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High Resolution Site Characterization as key element for proper design and cost estimation of groundwater remediation

La Caratterizzazione ad Alta Risoluzione come elemento chiave per la corretta progettazione e valutazione dei costi degli interventi di bonifica delle acque sotterranee

Pieter Dijkshoorn, Piero Mori, Mattia Cappelletti Zaffaroni

Riassunto: Ogni anno vengono impiegate considerevoli risorse finanziarie per bonificare le acque sotterranee da contaminazioni causate da attività industriali storiche. Troppo spesso, tuttavia, gli obiettivi di bonifica non vengono raggiunti entro i tempi previsti. Inoltre, i costi previsti in fase di progettazione si rivelano spesso largamente insufficienti per conseguire il raggiungimento degli obiettivi. Questa situazione, molto comune, comporta numerosi problemi per tutte le parti che sono coinvolte nel progetto di bonifica.

I motivi del non raggiungimento degli obiettivi o del non rispetto del budget previsto sono spesso riconducibili a un Modello Concettuale di Sito incompleto. Sulla scorta di numerosi interventi di Caratterizzazione ad Alta Risoluzione presso siti dove erano già stati effettuati interventi di bonifica, ERM ha riscontrato alcuni temi ricorrenti:

- manca l'identificazione dell'area sorgente e della piuma di contaminazione;
- inadeguata comprensione dell'architettura dell'area sorgente e della piuma (ad es. ricostruzione tridimensionale),
- inadeguata comprensione degli effetti delle condizioni idrogeologiche sulla possibilità di trattare le contaminazione (es. mediante iniezioni o estrazione di gas).

Il presente lavoro illustra perché spesso i progetti di bonifica non rispettano le previsioni di progetto, in termini di obiettivi e costi, e quali sono le alternative per evitare tali insuccessi. In particolare, è focalizzato su metodi e approcci di caratterizzazione alternativa che aiutano a definire un Modello Concettuale di Sito più completo (ad alta risoluzione). Questo modello concettuale permette di conseguire una progettazione più accurata e maggiormente efficace e riduce in maniera consistente le incertezze, a partire dal processo decisionale di selezione delle alternative tecnologiche per la bonifica.

I contaminanti che hanno una densità maggiore dell'acqua sono noti per la maggiore complessità, sia in termini di indagini, sia in termini di interventi di bonifica. Conseguentemente, il presente lavoro è focalizzato su tali composti.

Parole chiave: contaminazione, flusso delle acque sotterranee, modello concettuale.

Keywords: *contamination, groundwater flow, conceptual model.*

Abstract: *Substantial amounts of money are spent each year on cleaning up ground water contaminations that were caused by historical industrial site activities. Too often, however, remedial objectives are not achieved within the anticipated time frame. Moreover, remedial budgets which were estimated prior to the start of remediation turn out to be largely insufficient to meet the remedial objectives. This situation, very common, creates significant troubles for all the stakeholders involved in the remediation project.*

The reason for not meeting remedial regulatory closure criteria or exceeding remedial budgets is often due to an incomplete conceptual site model. Having conducted high resolution site characterization programs at numerous sites where remediation was previously conducted, ERM has found several recurring themes:

- *Missed source areas and plumes;*
- *Inadequate understanding of source area and plume architectures (i.e., three-dimensional contaminant distribution);*
- *Inadequate understanding of the effects of site (hydro)geologic conditions on the ability to access contamination (i.e., via remedial additive injections of groundwater/soil gas extraction).*

This paper explains why remediations often fail and what the alternatives to prevent these failures (and exceeding remedial budgets) are. More specifically, it focuses on alternative investigation methods and approaches that help to get to a more complete (high resolution) conceptual site model. This more complete conceptual site model in return helps a more focused remedial design with a higher remedial efficiency. As a minimum, it will take away a lot of (financial) uncertainty during the decision making when selecting a remedial alternative.

Contaminants that have a greater density then water are known to have a greater complexity in terms of both investigation as well as remediation. Therefore, they will be the main focus of this paper.

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Introduction

For the further discussion and in order to better explain why remediations often fail, the architecture of a groundwater contamination is split up in a source zone and a plume. A source zone is defined as a place where contamination was originally generated and where the most elevated concentrations are present (either in soil and/or groundwater and in the vadose or saturated zone). The plume is generated by leaching out from the source zone.

In order to address the short term migration risks of a contamination to the surrounding receptors, a contamination may be contained at the downgradient side of a contamination plume (e.g. to prevent further off site migration). However, in order to be also effective in the long run, a source zone should be remediated as well.

As long as the contaminant mass in the source zone is not significantly depleted or removed, there will be continuous lixiviation of contamination towards the groundwater. Therefore, the groundwater quality will not improve at the downgradient side, and continuous follow up of the plume will be required for a long period. It is like 'mopping' a floor, while the tap is still open and water is running out of the tap.

Aggressive active remedial techniques are needed to address the impacts in source zones. Once an active source remedial technique is activated, less aggressive active techniques or even passive remedial techniques may be sufficient to remediate the contamination plume. The quality of the groundwater at the downstream area will normally improve considerably when contaminant mass is removed from the source area(s).

The more contaminant mass is removed (with a minimum – financial - effort), the better and the faster the remediation efficiency. The quality of the groundwater will improve substantially once the contaminant mass is significantly removed in the source zone (and the source is significantly depleted). Once source significant depletion is realized, the contamination plume would turn to a shrinking situation.

Source abatement is often necessary to facilitate permanent abatement of down-gradient groundwater impacts and to achieve a permanent solution for the site (and permanent regulatory sign off).

Having conducted high resolution site characterization programs at numerous sites where remediation was previously conducted, ERM has found several recurring themes:

- Missed source areas and plumes;
- Inadequate understanding of source area and plume architectures (i.e., three-dimensional contaminant distribution);
- Inadequate understanding of the effects of site (hydro) geologic conditions on the ability to access contamination (i.e., via remedial additive injections of groundwater/ soil gas extraction).

Potential causes of remedial failures and exceeding remedial budgets

Location of source zone insufficiently known

For sites with a long operation history, it is often difficult to get a full picture of all historical potential polluting activities. Despite the good intentions, experience shows that conventional investigation techniques such as borings and monitoring wells are often inadequate to locate all source zones. Moreover, specific contaminants such as chlorinated solvents are difficult to investigate with conventional techniques, due to their complex unpredictable behaviour in the subsurface and large concentration differences on a small vertical interval.

