

Technical University of Denmark



Quantification of the groundwater-borne contaminant mass discharge to a stream using point-velocity probes (PVP)

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Published in:

Book of abstracts - 13th International UFZ-Deltares Conference on sustainable Use and Management of Soil, Sediment and Water Resources (AquaConSoil) 2015

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

Rønde, V., McKnight, U. S., Sonne, A. T., Devlin, J. F., & Bjerg, P. L. (2015). Quantification of the groundwater-borne contaminant mass discharge to a stream using point-velocity probes (PVP). In Book of abstracts - 13th International UFZ-Deltares Conference on sustainable Use and Management of Soil, Sediment and Water Resources (AquaConSoil) 2015 (pp. 73)

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AquaConSoil Copenhagen 2015

13th International UFZ-Deltares Conference on
**Sustainable Use and Management of
Soil, Sediment and Water Resources**
9–12 June 2015 • Copenhagen • Denmark

PROGRAMME • BOOK OF ABSTRACTS



REGION H The Capital Region
of Denmark

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HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
RESEARCH – UFZ

ATV JORD OG GRUNDVAND

Deltares
Enabling Delta Life

Get Together

Monday, 8 June, 18.30–20.00 h, Copenhagen Town Hall

The Get Together will take place at the beautiful Copenhagen Town Hall. Let's gather at a glass of wine and some snacks to get the right inspiration for a great conference in Copenhagen. (Registration on Mon: Before joining the Get Together, you have the chance to register for the conference at Bella Center, 16–18 h; we strongly recommend to do so, as it avoids queues on Tue morning.)

Opening Session

Tuesday, 9 June, 9.00–10.30 h, Bella Center, Auditorium 1st floor

Chairmen: Holger Weiss, Huub Rijnaarts

- **Welcome** by chairmen
- **Presentation by Ida Holm Olesen**, President of the ATV Foundation of Soil and Groundwater, Head of Section Department of Environmental and Natural Resources, The Region of Southern Denmark
- **Lecture by Steen Gade**, Member of the Danish Parliament (SF) and the Environment Committee in Parliament, chairman of the Climate, Energy and Building Committee in Parliament, member of the Nordic Council, former CEO of the Danish EPA,
- 'Assessing the risks posed by multiple stressors to water resources' **Scientific key lecture by Prof. Poul L. Bjerg**, Department of Environmental Engineering, Technical University of Denmark

Thematic Sessions and Special Sessions

Tuesday, 9 June – Friday, 12 June, Bella Center

For details on thematic sessions (ThS) and on the special sessions (SpS), please see pages 4 (overview) and 6 (detailed programme).

Poster Social

Tuesday, 9 June, 17:30-18:30 h

Use this opportunity to discuss this great variety of interesting posters with poster authors and enjoy a drink!

Conference dinner

Thursday, 11 June, 20:00 h, Den Blå Planet, € 60

Join you colleagues for a great evening at the new architectural landmark in National Aquarium Denmark – Den Blå Planet on Amager (the Blue Planet). For details, please see page 47.

Address: Jacob Fortlingsvej 1, 2770 Kastrup

Closing Session

Friday, 12 June, 11.00-12.00 h, Bella Center, Auditorium 1st floor

Chairmen: Holger Weiss, Huub Rijnaarts

- Conference **highlights** by AquaConSoil chairmen
- Discussion on existing and emerging challenges; opportunities for implementation of promising solutions (**Panel discussion**)
- **Poster awards**

Technical Tours

in parallel • 10 € • start: 12:30 h • end: approx. 16–17:00 h • start & end at Bella Center. For details, please see page 28.

Matchmaking

Wednesday, 10 June 2015, Bella Center, please see page 46.

Networking about town

Wednesday, 10 June 2015, Bella Center, evening, please see page 46.

Explanation

Hall number

Regular thematic session (ThS) or Special session (SpS)

Lecture title, presenter, co-authors, (institution, country)

Tuesday • 9 June • 11:00-12:30 h

Meeting Room 19

ThS 1A.1 Passive sampling

Chair: Frederic Coulon

- *Passive sampling for monitoring fate and transport of organic contaminants – field examples*
Sarah Hale, Hans Peter Arp, Nicolas Morin, Gudny Okkenhaug, Gijs Breedveld, Mona Hansen, Espen Eek, Paul Cappel- en, Gerard Cornelissen, Amy Oen (Norwegian Geotechnical Institute, NO)
- *Environmental forensic in groundwater by coupling passive sampling and high resolution mass spectrometry for non-target screening*
Coralie Soulier, Catherine Berho, Anne Togola (Brgm, DL)
- *Development and test of optical sensor for real time measurement of volatile organic contaminants in air*
Mette Christophersen, Lars Bennedsen, Jeppe Seidelin Dam, Peter Tidemand Lichtenberg, Christian Pedersen, Nancy Hamburger, Helena Hansen, Mads Terkelsen (Rambøll Denmark, DK)
- *Integrated passive flux measurements in groundwater: Principles and outlook*
Goedele Verreydt, Patrick Meire, Eric Struyf, Ilse Van Keer, Piet Seuntjens (University of Antwerp, BE)
- *Innovative assessment and modeling tools to minimize con- founding elements in vapor intrusion investigations*
Todd Creamer (Geosyntec Consultants, US)

Auditorium 11

ThS 1C.9 Bioremediation of chlorinated solvents in groundwater 1

Chair: Magda Grifoll

- *Effects of aquifer thermal energy storage on bioremediation of chlorinated ethenes* Zhuobiao Ni, Martijn Smit, Tim Grotenhuis (Wageningen University, NL), Pauline van Gaans (Del- tares, NL), Huub Rijnaarts (Wageningen University, NL)
- *"Post-mortem" of a successful ERD project in a German urban area*
Laura Simone, Thomas Held (ARCADIS Deutschland GmbH, DE)
- *Bioremediation at low pH - emerging tools and approaches for chlorinated solvent sites*
Jeff Roberts, Phil Dennis, Peter Dollar, Sandra Dworatzek (SIREM, CA)
- *Aerobic biodegradation of trichloroethene without auxiliary substrates*

Tuesday • 9 June • 14:00-15:30 h

Meeting room 19

SpS 1B.2Sa Workshop on groundwater contamination from pesticide point sources Part I

