured by Dakota Technologies (Fargo, ND, USA), being designed to identify petroleum NAPLs like petrol (gasoline), diesel, kerosene-type jet fuel or crude oil.

UVOST takes advantage of the fluorescence properties of polycyclic aromatic hydrocarbon molecules contained in petroleum NAPLs to excite them using an excimer laser that is transmitted to the formation through fiber optics, a parabolic mirror, and a sapphire window as shown in Fig. 1 (b). There is also a different LIF probe (DyeLIF™) capable of detecting non-fluorescent NAPLs (e.g., benzene NAPL or chlorinated NAPLs) by injecting a fluorescent, oleophilic dye ahead of the sapphire window (St. Germain 2023).

The UVOST system, which can also incorporate electrical conductivity sensors or hydraulic profiling modules, records the fluorescence response at centimetre scale. It measures the fluorescence intensity and lifetime at four wavelengths (350, 400, 450, 500 nm). The resulting multi-wavelength waveforms can be analysed to gain insight into the NAPL type, NAPL weathering conditions, and other subsurface characteristics like presence of oxygen or naturally fluorescent soils. As in the case of MIP logging, factors like the sediment type may influence the UVOST intensity readings (García-Rincón et al. 2020).

An important advantage of LIF systems compared to conventional monitoring wells is that LIF probes can detect residual and entrapped NAPL, which do not enter into wells. Residual and entrapped NAPL are relatively immobile but may act as long-term sources of contamination and should be addressed in the design of effective site management strategies (Lenhard and García-Rincón 2023).

3.4. Nuclear magnetic resonance (NMR)

Proton nuclear magnetic resonance (NMR) is a borehole logging technique well established in the oil and gas industry. In the last decade, NMR logging has been adopted by near-surface practitioners in the hydrogeology, contaminated land, geotechnical, and mining fields to obtain vertical profiles of water content (porosity in saturated materials), and hydraulic conductivity (Liu et al. 2023; Reid et al. 2023).

NMR probes incorporate permanent magnets and an induction coil and can be directly deployed in boreholes or, in the case of a specific probe developed by Vista Clara (Mukilteo, WA, USA), advanced into the ground using direct-push technology.

The permanent magnets create a static magnetic field that polarises the spins associated with hydrogen atoms present in the formation. A pulsed oscillating magnetic perturbation is applied at the Larmor frequency to induce the precession motion of the hydrogen atoms. Once this perturbation ends, the atoms return to the equilibrium state releasing energy that can be recorded by the induction coil in the probe. The initial magnetisation is indicative of the amount of hydrogen atoms while the relaxation time is function of the pore-size distribution of the geological medium (Liu et al. 2023). NMR response may also be influenced by other factors like the formation mineralogy (for instance, high iron content).

The derivation of hydraulic conductivity values from NMR data is commonly based on the Schlumberger Doll Research equation, which includes empirical parameters that are relatively well proven for consolidated formations. Knight et al. (2016) compared NMR logs with estimates of hydraulic conductivity at three unconsolidated sand and gravel aquifers in the United States and concluded that the empirical parameters were different to those for consolidated systems but did not vary significantly from site to site in the three areas studied. The practical range of hydraulic conductivity values that can be assessed seem substantially broader with NMR than with HPT, although HPT logging is generally faster than using NMR.

As discussed by Atekwana et al. (2023), NMR logging may also represent a promising solution to quantify NAPL volumes in situ, therefore complementing the application of other tools like UVOST.

4. Results from case studies

How the application of direct sensing tools contributes to improve the effectiveness, efficiency, and sustainability of an investigation is highly site specific, although case studies can provide some insight into it. For instance, Van de Putte et al. (2012) showed how using a customised MIP system at a site contaminated with chlorinated compounds in Belgium led to reducing the number of well installations, physical samples, and chemical analyses, therefore resulting in a cost saving of about 30% compared to performing a similar field campaign relying on conventional methods only. Dyment and Kady (2018) discussed the cost and benefits of using high-resolution site characterisation (HRSC) approaches based on a database of petroleum contaminated sites in the United States and considering the entire project lifecycle. The article recognised the uniqueness of each site and stated that most projects could afford the implementation of HRSC methods. Using approximate figures, they hypothesised that the benefits derived from adopting HRSC approaches in challenging sites along modest improvements in lower-cost sites would likely compensate the cost of applying HRSC at every petroleum contaminated site, which would also result in more robust conceptual site models and less uncertainty.