Too often, the extent and the exact location of a source zone is assumed, rather than exactly known. Analytical results from conventional investigation techniques are often not sufficiently conclusive, which may lead to erroneous interpretation of results and to wrong remediation designs and ineffective remediation. Experience shows that either the remediation is not carried out in the source zones and/or that more than one source zone is present. This is schematically illustrated in figure 1.

Furthermore, remediation is too often focused on groundwater contamination only, whereas a large portion of the contaminant mass may be present in the vadose zone.

The groundwater quality will not improve as long as residual soil contamination in vadose zone is still present and

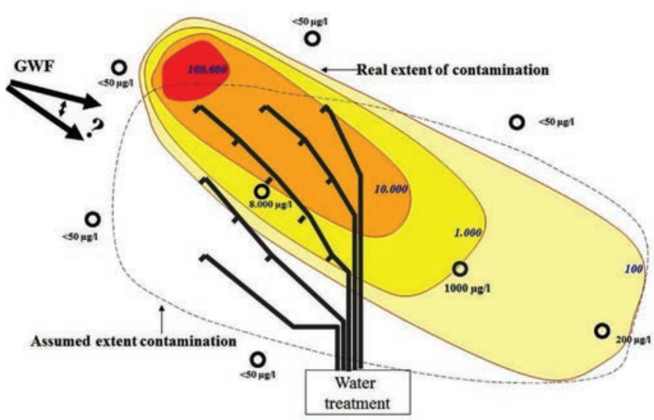

Fig. 1 - Difference between "assumed" source location based on monitoring wells data and actual source location, and consequent inaccurate design of remediation activities. Legend: GWF: main groundwater flow direction. Dark circles represent monitoring wells, along with the measured dissolved concentrations in µg/l. The dashed line shows the boundary of the "assumed extent of contamination" based on monitoring wells data only; based on such data the water treatment system (intended to treat the source zone) has not been located in the actual source. The "real extent of contamination" is shown as red/yellow areas with iso-concentrations in blue italic numbers.

Fig. 1 - Differenza tra localizzazione presunta della sorgente di contaminazione (basata sui soli dati di monitoraggio dei piezometri) e localizzazione reale, con conseguente inaccurata progettazione delle attività di bonifica.
Legenda: GWF: direzione principale del flusso delle acque sotterranee. I cerchi scuri rappresentano i pozzi di monitoraggio, con indicate le concentrazioni misurate in µg /l. La linea tratteggiata mostra il confine dell' "estensione stimata della contaminazione" basata solo sui dati ottenuti dai piezometri; sulla base di tali dati il sistema di trattamento acque (finalizzato a trattare la zona sorgente) non è stato ubicato in corrispondenza della reale sorgente di contaminazione. L'"estensione reale della contaminazione" è visualizzata con aree rosse/gialle e le isoconcentrazioni sono mostrate in numeri blu in corsivo.

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continuously can leach out towards groundwater. Even when the initial groundwater contamination is remediated, re-contamination might happen and remediation will take much longer than expected.

Assessment of the best available remedial technique and right implementation of technique is difficult when the exact location of source zones and/or the exact depth of contaminations in insufficiently known. This will result in an inefficient remediation and an exceeding remediation budget.

Plume architecture insufficiently known

With respect to determining the exact location of source zones and the exact depth of maximum concentrations for contaminations with more complex contaminations such as chlorinated solvents, the investigation strategy with conventional monitoring wells and analyses are rather carried out in a 'trial and error' approach which results in either a costly and time consuming effort or in a rather incomplete conceptual site model. This will in the end result in financial surprises and a long remediation duration. On the other hand, installing conventional monitoring wells with well screens at all possible depths would be rather costly.

The migration behaviour of chlorinated solvent plumes can be complex and unpredictable, due to subsoil heterogeneities and/or insufficient knowledge of the site-specific geology. A good understanding of the 3 dimensional presence of contaminant mass in the subsurface is not only key for carrying out a representative risk assessment, but also for a successful remediation at a later stage. A limited number of analytical data and a poor understanding of hydrogeology may lead to a misinterpretation of the extent of contamination plume.

Rivett et al. (2001) and Guibelt et al. (2005) showed that plumes are mostly narrow and long. The transversal dispersion is often overestimated. In case of multiple source zones, the mass distribution of contaminants inside the plume is complex but concentrated, as shown by transects with data points perpendicular to the groundwater flow. As a rule of thumb it can be stated that 70 - 80 % of the contaminant is present at 5-20 % of the cross-sectional area, as shown in figure 2.

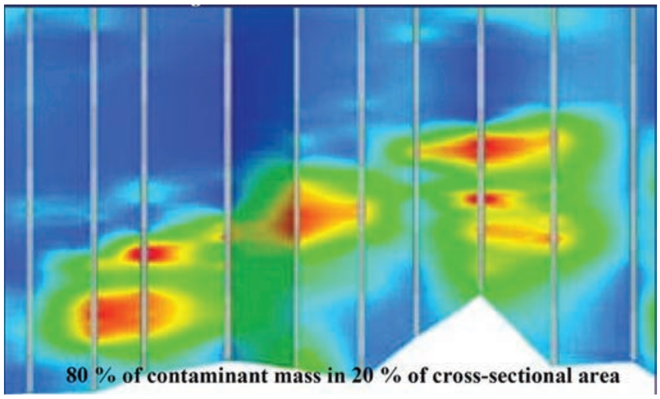

Fig. 2 - Transect perpendicular to groundwater flow direction. The figure shows that most of the contamination is located in limited soil volumes.

Fig. 2 - Transetto perpendicolare alla direzione di flusso delle acque sotterranee. La figura mostra che la maggior parte della contaminazione è localizzata in corrispondenza di limitati volumi di terreno.

Inadequate understanding of the effects of site (hydro) geologic conditions on the ability to access contamination

At many sites, the relationship between residual (i.e., trapped) and fluxing (i.e., mobile) contaminant mass is not sufficiently understood and mass transfer limitations (e.g., DNAPL dissolution, desorption or back diffusion) are responsible for the ongoing need for remediation system.

Back diffusion is a process that is important when only transmissive or more permeable layers are remediated (Chapman & Parker, 2005). Contamination which is often present in low permeable or clayey zones is often overlooked when assessing possible remedial alternatives and their limitations. Conventional extraction techniques focus mostly on the permeable zones, in which the contaminant mass can be reduced significantly fast. When the contamination appears to be remediated, the remedial system is switched off. However, the concentrations usually increase thereafter due to back diffusion from low to high permeable zones. Rebound of concentrations will happen and further remediation will then usually be requested which in turn results in exceeding remedial budgets . This is illustrated in figure 3.