Organizers: Poul L. Bjerg, (DTU Environment, DK), Nina Tuxen (Capital Region of Denmark), Ida Holm Olesen (Region of Southern Denmark)

Moderator: Poul L. Bjerg (Technical University of Denmark, DK)

Groundwater contamination from pesticide point sources – Knowledge exchange on extent of the problem, site investigation, risk assessment and remediation of pesticide contamination arising from point sources

Programme:

- 14.00-14.10 Motivation and programme overview; Poul L. Bjerg, Denmark
- 14.10-14.25 Ice breaker; Moderator: Poul L. Bjerg, Denmark
- 14.25-14.40 Pesticide sources, water resources and environmental challenges; Poul L. Bjerg, Denmark
- 14.40-14.55 Lessons from monitoring of pesticides in groundwater in Czech Republic; Vit Kodes, Czech Republic
- 14.55-15.15 Group discussion: Framing the problem; Moderator: Nina Tuxen, Denmark
- 15.15-15.30 Identification of pesticide point sources from pesticide monitoring; Nina Tuxen, Denmark
- 15.30-16.00 Break
- 16.00-16.15 How to manage pesticide point sources: challenges and solutions; Ida Holm Olesen, Denmark
- 16.15-16.30 Pesticides in groundwater and surface water in the Belgian context: status, management and regulation; Jaap van Nes, Belgium
- 16.30-16.40 Case studies: „Solutions“ of pesticide presence in selected drinking water sources; Petr Kvapil, Romana Suranova, Czech Republic
- 16.40-16.50 Risk assessment of pesticide point sources: A case study from Denmark; Hanne Møller Jensen, Denmark
- 16.50-17.10 Group discussion. How to manage pesticide points sources from a scientific and regulatory point of view? Moderator: Ida Holm Olesen, Denmark
- 17.10-17.25 Remediation of pesticide point sources: Current experience and challenges; Katerina Tsitonaki, Denmark
- 17.25-17.30 Wrap-up; Poul L. Bjerg, Denmark

Part II of this workshop is scheduled for Tuesday, 9 June, 16:00-17:30 h.

Auditorium 10

SpS 1B.1S Implementation of the EU Water Framework Directive – how to manage contaminated sites threatening surface waters

Organizers: Sandra Roost (Orbicon A/S, DK), Jens Aabling (Danish Environmental Protection Agency, DK), Nina Tuxen (Orbicon A/S, DK), Trine Korsgaard (Region of Southern Denmark, DK), Helle Overgaard (The Capital Region of Denmark, DK)

The implementation of the EU Water Framework Directive requires an integrating and holistic approach to legislation for water bodies with a goal of obtaining good environmental status for all receiving waters. While the risk from contaminated sites to groundwater has received a great deal of attention in the past, the risk from contaminated sites to surface waters (streams, lakes and coastal waters) has not yet been well examined. In Denmark alone there are more than 30,000 contaminated sites registered – many of them located close to surface waters.

However, the hypothesis is that only a minor part of these sites actually pose a real risk towards surface waters. Thus a robust method is needed to identify the few relevant sites which still comply with the precautionary principle.

Together with leading experts from universities, consulting companies and regional authorities, the Danish EPA developed a screening tool to identify contaminated sites that threaten surface waters. The screening system integrates national data of the contaminated sites: location, distance to surface waters, contamination activity, contaminant area and mass flux and calculates the mixing in surface waters.

Programme:

- Experience with the Water Framework Directive and contaminated sites in the Netherlands
- Challenges and experience for the Danish authorities in screening and identifying contaminated sites threatening surface waters in Denmark
speaker to be defined (Danish Regions, DK) Auditorium 11

Auditorium 11

ThS 1C.10 Bioremediation of chlorinated solvents in groundwater 2

Chair: Katrin Mackenzie

- *SILPHES – Investigation of chemical treatments for the remediation of recalcitrant chlorinated solvents: at the roots the development of an innovative in situ eco-friendly process*
Romain Rodrigues, Stéphanie Betelu, Frédéric Garnier, Stéfan Colombano (BRGM, FR), Antoine Joubert (Serpoll, FR), David Cazaux (SOLVAY, FR), Guillaume Masselot (Ademe, FR), Theodore Tzedakis (Laboratoire de Génie Chimique, FR), Ioannis Ignatiadis (BRGM, FR)
- *Dichloroelimination of polychlorinated alkanes by a Dehalogenimonas-containing enrichment culture*
Ernest Marco-Urrea, Lucia Martín-González, Siti Hatijah Mortan (Universitat Autònoma de Barcelona, ES), Lorenz Adrian (Helmholtz Centre for Environmental Research – UFZ, DE),

1. Assessment and monitoring

been compared. The hypothesis was that analysis of mesocosms, compared to analysis of groundwater and artificial Bio-Trap®, would give a more reliable result for presence of specific microorganisms and better register changes in the microbial composition after biostimulation and bioaugmentation, due to the larger amount of colonizing bacteria.

The aim of this presentation is to share experiences and conclusions from the pilot trial, performed during 2012-2014. More specific we wish to present /show apparent responses from the different sampling techniques/tools to biostimulation and bioaugmentation by evaluating detection sensitivity and sensitivity to variations in the microbe gene sequences over time.

During the trial period, microbes were collected from three closely situated groundwater wells. All three wells were subjected to biostimulation (molasse and Newman Zone®), while two of the sampling wells were bioaugmented with KB-1® culture and smaller amount of lactate.

- Preliminary results from the trial show higher bacterial density (a factor 102 – 103) in soil mesocosms compared to both groundwater and Bio-Trap®.
- Bacteria dechlorinating PCE and TCE (*Dehalobacter restrictus*, and *Desulfuromonas* spp.) were continuously identified by the soil mesocosms, while groundwater and the artificial samplers did not always identify *Desulfuromonas* spp.
- After bioaugmentation, the groundwater (snapshot) and Bio-Trap® (passive sampler) showed quick responses, measured as Dehalococcoides spp. and gene copies involved in VC and ethene/ethane formation in comparison with the development in the mesocosms. The responses from the soil mesocosms were delayed, and while VC and ethane production declined, the number of gene copies, involved in the formation of VC and ethane, were increasing.