In Australia, direct sensing technologies have been employed at hundreds of sites during the last decade. Examples included brief campaigns (2–3 days) providing data detailed enough to support the assessment of low-risk conditions and abandon costly remediation plans (valued in hundreds of thousands of dollars) in favour of passive, monitored natural attenuation approaches.

One site illustrative of the advantages of collecting direct sensing data was a service station located in a residential area on the coast of Queensland. According to the stratigraphic logs and information provided by the investigators, it seemed to consist of a relatively homogeneous aquifer primarily comprising medium-grained sand where a release of fuel hydrocarbons had occurred, although no NAPL was observed in wells screened down to 6.5 m bgs (below ground surface) in the last campaign prior to the application of direct sensing tools. Before that, conventional investigation was conducted over five years and there were plans to inject remedial amendments over 6.5 m bgs.

The direct sensing works included the use of UVOST and MiHPT over three days. As depicted in Fig. 2, the first UVOST log and the first MiHPT log obtained on site (adjacent to each other) provided information that improved the conceptual site model. Positive UVOST response indicating the existence of petrol (gasoline) NAPL was recorded, particularly below 6.6 m bgs (multi-wavelength waveforms not shown in Fig. 2). This interval likely contaminated with NAPL coincided with a preferential flow pathway as suggested by the HPT pressure log, where an increase in HPT pressure was observed at 6.2 m bgs until it dropped around 6.6–6.7 m bgs. The existence of petroleum hydrocarbons at this interval was supported by an increase in PID readings, which reached the upper limit of quantification of the detector (considering the GC settings employed) and led the direct sensing technician to end the MiHPT log with the objective of preventing damage to the system.

Similar observations were made in other logs, finding positive UVOST response below the water table elevation over a 25-m transect. This suggested the existence of entrapped NAPL, which is practically

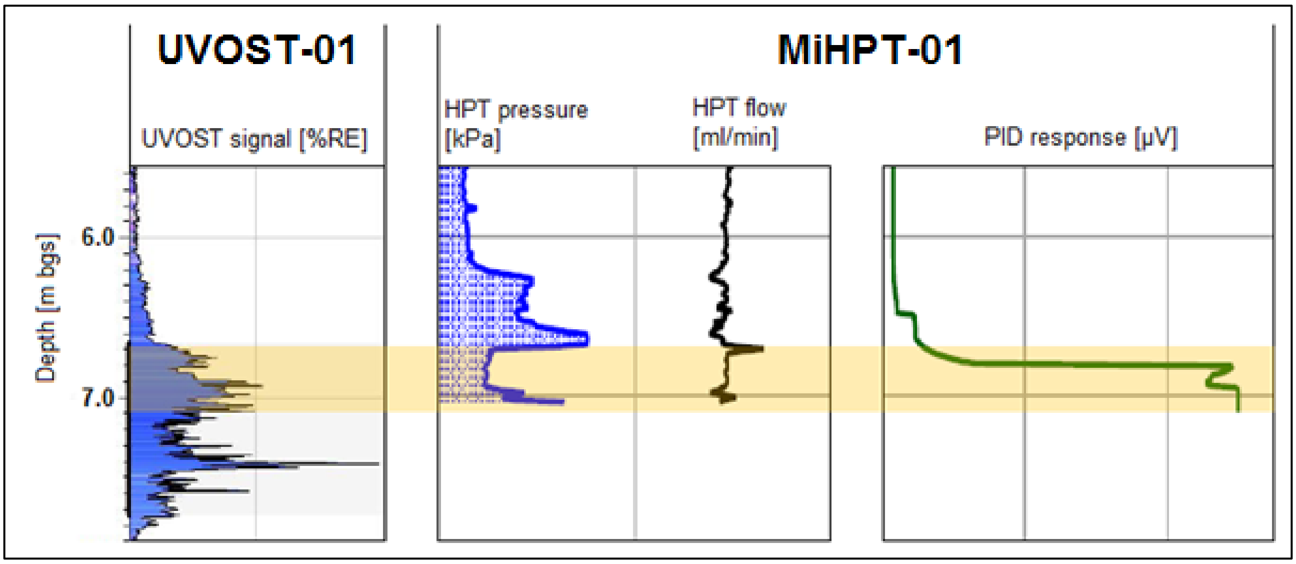

Figure 2. Comparison of adjacent UVOST and MiHPT logs at a service station in Queensland, Australia.