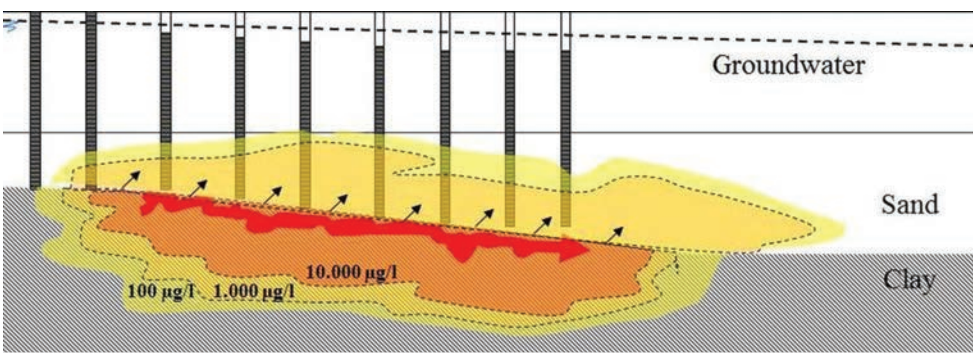

Fig. 3 - Rebound effect from low-permeability layers after remediation of high-permeability layers. If remediation activities are focused on high-permeability layers only, dissolution of residual contamination located in low-permeability layers may generate rebound effects.

Fig. 3 - Effetto "*rebound*" associato alla presenza di livelli a bassa permeabilità contaminati, successivamente alla bonifica degli orizzonti a permeabilità maggiore. Se le attività di bonifica sono eseguite solo in corrispondenza degli orizzonti ad alta permeabilità, la dissoluzione della contaminazione residua situata in strati a bassa permeabilità può generare un effetto "*rebound*".

Failing remediation due to failing delivery techniques

In situ chemical oxidation or enhanced biodegradation rely on in situ destruction of contaminants and have been popular remediation techniques in the last few decades. These techniques are, however, also been known to be less successful due to rebound of concentrations in groundwater (McGuire et al., 2006) and may result in remedial durations longer than expected, exceeding the related budget.

The destruction of contaminants is usually realized by injection of chemicals or nutrients in the subsurface. However, in order to get full destruction of contaminants, it is crucial to bring oxidizing chemicals or nutrients in direct contact with the contaminants. By applying standard injection techniques, it will be challenging to get an even distribution in tight formations (Newell et al., 2012), that may nevertheless contain relatively high masses of contaminants. In that respect, the injection radius will mostly depend on the specific type of geology, as shown in figure 4. Heterogeneities rule, even in apparently homogeneous soils.

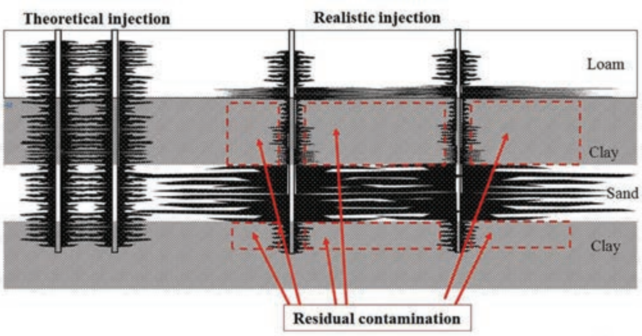

Fig. 4 - Differences between theoretical and actual injection radius due to soil heterogeneities. Different injection radii are actually obtained due to soil heterogeneities (the lower the permeability, the smaller the radius of influence), thus leading to incomplete remediation of target areas.

Fig. 4 - Differenza tra raggio di iniezione teorico e reale, a causa delle eterogeneità del terreno. Differenti raggi di iniezione sono presenti a causa delle eterogeneità del terreno (minore è la permeabilità, minore è il raggio di iniezione); questo può causare l'incompleta bonifica delle aree bersaglio.

Why are contaminations easily missed during investigation in vadose zone?

The characterization of volatile contaminants in the vadose zone can be difficult due to significant difference in concentrations of such contaminants on a centimeter scale. The subsurface environments almost always contain complex distributions of different geologic media that have widely varying capacities to transmit fluids (permeability). Geologic complexity and the associated spatial variations in permeability are widely referred to as heterogeneity.

Contaminations preferentially move through soil with the greatest permeability. Normally, contaminations will not enter low permeability zones. However, an exception is when secondary features are present in low permeability layers such as fractures, root casts, or animal borings. Therefore, subsurface contamination occurrence is often presented as sparsely distributed fingers of product ganglia and pools (such as DNAPL). Intervals where DNAPL is present are surrounded by intervals that are largely free of DNAPL. The high concentration variances partially explain why it is usually difficult to find DNAPL (Sale et al. 2008).

Conventional soil samples, even undisturbed samples, are often not adequate to fully characterize the contamination in soil as: 1) they don't allow to assess heterogeneities completely since often a sufficient number of cores cannot be taken, due to the associated costs; and 2) the components are already volatilized before the arrive in the laboratory.

Supporting volume of samples

Conventional soil samples are often not representative as they do not take large concentration variations on a small (centimeter) scale into account and, on the other hand, they are representative of a limited volume of subsoil and may fail in identifying source zones. Therefore they are considered less adequate as characterization tool.

On the other hand, soil gas samples (especially passive) are more representative for larger areas in vadose zone and therefore better placed as characterization tool to locate source zones which are difficult to find with more conventional techniques.

What is high resolution site characterization?

Site investigation programs are known for seemingly endless phases of assessment and high degrees of uncertainty, due to the use of traditional investigation tools and approaches. This lack of certainty affects one's ability to make sound decisions with respect to a host of health, environmental, financial, and reputational risks.

High Resolution Site Characterization (HRSC) is an alternative approach to site investigation that significantly reduces uncertainty and enables development of cost effective solutions to address identified risks. By applying proven scientific principles, investigation approaches and characterization tools, it is possible to generate detailed 2- or 3-dimensional conceptual site models (CSMs) to support effective decision making.