INTEGRATED CHARACTERIZATION OF THE DEVELOPMENT IN NATURAL ATTENUATION OF A PCE PLUME OVER 7 YEARS AFTER THERMAL REMEDIATION OF THE SOURCE ZONE WITH USE OF DUAL STABLE ISOTOPE AND MICROBIAL METHODS

*Mette Martina Broholm*¹, *Alice Badin*², *Carsten Suhr Jacobsen*³, *Phil Dennis*⁴, *Just Niels*⁵, *Daniel Hunkeler*²

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⁴SiREM, Guelph, CA

⁵Region of Southern Denmark, Vejle, DK

PCE DNAPL contamination at the former central dry cleaning facility in Rødekro, Denmark, was subject to thermal (steam) source zone remediation in late 2006. A > 2 km long plume of chlorinated ethenes (PCE and chlorinated degradation products) which has migrated downgradient from the source zone has not undergone active remediation. A study of the natural degradation within the plume prior to source treatment including stable isotope monitoring was conducted in 2006(-2007) by Hunkeler et al. (2010). This investigation documented complete degradation of PCE via TCE to DCE by reductive dechlorination 1-1.5 km downstream the source area, where the plume descends into more reduced groundwater. It further proved that cDCE was further degraded by reductive dechlorination to VC, and that VC was not accumulated but further degraded, potentially by

another pathway (not reductive dechlorination). Detection (< quantification limit) of specific degraders (*Dehalococcoides*) enforced that cDCE degradation was biotic reductive dechlorination. The understanding of the degradation within the plume, not least the documentation of VC degradation, was essential in the risk evaluation of the plume.

The scope of the new (2014) study is to evaluate how the source remediation has impacted the plume and in particular the natural attenuation within the plume.

The evolution in plume composition and attenuation has been monitored by the Region of Southern Denmark on an annual basis since the remediation, and in 2014 a large monitoring campaign including redox, chlorinated ethenes, non-chlorinated degradation products, carbon and chlorine stable isotope composition, specific degraders and their activity and next generation sequencing (454 pyrotag) for bacterial composition was conducted.

The source remediation has, in addition to direct reduction of the concentration level in and flux from the source area, resulted in the release of dissolved organic matter and some geochemical changes. This has had an effect on redox conditions and biodegradation by reductive dechlorination particularly in the near source area. However, also in the further downstream area of the plume redox and contaminant levels have changed, suggesting an evolution in natural attenuation at significant distance (>1 km downgradient) from the treated source area. Dual isotope analysis are currently being conducted. Dual isotope and microbial data will be processed for interpretation of the changes in redox and degradation processes within the plume.

The understanding of the degradation processes within chlorinated solvent plumes and the effects of source remediation on these is essential for the risk evaluation of the plumes, and it has significant influence on decisions regarding costly plume remediation efforts. This project is unique in the integrated characterization approach for line of evidence evaluation of the natural attenuation of cDCE and VC in the DCE dominated plume and the monitoring of the effects of source remediation on plume natural attenuation.

Reference:

Hunkeler, D., Abe, Y., Jeannotat, S., Westergaard, C., Jacobsen, C.S., Aravena, R., and Bjerg, P.L., (2011). Assessing chlorinated ethene degradation in a large scale contaminant plume by dual carbon-chlorine isotope analysis and quantitative PCR, J. Contam. Hydrol., 119, 69-79.

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ThS 1A.3 Novel monitoring approaches I

Wednesday | 10 June | 9:00 - 10:30 | Meeting Room 19

QUANTIFICATION OF THE GROUNDWATER-BORNE CONTAMINANT MASS DISCHARGE TO A STREAM USING POINT-VELOCITY PROBES (PVP)

Vinni K. Rønde¹, Ursula McKnight¹, Anne T. Sonne¹, John Frederick Devlin², Poul L. Bjerg¹

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²University of Kansas, Lawrence, KS, US

The application of Point-Velocity Probes (PVP) for both groundwater velocity and groundwater-borne contaminant mass discharge quantification was investigated. The PVP is a novel method to directly measure groundwater velocity at the centimeter scale based on a small-scale tracer test (Labaky et al., 2007), and it has not previously been used to quantify aquifer-stream interactions or contaminant mass discharge.

In the spring 2014, 8 PVPs were successfully assembled and installed at the bank of Grindsted stream, located in the Region of Southern Denmark. The stream of around 10 m width and 1.7 m depth is impacted by xenobiotic organic contamination from two large contaminated sites, Grindsted factory site and Grindsted landfill, which are located 1.5 km north and 2 km south of the stream, respectively.

Numerous injection experiments were conducted in the 8 PVPs, as well as in 4 PVPs installed prior to this study. Horizontal flow directions pointed generally towards the stream, and average seepage velocities ranged from 0.3 to 2.5 m/d with standard deviations between 0.05 and 0.66 m/d.

The groundwater seepage velocities obtained from the PVPs were compared to those obtained from temperature profiling and Darcy's law. The Darcy-based seepage velocities were on average 6 times higher than the PVP values, which were in turn 10% higher than the temperature-based values. Differences may be related to scale differences of the methods, temporal variations as well as uncertainties in the estimates of geological parameters. This latter concern does not apply to PVP measurements, which are based on tracer transport times, making PVPs a useful addition to these kinds of investigations. The fact that the PVP-based seepage velocities fall in between those obtained from the other methods indicates that PVPs are capable of measuring groundwater velocity with an accuracy comparable to that of temperature profiling and Darcy's law.

The PVP-based seepage velocities were combined with groundwater contaminant concentrations to quantify the groundwater-borne contaminant mass discharge. Considering various scenarios, mass discharges for vinyl chloride (VC), benzene and total chlorinated solvents of 37-48 kg/y, 18 kg/y and 0.7-1.4 kmoles/y were found, respectively. Up to 80% of the contaminant mass discharge was found within 13% of the total contaminant plume width (hotspot). This indicates that contaminant plumes may be highly heterogeneous even in homogeneous sandy aquifers, hence fine-scale-monitoring is needed.

Observed contaminant stream concentrations of VC, benzene and chlorinated solvents were between 2.0-3.1 times higher than those calculated from the contaminant mass discharge. This suggests an underestimation of the mass discharge, likely caused by large spatial variations in groundwater velocity and contaminant concentrations.

In order to improve the estimates of the contaminant mass discharge, a second measuring round was carried out in the fall/winter 2014, including i) injection experiments in the 12 PVPs as well as in 2 additional PVPs, ii) multi-level measurements of groundwater contamination in a fine monitoring grid along the stream bank, and iii) slug tests along the stream bank. Preliminary results from the second measuring round support a highly focused discharge to the stream. It seems that a narrow plume embedded in a larger plume accounts for most of the contaminant mass discharge to the stream.