immobile and does not enter wells nor can be removed through hydraulic recovery systems. The direct sensing data also revealed that, due to the fine-scale changes in permeability, most remedial amendments injected over 6.5 m bgs would likely remain over that depth missing the contamination mass largely residing below 6.6–6.7 m bgs.

Another site, a service station located in a rural town in Western Australia, was established as an experimental site to study the fate and transport, characterisation, and in-situ remediation of petroleum NAPLs after a release of petrol (gasoline) occurred in 2013 (García-Rincón et al. 2020). The stratigraphic profile generally consisted of a heterogeneous sandy aquifer (where the NAPL was typically found) with variable amounts of clays, silts, and gravels, overlain by a confining, finer-textured layer, and underlain by clays.

In the first 2–3 years of field activities, a relatively large number of monitoring points was installed, including 36 long-screened wells, 5 multi-level wells with thermistors, and 16 vapour points (García-Rincón 2020). Most of the fieldwork focused on assessing NAPL hydraulic conditions (by monitoring in-well fluid levels) as well as NAPL mobility, transmissivity, and recoverability (through baildown testing and the implementation of NAPL mass recovery systems). Field campaigns were commonly conducted every 1-2 months in the 1.5 years prior to the direct sensing investigation, which consisted of four days for the completion of 20 UVOST profiles and 10 HPT logs.

In terms of NAPL mobility, the outcomes of the brief direct sensing investigation were consistent with the conceptual site model based on the previous testing. The UVOST and HPT data suggested differences in NAPL mobility supported by NAPL mass recovery trials performed. In this site, the UVOST response seemed to work as an indicator of NAPL transmissivity better than the estimations of NAPL saturation based on physical sampling. The analysis of UVOST multi-wavelength waveforms also enabled rapid identification of long-term entrapped and residual NAPL as corroborated by the comparison with in-well fluid level data. In addition, UVOST and HPT revealed fine-scale variations of hydrostratigraphic characteristics and contaminant distribution that could not be captured with that confidence using conventional methods. Producing minimal waste and in only one mobilisation, a relatively short direct sensing campaign resulted in rapid collection of valuable data that complemented the results obtained after numerous mobilisations using conventional methods and in some cases producing large amounts of contaminated waste.

Further details on investigations conducted at this site can be found in the literature (Gatsios et al. 2018; García-Rincón 2020; García-Rincón et al. 2020).

5. Conclusions

Compared to conventional approaches, the application of direct sensing technologies can contribute to investigate and manage contaminated sites in a more efficient and sustainable way, especially thanks to the collection of high-resolution data, the development of adaptive field strategies based on real-time results, and the relatively low production of investigation-derived waste.

Consequently, the implementation of direct sensing tools could be considered throughout all the phases of the project lifecycle when dealing with unconsolidated environments. In the initial stages of a contaminated site investigation, direct sensing would result in better coverage of the site, enabling detection of contamination hotspots (if they exist) and targeted sampling for quantitative risk assessment. In sites with low contamination levels, this could be corroborated with direct sensing tools to a greater degree of confidence and certainty than using conventional, low-resolution sampling, and producing less unnecessary waste. In sites presenting higher risk and requiring remediation, direct sensing results would help to optimise the typically expensive remedial plan and increase its effectiveness.

As in the case of many other methods, direct sensing measurements are generally influenced by multiple factors (e.g., contaminant type or sediment type). To better liaise with the existing uncertainties, direct sensing tools are often implemented as part of a multiple lines of evidence approach, where other methods like physical sampling and installations are still employed but in reduced numbers, therefore reducing their environmental footprint and the associated cost.

Future needs include further research on how different geo-materials and subsurface conditions influence direct sensing readings, the development of tools with improved quantification capabilities, and the embracement of non-deterministic methods for the interpretation of results.

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