The overburden site characterization toolbox includes Passive Soil Gas Samplers, Membrane Interface Probe (MIP), Laser Induced Fluorescence (LIF), Cone Penetrometer (CPT), Waterloo Advanced Profiling System, sonic drilling, and field laboratories, among others. When subsets of these tools are used together to produce collaborative datasets, one can efficiently generate high resolution CSMs. Where HRSC programs have been implemented from the outset, complex sites have been characterized over a period of months, resulting in accurate definition of sources and plumes, and evaluation of various risks. The evaluation of risks, compliance with regulatory requirements, establishment of reserves, and initiation of remediation or mitigation measures can be completed both quickly and accurately – typically within one to two years of problem discovery. This approach has demonstrated sig-

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nificant reductions in business risk, stakeholder concerns, and life-cycle costs, in addition to improved safety and overall sustainability relative to more conventional approaches (U.S. EPA website– Technology Innovation and Field Services Division – Contaminated Site Clean-Up Information – High Resolution Site Characterization).

Recent experience with HRSC programs at sites with more than a decade of investigation and remediation history found that source areas were overlooked in past investigations, potential risks to receptors were missed, and (not surprisingly) remediation programs failed. In some cases, these failures have led to litigation and findings of substantial damage. In all cases, significant amounts of money were spent with little actual improvement, making it difficult to justify spending more money on site investigation. Conducting a HRSC program at these mature sites enabled substantial progress toward a satisfactory and cost effective endpoint.

Source zone investigation by passive soil gas sampling

In order to assess the exact location of source zones and extent of the contamination impact, a comprehensive passive soil gas survey can be carried out (Interstate Technology & Regulatory Council, 2007 & 2014; U.S.EPA 1998). The passive soil gas sampling can be carried out with various types of samplers. The survey will allow determining the exact location of the possible source area(s) with organic contaminants.

The advantage of the passive soil gas sampling is that the technique usually does not need drill rigs to be implemented and it is relatively cheap (in comparison to conventional sampling techniques), and much more sensitive than conventional soil sampling. Experience suggests that with conventional techniques (borings and soil samples), VOC-contaminations are easily missed due to its volatility and the complex behaviour of the components in the subsurface.

A general description of the installation and an example of what the typical output of a passive soil gas survey looks like, is given in figure 5 and figure 6.

Fig. 5 - Passive soil gas samplers. Field examples of installation procedure.

Fig. 5 - Campionatori passivi di soil gas. Esempio di procedura di installazione.

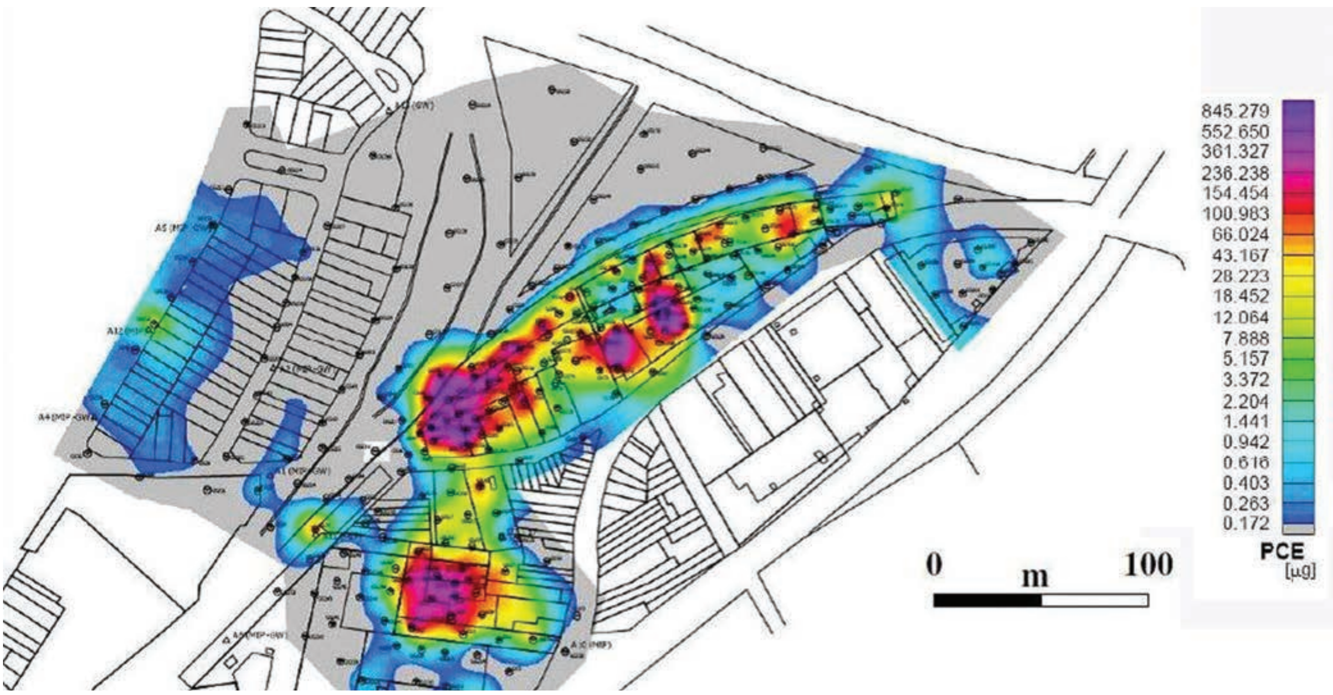

Fig. 6 - Passive soil gas samplers – Typical results of the investigation. The most impacted areas are shown in purple. Passive soil gas sampling data are reported in units of mass (as shown in the column on the right sector of figure), although concentration data can be in some cases calculated.

Fig. 6 - Campionatori passivi di soil gas – Esempio di restituzione grafica dei risultati. Le zone maggiormente impattate sono mostrate in viola. I dati ottenuti sono riportati in unità di massa (come mostrato nella colonna sul settore destro della figura); in alcuni casi è possibile anche risalire a dati di concentrazione.

Membrane Interface Probe (MIP) Investigation

After the passive soil gas sampling campaign, a Membrane Interface Probe (MIP) can be used to perform a quick vertical qualitative investigation of the contamination. The MIP provides real-time detection of volatile organic chemicals (VOCs) or NAPL in the vadose and saturated zones. The MIP fits onto conventional direct push technology (DPT) equipment and is inserted into the target investigation zone in a manner similar to a standard DPT sampling device. This technique is much cheaper than the installation of permanent monitoring wells and it determines the exact depth at a higher resolution at which maximum concentrations of contaminants are present. Simultaneously with the MIPs, also a cone penetration test (CPT) is carried out and soil conductivity is measured. The data are reported along with the output from the VOC detectors. Data are plotted as a function of depth below ground surface. With these data, it is possible to identify changes in soil permeability as well as elevated levels of VOCs. The results of the MIP investigation assist in determining the locations of high-concentration source areas of contaminated soil or groundwater (Geoprobe systems, 2012; .Griffin et al, 2002; Heron et al., 2009; U.S.EPA, 2004 & 2005). In addition, special probes may be installed and allow the in situ qualitative definition of the distribution of the formation permeability (McCall, 2011).