In conclusion, this study illustrates the high potential of PVPs for groundwater velocity quantification near streams, as well as for groundwater-borne contaminant mass discharge quantification. The results from the fall/winter campaign, in-depth interpretation of the field data and perspectives for contaminant mass discharge estimations at streams threatened by point sources will be presented at the conference.

References:

Labaky, W., Devlin, J. F., and Gillham, R. W. (2007). Probe for measuring groundwater velocity at the centimeter scale. *Environmental Science and Technology*. 41(24):8453-8458.

A NEW, FAST, CLEAN AND EASY WAY TO PREDICT ORGANIC CONTAMINANT AVAILABILITY USING THERMODESORPTION – GAS CHROMATOGRAPHY – MASS SPECTROMETRY/FLAME IONIZATION (TD-GC-MS/FID)

Coralie Biache¹, Catherine Lorgeoux¹, Alain Saada², Stéfan Colombano², Pierre Faure¹

¹CNRS / Université de Lorraine, Vandœuvre les Nancy, FR

²BRGM, Orleans, FR

There are currently several methods used to determine the available fraction of organic contaminants in soils and sediments (e.g. mild-solvent extraction, Tenax extraction, cyclodextrin extraction, passive sampling, biosensors...). However, the comparison of these methods often shows discrepancies in the results, which underlines the need of a standardized method for availability measurement.

The aim of this study was to develop a new tool for the determination of the available fraction of organic compounds in contaminated soils. It consists in a thermodesorption – gas chromatography – mass spectrometry/flame ionization coupling (Td-GC-MS/FID). The idea is to link the binding energy between the compound and the matrix with the desorption temperature. In order to test the feasibility of such technique, polycyclic aromatic hydrocarbon (PAH) contaminated soils presenting various levels of contaminant availability were analyzed. For each PAH, the desorption temperature profile was compared to the efficiency of chemical (Fenton-like and KMnO₄ oxidations) and biological (microbial incubation) treatments to degrade PAHs. A gas plant soil, a wood treating facility soil and two coking plant soils were selected. One milligram of each soil was thermodesorbed at 10 °C/min from 100 °C to 800 °C according to the following temperature ranges: from 100 to 300 °C with six 50°C-steps, then from 400 to 500 °C and finally from 500 to 800 °C. The thermodesorbed compounds were subsequently separated by GC, PAH were identified by MS and quantified with the previously calibrated FID.

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intrusion: summary report. Waterlines Report Series No 85, Australia, 185 pp.
 BMJ (BUNDESMINISTERIUM FÜR JUSTIZ) (2013): *Trinkwasserverordnung in der Fassung der Bekanntmachung vom 2. August 2013 (BGBl. I S. 2977), die durch Artikel 4 Absatz 22 des Gesetzes vom 7. August 2013 (BGBl. I S. 3154) geändert worden ist.* – Berlin.

INNOVATIVE FIELD INVESTIGATIONS IN LIMESTONE USING A FACT-FLUTE

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The understanding of chlorinated solvents behavior in fractured limestone aquifers is a challenging task because of the preferential flow of contaminants in fractures and the exchange with the limestone matrix. Characterization of the contaminant distribution, particularly in the matrix, is challenged by difficulties in intact sample collection (coring) for sufficiently discretized data. The characterization is important for the development of a conceptual understanding, for risk assessment and for the choice and operation of an appropriate remediation strategy. The FACT (FLUTE activated carbon technique) is an innovative monitoring technique, which allows determining the distribution of a contaminant in the surrounding of a borehole with a higher resolution than conventional monitoring methods. The FACT technique proved to be a helpful tool for characterization of contaminant distribution in the limestone aquifer at Naverland, a contaminated site in Denmark (Janniche et al. 2013, Broholm et al. 2013, Kerrn-Jespersen et al. 2013). While the sorbed concentration of contaminant in the carbon felt is obviously related to concentrations in the formation, there is no direct relation between measured sorbed concentration (mg/g AC) and the aqueous pore water concentration (mg/L). The objective of the research presented was to develop a tool for the interpretation of FACT measurements and apply it to the Naverland dataset for comparison with concentrations in groundwater samples sampled from the Water-FLUTE multilevels (Janniche et al. 2013 and 2013b) at the site.

The FLUTE Activated Carbon Technique was described e.g. in Janniche et al. (2013). The sorption of chlorinated ethenes on activated carbon was determined in laboratory experiments as described in Sørensen et al. (2014) to obtain equilibrium sorption coefficients (K_d) for individual and mixed chlorinated ethenes on activated carbon from aqueous solution. As the uptake on FACT in limestone aquifers will depend on transport (advection and/or diffusion and retardation by sorption) in the limestone matrix and fractures as well as on the sorption to activated carbon, a modeling tool was developed (Mosthaf et al. 2014) which allows for the interpretation of field data and the analysis of the influence of various aquifer parameters. The model provides a link between sorbed concentrations on the FACT and the prevailing aqueous pore water concentrations for a range of hydraulic parameters and conditions typical for limestone aquifers.

The sorption experiments showed very strong sorption with reasonably linear sorption isotherms over a very large concentration range for individual chlorinated ethenes. At high PCE concentrations, competition for sorption sites resulted in non-linearity and much lower sorption of the less hydrophobic

compounds TCE and particularly c-DCE. The model simulation results demonstrate the influence of common aquifer parameters on the observed sorbed concentrations on the FACT. The influence of the porosity and of the positioning of the FACT with respect to the flow is comparably small (factor 2-3), whereas the influence of sorption coefficients is increasing with the sorption coefficients and is particularly important for K_d-values above 10-3 L/kg. The hydraulic conductivity has only little influence for values below 10-5 m/s, but up to orders of magnitude influence above that until diffusion within the FACT is limiting the transport processes. For given hydraulic parameters, conditions and exposure time of the FACT, a linear relation between activated carbon concentration and aqueous concentration can be established. This allows the FACT-FLUTE technology to be employed for the characterization of contaminant distribution in limestone aquifers. A comparison between the aqueous (pore water) concentrations calculated with the model from the FACT-FLUTE data with groundwater concentrations from the Water-FLUTE multilevels at the Naverland site showed good correspondence. An advantage of the FACT technique is that it provides discretized data for the matrix and is less influenced by the preferential flow in high conductive zones than multilevel water sampling. It can also be applied in a matrix with strong variation in the hardness (e.g. softer limestone with interbedded chert layers). Furthermore, DNAPL presence in hydraulically active fractures can potentially be identified by high concentration peaks on the FACT.