It should be also noted that MIP results can be reported in real time, thus allowing to locate in field the next investigation points based on the results of the previous ones.

A typical output of the CPT/MIP-data is presented in figure 7.

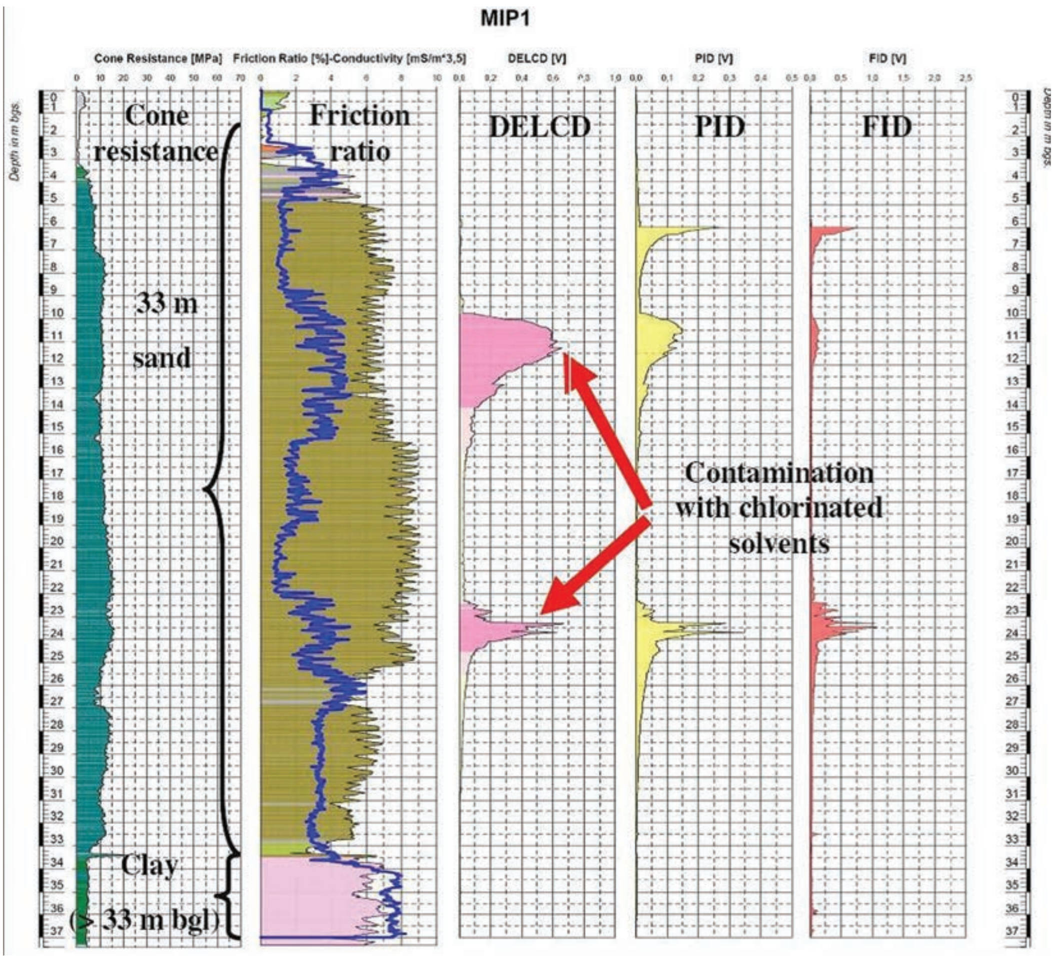

Fig. 7 - CPT/MIP – Typical log of results. All columns show CPT and MIP results from ground level (top of columns) downwards. The first two columns represent "cone resistance" and "friction ratio" values, which can be used to collect rough information about the soil type (sand, clay, etc.). The third column "DELCD – Dry Electrolitic Conductivity Detector" shows the MIP response to compounds with organic bonded chlorine. The last two columns "PID – Photo Ionization Detector" and "FID – Flame Ionization Detector" shows the MIP response to organic compounds that can be read by Flame Ionization Detector and Photo Ionization Detector (chlorinated or not). In this case MIP results suggest the presence of 1) two peaks of chlorinated compounds at about 10-14 m bgl and 23-25 m bgl (detected by DELCD, PID and FID), and 2) a peak of organic non-chlorinated compounds at about 6 m bgl (detected by PID and FID only).

Fig. 7 - CPT / MIP – Esempio di restituzione grafica dei risultati. Tutte le colonne mostrano i risultati di CPT e MIP a partire dal piano campagna verso quote inferiori. Le prime due colonne rappresentano la " *cone resistance*" ed i valori di "*friction ratio*", che possono essere utilizzati per desumere informazioni di massima sulla tipologia di terreno attraversato (sabbia, argilla, ecc). La terza colonna "DELCD – *Dry Electrolitic Conductivity Detector*" mostra la risposta del MIP ai composti organo-clorurati. Le ultime due colonne "PID - *Photo Ionization Detector*" e "FID - *Flame Ionization Detector*" mostrano la risposta del MIP ai composti organici che possono essere letti dal FID e dal PID (clorurarti o meno). In questo caso i risultati del MIP suggeriscono la presenza di: 1) due picchi di composti clorurati a circa 10-14 m da p.c. e 23-25 m da p.c. (rilevati da DELCD, PID e FID), e 2) un picco di composti organici non clorurati a circa 6 m da p.c. (rilevato da PID e FID).

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Care must be used in the interpretation of MIP results, particularly in determining source thickness when multi-constituent sources are present, since the presence of compounds with different volatility in the same source may result in an exaggerate thickness of the detected source due to carry-over effect. In fact due to such effect, the upper bound of the detected source can be considered correct, while the lower bound may be identified by MIP ad a deeper depth than the actual one (Bumberger et al., 2012). Carry over effects may be present when high concentration zones are encountered and the amount of time to flush mass from the MIP trunk line is inadequate. Uplogging (i.e. operating the data collection mode in the opposite – upward – direction at the same location) and/or increasing the carrier gas flow rate in high-concentrations zones may help reducing carry-over effects (Bumberger et al. 2012, Adamson et al. 2013).

Conventional investigation wells/analyses

Conventional wells can be installed on specific places and at specific depths that are representative for the source and/or plume. This is to verify the groundwater quality locations which were identified with passive soil gas sampling and MIPs. The results are used to complete the conceptual site model and the monitoring wells are of good use for long term monitoring purposes.

High Resolution Site Characterization: A Case Study

General Site Description

A former industrial site located in Northern Italy was selected for the application of HRSC method, after carrying out a number of conventional investigation activities (soil borings and monitoring wells). Site area is about 12,000 m^2 and impacts with chlorinated solvents had been detected mainly in groundwater, as shown in Figure 8.

Fig. 8 - Site Groundwater Impacts. Monitoring wells (MW) names are shown (screened intervals in m bgl are reported in round brackets). Chlorinated impacts are shown in green (<10 µg/l), yellow (10-100 µg/l), orange (100-1000 µg/l), purple (1,000-10,000 µg/l) and red (> 10,000 µg/l) circles. Main groundwater flow is West-East. MW14 and MW15 are hydraulic barrier wells. The main production building is located just East of monitoring wells MW6 and MW10P.

Fig. 8 - Contaminazione rilevata nelle acque sotterranee. I piezometri sono indicati con codice MW (gli intervalli fessurati sono riportati tra parentesi tonde). Le concentrazioni di composti clorurati sono mostrate con cerchi verdi (<10 µg / l), gialli (10-100 µg / l), arancioni (100-1.000 µg / l), viola (1.000-10.000 µg / l) e rossi (> 10.000 µg / l). La direzione del flusso di falda principale è Ovest-Est. MW14 e MW15 fungono da pozzi barriera. L'edificio produttivo principale si trova di fianco ai piezometri MW6 e MW10P, in direzione Est.

Figure 9 shows an interpretive stratigraphy through the Site (direction W-E).

Based on figure 8, two main source areas were identified: one near MW6 and MW10P, and one near MW14. It should be noted that, if remediation activities had been planned based on the available information, such activities would have been focused around MW14 in the Eastern part of the site and around MW10P/MW6 in the western part of the site. Instead, a detailed HRSC approach was carried out to identify the exact locations of the source zone(s). The results are described in the following sections.

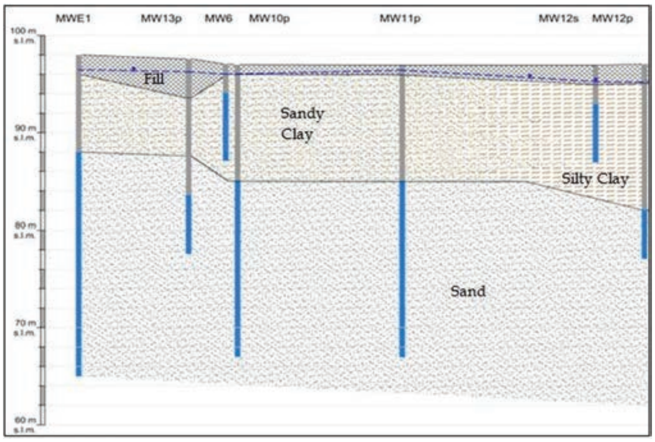

Fig. 9 - Interpreted Stratigraphical Section (W - E). The figure shows several monitoring wells depths and screened zones (in blue). Throughout the site the piezometric surface of the main aquifer is located at about 2 m bgl. In the Western sector the aquifer is unconfined and the piezometric surface represents the water table, while in the Eastern part it is confined and water is present in the Sand layer mainly; a low amount of groundwater is present in the in the silty clay layer as well, but it is not hydraulically connected with the underlying Sand layer.

Fig. 9 - Sezione stratigrafica interpretativa (Ovest - Est). La figura mostra la profondità dei pozzi di monitoraggio ed i loro intervalli fessurati (in blu). Lungo tutto il sito, la superficie piezometrica della falda principale si trova a circa 2 m da p.c.. Nel settore occidentale la falda non è confinata e la superficie piezometrica rappresenta la superficie della tavola d'acqua, mentre nella parte orientale è confinata e l'acqua è presente principalmente nel livello sabbioso; una piccola quantità di acqua è presente anche nello strato argilloso limoso, ma non è collegato idraulicamente con il livello sabbioso sottostante.

Investigation Activities

A combination of MIP (in both source areas) and passive soil gas samplers (in the Eastern part of the Site only) was used for further characterizing the source zones. figure 10 and figure 11 show the location of the MIP and passive soil gas samplers investigation points.

MIP investigations were carried out by means of a direct-push machine equipped with CPT and DELCD, PID and FID detectors. Distances between MIP points were less than 10 m and each MIP point was pushed down to about 15 m bgl (crossing both the vadose and saturated zone). Field MIP-related activities lasted about 30 working days. MIP locations were re-assessed every day based on the real-time MIP results and as such a dynamic investigation approach was followed.

Passive soil gas samplers were manually installed at a depth of about 40 cm bgl (in the fill material) and left in place for 7 days before their collection and delivery to the laboratory for the analyses of volatile compounds (including chlorinated compounds and total petroleum hydrocarbons).

Fig. 10 - Location of MIP points in the Western site sector. Purple and brown points show the MIP locations. A total of 36 MIP points was located in the Western site sector inside and near the main production building.

Fig. 10 - Localizzazione dei punti di indagine MIP nel settore occidentale del sito. I punti in viola e marrone mostrano le localizzazione dei punti MIP. Un totale di 36 punti MIP sono stati eseguiti nel settore occidentale del sito all'interno e nelle vicinanze dell'edificio produttivo principale.

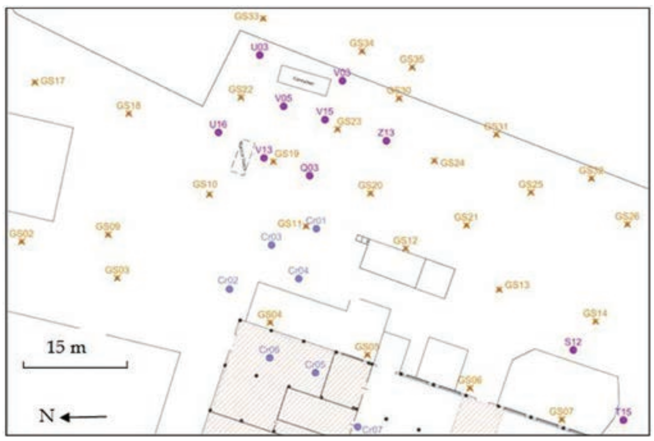

Fig. 11 - Location of MIP points and passive soil gas samplers in the Eastern site sector. Purple points show the MIP locations; a total of 8 MIP points was located in the Eastern site sector. Orange crosses show the passive soil gas samplers location. Points named "Cr…" are soil borings not described in the present article.