Literature

Broholm, M.M. et al., 2013. *Udvikling af konceptuel forståelse af DNAPL udbredelse i moræner og kalk ved integreret anvendelse af direkte og indirekte karakteriseringsmetoder.* ATV Vintermøde, Vingsted, 5-6. marts 2013.

Janniche, G.S., Fjordbøge, A.S., Broholm, M.M., 2013. *"DNAPL i moræner og kalk. Vurdering af undersøgelsesmetoder og konceptuel modeludvikling. Naverland 26AB, Albertslund."* DTU Miljø og Region Hovedstaden. www.sara.env.dtu.dk.

Janniche, G.S. et al., 2013b. *"Anvendelse af Water FLUTE multi-level vandprøvetagning til DNAPL karakterisering."* Jordforurening.info 2-13, p. 4-8. Videncenter for Jordforurening. www.jordforurening.info

Kerrn-Jespersen et al., 2013. *"Undersøgelsesmetoder til karakterisering af DNAPL i kalk."* Jordforurening.info 1-13, p. 20-23. Videncenter for Jordforurening. www.jordforurening.info

Mosthaf, K., Broholm, M.M., Binning, P., 2014. *"The FACT-FLUTE technology. A modeling tool for interpreting field data."* DTU Environment and Region Hovedstaden. To appear on www.sara.env.dtu.dk

Sørensen, M.B., Broholm, M.M., 2014. *"Sorption af chlorerede opløsningsmidler på FACT."* DTU Miljø og Region Hovedstaden. www.sara.env.dtu.dk.

THE DELFT CASE – IMPROVED WATER AND SOIL MANAGEMENT THROUGH SMART MONITORING

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¹Witteveen+Bos, Deventer, NL

²Municipality of Delft, Delft, NL

³Delft University of Technology, Delft, NL

The old city centre of Delft is sensitive to both pluvial and fluvial flooding, especially specific areas in the eastern part of the city centre. This includes high groundwater levels, overflowing of canals, surcharging of sewers and flooding of streets and buildings due to storm events. In order to reduce flooding impacts, the canals in the city centre have been separated from the main water system around Delft by means of several weirs

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field tests will be presented, with focus on the functioning of the MIP-IN device and its added value. Further, the potential of the MIP-IN based remediation strategy will be explained and illustrated with an example.

EVOLUTION OF A SITE CONCEPTUAL MODEL USING MULTIMEDIA CSIA TO SUPPLEMENT TRADITIONAL TECHNIQUES

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²ENVIRON, Irvine, US

³ENVIRON, Los Angeles, US

Since the 1980s, several subsurface investigations conducted to evaluate impacts at an industrial facility in California have identified volatile organic compounds (VOCs) in shallow soil and soil gas underlying the site. VOCs have also been identified in groundwater encountered at approximately 180 feet (ft) below ground surface (bgs). However, the assemblage of detected VOCs in the shallow horizons (soil/soil gas) is significantly different than that observed in the deeper groundwater. Shallow VOC impacts (i.e., <~55 ft) are predominantly tetrachloroethene (PCE) with minor amounts of benzene, toluene, ethylbenzene, and xylenes (BTEX), carbon tetrachloride, other substituted benzenes, and a notable near absence of trichloroethene (TCE). The deeper groundwater is characterized by a predominantly TCE signature, with very low PCE concentrations. Collectively, the site data suggest that PCE impacts from historic site uses were limited to shallow depths, and the observed TCE in groundwater beneath the site had likely migrated from an upgradient location off-site. However, additional lines of evidence were needed to confirm this conceptual model, support traditional site assessment data, and to direct the path of future investigation and/or remediation efforts.

ENVIRON conducted an investigation to evaluate the vertical distribution of VOCs in soil gas beneath areas of the site where elevated PCE concentrations had been identified in previous testing. Borings were advanced to approximately 100 ft bgs, and nested soil vapor probes were installed. Soil vapor samples were collected and analyzed for VOCs including PCE, TCE, cis-1,2-dichloroethene, trans-1,2-dichloroethene, and vinyl chloride. Based on the bulk compositional analyses, select soil vapor samples were collected for compound specific isotope analysis (CSIA) of carbon and chlorine. In addition, groundwater samples from monitoring wells at the site were submitted for CSIA (carbon, chlorine).

ENVIRON used the CSIA and bulk composition results in soil gas and groundwater, coupled with fate and transport modeling for the site to evaluate and ultimately confirm the original conceptual model – that groundwater impacts beneath the site originates from an upgradient source. Moreover, the data suggest that the shallow VOCs (predominantly PCE) in soil gas have not undergone reductive dechlorination during transport, further evidence that a putative source for the TCE in groundwater does not exist on-site. The isotopic data from soil vapor and groundwater, combined with traditional site characterization data helped to validate and refine the conceptual site model. New CSIA results from additional vapor probes installed in early 2015 will be included that provide further resolution of the isotopic conditions at the site.

MODEL OF THE INFLUENCE OF MEANDERS AND TIME VARYING STREAM LEVELS ON GROUNDWATER DISCHARGE TO STREAMS

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Groundwater discharge can be an important contaminant source to surface water bodies and must be addressed when responding to legislation like the EU Water Framework Directive, which aims to protect and restore surface water bodies. Since contaminated sites are a major source of contaminants in groundwater resources it is important to evaluate the risks posed by them to streams. Such risk assessments are the basis the selection of appropriate and cost-effective remediation actions. This is a challenge because little is known about how contaminant discharge to stream varies because of stream meandering and changes in the water levels in streams and in aquifers.

This study aimed to develop a model of groundwater discharge to streams that incorporates the stream morphology and the time varying water levels in streams and in aquifers. The model was applied in order to determine the likely location of groundwater discharge in streams, and determine the origin of that groundwater. The models also showed that time-varying stream water level and groundwater head affect the discharge. The model was developed for a field site at Grindsted stream, a study site located in Denmark. The study aimed to use the model to analyze groundwater discharge measurements obtained at the field site. The work provided new insight on groundwater/surface water interaction and the interpretation of field data.