Fig. 11 - Posizione dei punti di indagine MIP e dei campionatori passivi di soil gas nel settore orientale del sito. I punti viola mostrano le posizioni dei punti MIP; 8 punti MIP sono stati eseguiti nel settore orientale del sito. Le croci arancioni indicano la posizione dei campionatori passivi di soil gas. I punti indicati con la sigla "Cr ..." sono sondaggi non descritti nel presente articolo.

Results and Discussion

MIP results allowed to draw, in both Eastern and Western areas: a) a 3D picture of the main impacts identified by the DELCD sensor (i.e. chlorinated compounds – CHC, mainly trichloroethylene) down to 15 m bgl and b) several maps of detected impacts at different depths, as shown in Figure 12 and Figure 13.

The figures above show that MIP results allowed identifying the locations of the main CHC subsoil impacts (in both Eastern and Western areas), where remediation would be required. Interestingly: a) the most impacted subsoil area detected by MIP in the Western Site sector is located at about 15-20 m far from the "assumed source area" that had been previously identified by means of monitoring wells MW6 and MW10P. A monitoring well subsequently installed in the actual source area identified a CHC (mainly trichloroethylene) groundwater impact exceeding 1,000,000 μg/l (two orders of magnitude greater than MW6).

The passive soil gas samplers located in the shallow fill material in Eastern site sector did not identify a significant presence of chlorinated compounds, contrary to the results of the MIP (which identified CHC impacts at about 7-10 m bgl). This may be due to the location of the subsoil main impacts in the area of interest, corresponding to the fine grain-sized silty clay layer, that probably obstacles the upward migration of vapors.

Instead, the passive soil gas sampler GS19 identified a unexpected shallow total petroleum hydrocarbon impact (as shown

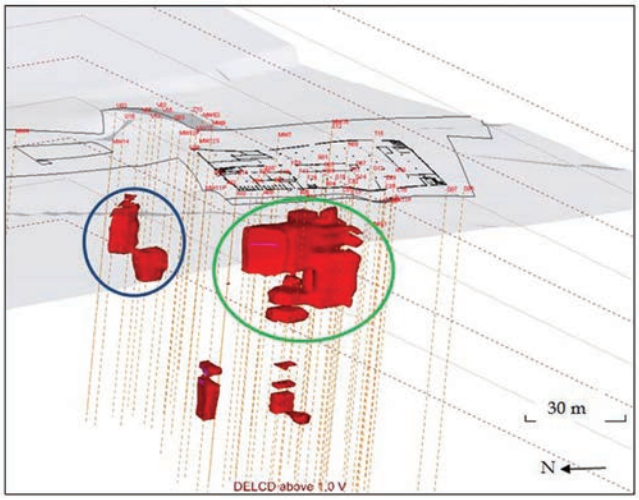

Fig. 12 - 3D Interpretation of CHC main subsoil source areas. Main CHC subsoil impacts, interpreted based on DELCD sensor results, are shown as red volumes. Ground level is shown as a grey plain. Dashed lines represent MIP vertical depths (about 15 m bgl). The area of the main production building is visible above the greatest subsoil impacted area located in the Western site sector (green circle, at about 2 - 5 m bgl). In the Eastern site sector subsoil main impacts were identified at about 7 - 10 m bgl (blue circle).

Fig. 12 - Ricostruzione interpretativa in 3D dei volumi di terreno impattati da composti clorurati. Gli impatti principali rilevati nel sottosuolo a carico di composti clorurati, definiti sulla base del sensore DELCD, sono rappresentati in rosso. Il piano campagna è mostrato con un piano grigio. Le linee tratteggiate rappresentano le profondità raggiunte dai punti MIP (circa 15 m da p.c.). L'area dell'edificio produttivo principale è visibile al di sopra del volume di terreno maggiormente impattato nel settore occidentale del sito (cerchio verde, a circa 2 - 5 m da p.c.). Nel settore orientale del sito gli impatti principali sono stati individuati a circa 7 - 10 m da p.c. (cerchio blu).

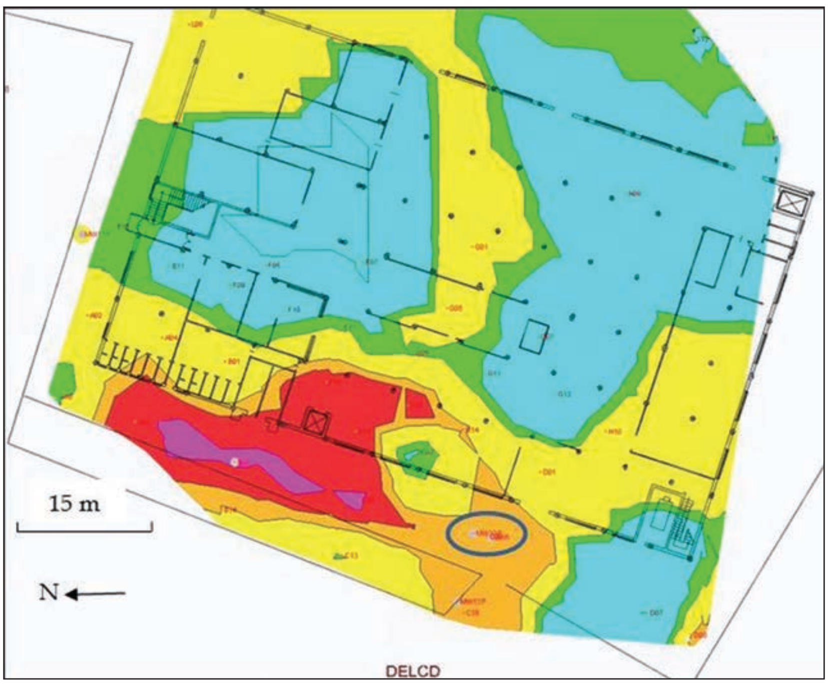

Fig. 13 - Western Site Area - 2D Interpretation of CHC Main Subsoil Source Areas at 2 m bgl. Main CHC subsoil impacts identified by the DELCD sensor at 2 m bgl are shown in purple and red. The location of the most impacted monitoring wells MW6 and MW10P is shown in the blue circle right of the most impacted subsoil area.