The project successfully developed a three-dimensional COMSOL Multiphysics model for groundwater discharging into Grindsted stream. The model accounts for the geometry of the stream and the geological heterogeneity of the aquifer. In addition, it includes the time variability in stream and aquifer water levels.

The study site was characterized by an extensive field campaign. The model was used to design the field monitoring and then, once data was collected, was compared with Point Velocity Probe and stream temperature measurements which provided data on the location, magnitude and direction of groundwater discharge to the stream. The results were also compared with time series of head data at monitoring wells located next to the stream. The model was shown to reproduce field data very well, leading to confidence in results.

It was observed that the discharge into the stream is highly dependent on the gradient between the stream and the aquifer. Thus, temporal variability in the discharge is correlated to changes over time of the gradient. In addition, the geological heterogeneity of the aquifer underneath the stream was shown to affect the groundwater flow, the discharge into the stream and the provenience of the discharged water.

This study showed that the presence of meanders had high impacts on the discharge and on the groundwater flow in proximity of the stream. The results indicated that the upper part of the aquifer mostly discharges in the outward pointing meanders, while groundwater from the lower part enters the stream from the opposite side. Furthermore, the groundwater discharge velocity is higher in the outer part of the meander bends. The observation was supported by contaminant concentration measurements in the groundwater collected nearby the stream. This suggested that

1B. Risk assessment and management

MIHPT system is a combination of the MIP and HPT systems and has proved to be very efficient for field investigations in hotspots and areas with high contaminant levels. However, the detection limits of the standard MIHPT system are too high for delineation of contaminant plumes where the concentration levels are significantly lower than in the source zones. The Low-Level MIHPT system is developed with the objective to detect contamination at low concentrations and thus provides a means for conducting more time efficient and cost-effective delineation of contaminant plumes in unconsolidated saturated formations.

The LL-MIHPT systems have been tested at two sites located in the towns of Farum and Slangerup in Denmark as part of ongoing field investigations at the two sites.

The purpose of this project was to test the LL-MIHPT technique for delineation of contaminant plumes in groundwater at two sites with different geological formations; sandy and clayey, respectively. The objectives have thus been to determine at which concentration level the LL-MIHPT system could detect the site specific contaminants and to investigate the correlation between observed LL-MIHPT responses and results from analysed water samples from targeted depths.

9 LL-MIHPT logs to 20-25 meters below surface have been carried out. At each log water samples were collected at specific depths with the GeoProbe for verification of the observed responses from the LL-MIHPT and for correlation of contamination levels. For further correlation of the LL-MIHPT data core samples were collected at three locations.

The results from the field tests show that it is possible with the LL-MIHPT to track relatively low concentrations of chlorinated solvents and BTEX's in the saturated zone. Hence, for chlorinated solvents a detection limit in the order of 10 ug/L can be expected. For comparison the detection limit for chlorinated solvents with the standard MIP system is in the order of 1-10 mg/L.

Based on the results and experiences obtained from the field tests the new LL-MIHPT system shows good promise for delineation of contaminant plumes in the saturated zone with simultaneous retrieval of hydrostratigraphic data from the saturated zone. Thus, LL-MIHPT logs followed by depth specific groundwater sampling with the GeoProbe system is considered to be an optimal set-up for delineation and characterization of contaminant plumes in saturated zones in unconsolidated geological formations.

The field tests were conducted and evaluated in the fall of 2013 and spring of 2014. Since then NIRAS A/S has used the LL-MIHPT system at field investigations at several other sites. Thus, the presentation will include results from the field tests in Farum and Slangerup complemented with the most recent data.

SpS 1A.7S US EPA Session 1: Best Practices for site characterization

Wednesday | 10 June | 14:00 - 15:30 | Meeting Room 19

Organizers: Carlos S. Pachon, Stephen A. Dymont (United States Environmental Protection Agency)

For session details please have a look at page 14.

SpS 1B.1S Implementation of the EU Water Framework Directive – how to manage contaminated sites threatening surface waters

Tuesday | 9 June | 14:00 - 15:30 | Auditorium 10

Organizers: Sandra Roost (Orbicon A/S, DK), Jens Aabling (Danish Environmental Protection Agency, DK), Nina Tuxen (Orbicon A/S, DK), Trine Korsgaard (Region of Southern Denmark, DK), Helle Overgaard (The Capital Region of Denmark, DK)

For session details please have a look at page 8.

SpS 1B.2S Workshop on groundwater contamination from pesticide point sources

a: Tuesday | 9 June | 14:00 - 15:30 | Meeting Room 19

b: Tuesday | 9 June | 16:00 - 17:30 | Meeting Room 19

Organizers: Poul L. Bjerg, Professor (DTU Environment, DK), Nina Tuxen (Chief consultant, Capital Region of Denmark), Ida Holm Olesen (Head of Section, Region of Southern Denmark)

Pesticides are among the most widespread contaminants in the European groundwater. Recent findings in Denmark indicate that between 20 and 45 % of the pesticide findings in the groundwater can be attributed to point sources. Danish researchers, authorities and consultants have developed innovative tools for data analysis, catchment scale risk assessment and remediation.

We believe we are on the right path, but we are very well aware that we have not yet found the recipe for efficient management of pesticide-point sources. Judged by the limited amount of literature on pesticide point sources available, it seems that other European countries are in a similar situation. Therefore, the aim of this workshop is knowledge exchange and mutual inspiration on the topic of pesticide point sources. Ideally, the session will facilitate forming of new European partnerships on further research and development among authorities, consultants and researchers. All participants are invited to contribute to knowledge exchange by brief presentations and participation in discussions on key issues

For further session details please have a look at page 8.

1C. Remediation technologies and approaches

DEVELOPMENT OF A GREEN REMEDIATION TOOL FOR SUSTAINABILITY ASSESSMENT OF SOIL REMEDIATION IN JAPAN

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In order to promote sustainable remediation of contaminated sites, we developed a green remediation tool inserted with 16 soil remediation methods. This tool includes 19-100 (?) environmental inventories, and can integrate these inventories into a single index (a monetary value “yen”) using a life cycle impact assessment method based on endpoint modeling (LIME2).

In this study, we used this tool to evaluate remediation of an arsenic-contaminated site. Five remediation methods, were compared: 1) excavation and off-site landfill disposal (EOL), 2) excavation and on-site landfill and washing of contaminated soil (EOW), 3) in situ insolubilization (ISI), 4) in situ containment (ISC), 5) and groundwater monitoring (MN).

Our results showed that the integrated environmental impact associated with the EOL method totaled 1.3 million yen/3000m³, followed by 1.18 million yen/3000m³ for the EOW method, 0.72 million yen/3000m³ for the ISC method, and 0.61 million/3000m³ yen for the ISI method, indicating that in situ remediation is more advantageous, in terms of environmental impact, than off-site remediation. At 0.01 million yen/3000m³, the MN method exhibited the least impact. Based on the damage analysis, all of the remediation methods were associated with markedly higher integrated impacts on human health and social assets than on biodiversity and primary production. In terms of impact category analysis, major impacts associated with each remediation method were global warming, urban area air pollution, and resources consumption. Furthermore, contribution analysis of each remediation process to the total integrated impact revealed that energy consumption contributed markedly to the impact of off-site remediation, whereas the utilization of materials accounted for over 70% of the total impact of in situ remediation. Transport of contaminated soil was a major factor affecting the impact of off-site remediation. The changes of inventories including CO₂ emission, PM₁₀ generation and oil combustion were the main contributors to the impact associated with all remediation methods. We believe that these results could serve as an effective reference for remediating heavy metal-contaminated sites or for identifying weaknesses in a particular remediation process.

RECENT TRENDS IN THE ASSESSMENT OF SUSTAINABLE REMEDIATION: DOES THE TAIL WAG THE DOG?

Gernot Döberl, Dietmar Müller-Grabherr
Environment Agency Austria, Vienna, AT

Within the last decade “sustainable remediation”, i.e. enhancing the “sustainability” of contaminated site remediation by applying the principles of sustainable development has been discussed intensively by different networks and stakeholder groups from different perspectives (SURF networks, NICOLE, Common Forum and others). Among others, the need for appropriate (holistic) assessment frameworks, methods and indicators to compare and rank different remediation options regarding their sustainability

has been identified as one commonly accepted outcome of these discussions.

While only a few assessment frameworks have been published so far (e. g. SURF UK), a large variety of “tool-boxes” and “ready-to-use” software packages are in use to identify the most sustainable among different remediation options. As the principle of sustainable development is claiming intra-/intergenerational equity in terms of environmental, economic and social implications, comparing different options regarding their sustainability can be seen as a classical multi-criteria assessment problem. Although the multi-criteria problem is recognised and all three pillars of sustainability are addressed by most of the assessment approaches, there are remarkable methodological differences. Surprisingly, this applies in particular for the assessment of environmental effects.

In our contribution we will give a brief overview on the historical development of sustainable remediation and the main players promoting its implementation into contaminated site management. We will address the theoretical background of assessing sustainability and discuss the suitability of different assessment methods. Special emphasis will be given on the selection of environmental sustainability indicators since identifying appropriate environmental indicators, in our opinion, represent one of the most crucial issues in order to get reliable assessment results. The theoretical discussion will be exemplified by an analysis of recent trends in the assessment of sustainable remediation. Based on contributions to scientific conferences, such as AquaConSoil 2013 or the International Conferences on Sustainable Remediation 2012 and 2014, it can be shown that contrary to secondary environmental effects, which are considered by almost all assessment methods, only a minority of assessment methods are counting for primary environmental effects. Generally, primary environmental effects are linked to the environmental goals of remediation measures (e.g. reducing risks for humans and the environment), whereas secondary environmental effects comprise accompanying side effects (e. g. greenhouse gas emissions, waste generation, water consumption, energy demand), which mostly are unintended. Similar to secondary environmental effects, remediation options may also differ in their ability to meet environmental goals significantly; meeting the remediation targets set by the authority may be seen as a minimum requirement. Thus, neglecting primary environmental effects may result in a biased ranking of remediation options. Other examples for a considerable impact on assessment results are related to the role of holistic assessment frameworks and system boundaries.

In conclusion, an inappropriate selection of sustainability indicators, and in particular counting for secondary environmental effects only, implies the danger of the tail wagging the dog.

A MULTI-CRITERIA METHOD FOR ASSESSING THE SUSTAINABILITY OF REMEDIATION ALTERNATIVES

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In order to improve and support decision-making regarding the selection of remedial techniques for contaminated sites a multi-

1C. Remediation technologies and approaches

criteria assessment (MCA) method has been developed. The MCA tool compares the sustainability of remediation alternatives by integrating environmental as well as societal and economic criteria in the assessment. In addition, the method encourages stakeholder participation by including stakeholder-derived criteria weights.

The MCA method was developed using a hierarchical structure and includes five main decision criteria: Remedial effect, remediation cost, remediation time, environmental impacts and societal impacts. Environmental impacts and societal impacts are subdivided into a number of sub criteria. The environmental impacts cover mainly secondary impacts to the environment caused by the remedial activities and are assessed in a life cycle assessment (LCA). The societal impacts are to a large extent local impacts and are mainly assessed in a more qualitative manner on a scale from 1-5. The performance on each main criterion is converted to a score and an overall score is obtained by multiplying each score by a criteria weight.

To illustrate the use of the method it was applied to assess four management scenarios for the Groyne 42 site in Denmark. Groyne 42 is one of the largest contaminated sites in Denmark with an area of 20,000 m² and is located on the west coast of Jutland. In the 50s and 60s large amounts of waste, mainly residues from pesticide production, was disposed of at the site. In the 70s and 80s, parts of the contamination were excavated, but the deeper contamination was not removed and contains approximately 100 tons of contaminants. In 2006 a sheet pile wall was installed around the contaminated site in order to prevent the transportation of the contaminants to the North Sea.

The Central Denmark Region is responsible for the management of the site and have proposed four different management scenarios: (1) Excavation of the site followed by soil treatment, (2) In situ alkaline hydrolysis, (3) In situ steam enhanced extraction and (4) Continued encapsulation of the site (no removal of contaminants).

The five management scenarios were assessed using the MCA method described above. The various impacts were weighted using a stakeholder panel who assessed the importance of the five main criteria (Effect, Economy, Time, Environment and Society) in relation to each other. The stakeholders gave the highest weighting to the remedial effect of the methods and to the societal impacts.