Fig. 13 - Settore occidentale del sito – Ricostruzione interpretativa in 2D delle aree impattate da composti clorurati a 2 m da piano campagna. Gli impatti principali ritrovati nel sottosuolo a carico di composti clorurati a 2 m da p.c. sono mostrati in viola e rosso. L'ubicazione dei piezometri che avevano fatto rilevare le concentrazioni maggiori nelle acque sotterranee (MW6 e MW10P) è mostrata nel cerchio blu.

in figure 14), that was confirmed also by the near MIP point V13 and subsequent soil excavation, as shown in figure 15.

In summary MIP investigations allowed to gather important information for the further remediation design; in fact, if the described HRSC activities had not been carried out, remediation efforts in the Western Site Area would have been focused on an area 15 – 20 m far from the actual source (a case of "location of source zone insufficiently known", as reported in Section 1.2).

Interestingly MIP activities were carried out with lower costs and reduced time when compared with traditional investigation techniques. In fact, the execution of 44 MIP points down to 15 m bgl with the identification of CHC presence along the entire vertical investigated depth costed about 70 K€; the costs associated to the execution of similar activities consisting of traditional drilling techniques with laboratory analyses of CHC (considering 4 laboratory analyses/meter) would likely exceed 100 K€. In addition, the use of traditional techniques: 1) would not have allowed the daily re-assessment of investigation points location (reducing the efficiency of the investigation); 2) may generate loss of volatiles during sampling generating inaccurate results, and 3) would result in a longer time for obtaining results due to the time needed for the laboratory analyses (7 - 10 working days may be reasonably considered as a standard turnaround time).

With regard to soil gas passive samplers, they allowed identification of a previously unknown source area.

Fig. 15 - Identified TPH-impacted soil near to passive soil gas sampler GS19.

Fig. 15 - Terreno impattato da idrocarburi, identificato nei pressi del punto di indagine GS19.

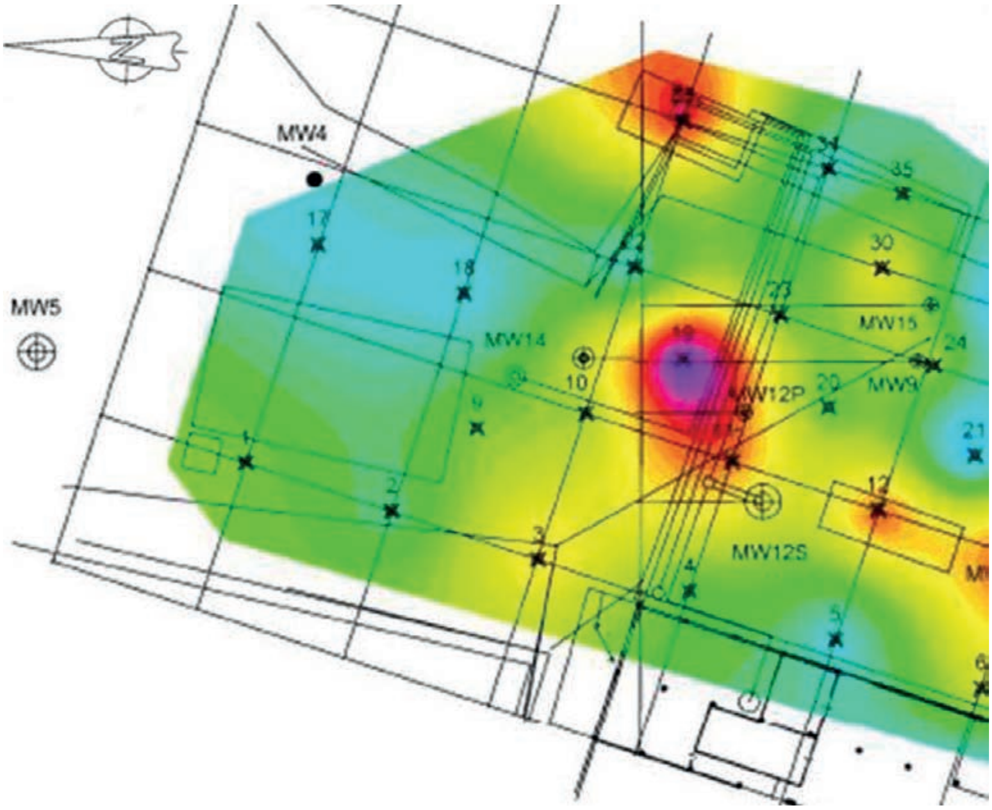

Fig. 14 - TPH – Soil gas passive samplers results in the North-Eastern site sector. The main TPH impact detected by the passive soil gas sampler n. 19 (whose location is shown in Figure 11 as "GS19", near MIP point V13) is shown in purple.

Fig. 14: Idrocarburi (TPH) - risultati dei campionatori passivi di soil gas nel settore Nord-Est del sito. Gli impatti principali a carico del parametro "total petroleum hydrocarbons" sono stati individuati dal campionatore passivo n. 19 e sono mostrati in viola (la posizione del punto 19 è mostrata anche in Figura 11 con la sigla "GS19", nei pressi del punto MIP V13).

Conclusions

An incomplete conceptual site model is mostly the reason for unsuccessful or failing remediations. The recurring themes why the conceptual site models are incomplete are:

- Missed source areas and plumes;
- Inadequate understanding or source area and plume architectures (i.e., three-dimensional contaminant distribution); and
- Inadequate understanding of the effects of site hydrogeologic conditions on the ability to access contamination (i.e., via remedial additive injections of groundwater/soil gas extraction).

High resolution site characterization is an alternative site investigation approach that significantly reduces uncertainty and enables development of cost effective solutions to address remediation of soil and groundwater contamination.

A case study was presented which shows the use and application of passive soil gas samplers and MIPs, aiming at identifying precisely the source zones to be remediated. Such technologies allowed the precise identification of expected (and also unexpected) subsoil source areas. The obtained results were used for the subsequent remediation design and allowed to focus the intervention on the actual most impacted soil volumes; if no investigation had been carried out, remediation activities would have focused on a moderately impacted area and not on the source zone, thus reducing significantly remediation activities efficiency.

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