The developed multi-criteria method provides useful insight into how the remediation scenarios compare to each other in terms of remedial effect, cost, time use and external impacts to environment and society. In addition, it offers a possibility for summing the weighted criteria scores in order to identify which option is more sustainable. For the Groyne 42 case study, the excavation option obtained the lowest overall score in the MCA and was therefore found to be the more sustainable option. This was especially due to the fact that this option could efficiently remove both pesticides and mercury and therefore obtained a high score in Effect, which was given a large weight by stakeholders. The continued encapsulation was found to be less sustainable than the other options. This was partly due to the fact, that this option would not improve the reputation of the area and therefore had large social impacts.

ThS 1C.2 Integrating sustainable remediation into other policies

Tuesday | 9 June | 16:00 - 17:30 | Meeting Room 20

THE REGULATORY BASIS FOR SUSTAINABLE REMEDIATION PRACTICE IN THE EUROPEAN UNION AND UNITED KINGDOM

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Sustainable Remediation involves the balanced consideration of environmental, social and economic factors in soil and groundwater risk assessment and risk-management decisions. The principles and practice of Sustainable Remediation are being increasingly promoted and applied to the management of contaminated soil and groundwater in the European Union (EU), including the United Kingdom (UK).

This paper presents the findings of an assessment as to how the actual wordings issued by legislative bodies in the EU and UK can require, promote, or support the application of Sustainable Remediation principles, and how such sections of regulatory text can be drawn upon by contaminated land practitioners and regulatory authorities to develop or support an argument for a sustainable remediation approach.

To fulfil this objective, legislative, regulatory, and technical guidance documents relevant to the contaminated land regime in the EU and UK were subjected to a detailed, systematic review. Specific areas of text identified as both explicitly or implicitly supporting sustainable approaches to remediation were subsequently collated and presented in a format reflecting the phased, risk-based approach to contaminated land management adopted in the UK.

The review found sustainability principles embedded in a wide body of EU directives, and UK legislation, regulation, and technical guidance. These included the Water Framework Directive (2000), the Environmental Liabilities Directive (2004), the Groundwater Directive (2006), the Waste Framework Directive (2008), the Industrial Emissions Directive (2010) and the Priority Substances Directive (2013) as well as the Common Implementation Strategy (CIS) guidance for the WFD and Groundwater Directives.

Some of these principles were over-arching statements that were applicable throughout the project life cycle whereas others were specifically relevant to particular scenarios, that might be encountered at particular stages in progressing from site assessment to remediation: in the UK for example sustainability principles could be brought to bear during the risk assessment process in the setting of the compliance point to protect water resources. In fact, documented regulatory support for sustainable remediation principles encompassed almost all facets of the site assessment and remediation process, including: risk assessment, selection of remedial objectives, remedial options appraisal, and, the implementation of remedial strategies.

Sustainability themes were also strongly represented in sections of key planning policy documents relevant to the contaminated land regime, such as the promotion of brownfield development in urban planning strategies.

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SpS 1C.6S Sustainability in contaminated site management – case Finland

Thursday | 11 June | 09:00 - 10:30 | Meeting Room 20

Organizers: Jaana Sorvari (Aalto University, FI), Seppo Nikunen (Pöyry Finland Oy, FI), Jussi Reinikainen, Outi Pyy (Finnish Environment Institute, FI), Anna-Maija Pajukallio (Ministry of the Environment, FI)

Moderator: Jaana Sorvari (Aalto University, FI)

For session details please have a look at page 19.

ThS 1C.7 Strategies for remediation and brownfield regeneration

Thursday | 11 June | 11:00 - 12:30 | Meeting Room 20

REGENERATION OF BROWNFIELD MEGA-SITES – A REVIEW OF EXISTING AND EMERGING TECHNOLOGIES AND THEIR APPLICATION FOR A TEST-SITE

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This study aims to answer the question of which technologies that can overcome the remediation challenge of brownfield mega-sites. We reviewed potential remediation strategies and assessed their applicability for a former Soviet military air-base at Szprotawa, Poland, with a BTEX contaminated area of roughly 75 ha. The remediation technologies reviewed are: monitored natural attenuation MNA, phytoremediation or phyto-enhanced natural attenuation, in-situ chemical oxidation (ISCO), soil-flushing and ex-situ composting. The assessment is done based on data acquired by site screening with direct-push, soil gas measurements, phytoscreening and soil and groundwater monitoring.

Results from the screening allowed us to make a pre-selection of methods. Soil gas measurements on methane (high), oxygen (low) and CO₂ (high) prove ongoing natural attenuation processes. The high permeability of the soil allows air sparging, bioventing or soil-flushing of the source zone. Presence of BTEX in tree cores shows that tree roots reach the subsurface plume. By uptake of pollutants, rhizo- and phytodegradation, natural attenuation would be enhanced. Most importantly, trees transpire water which increase aerated soil pore space and lower groundwater level – drawing down oxygen. Direct-push did not only give a 3-D picture of the NAPL, but yielded also information on the hydrological conditions and aquifer material. The hot spot areas (approx. 100 000 m³) has levels above 10 g/kg hydrocarbons, mostly kerosene, and cannot be treated by MNA or phytoremediation within reasonable time. Here, in-situ treatments like ISCO or air sparging would be applicable. Conclusion: The use of pre-screening methods, such as soil gas measurements, tree coring and direct-push, does not only lead to a denser grid and better survey of

contaminated sites. The information collected can also be used to judge and pre-select remediation methods, as was shown for the former Soviet military airport Szprotawa. In this case, ISCO, soil-flushing and air sparging for the centre of the plume, combined with phytoremediation and MNA, would be suitable and cost-efficient. At construction sites, where soil is excavated anyway, on-site composting or dumping are rapid alternatives.

POLLUTION OF SOIL AND GROUNDWATER BY INDUSTRIAL OILS DUMPING IN JARAMA RIVER BASIN (MADRID, SPAIN)

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In the eighties of the last century, heavy oils of industrial origin were poured in an abandoned gravel quarry in the quaternary aquifer of the Jarama River, close to Madrid (Spain). The quarrying activities have generated lakes, nowadays protected by several environmental figures. The regional government has decided to clean up contaminated soils and groundwater at the site. In December 2013, the environmental impact assessment and the development of a remediation methodology were carried out. According to the studies, ex situ and in situ techniques will be combined. The ex situ techniques will consist in the removal of oil, by pumping the more fluid layers and mechanically the denser ones, and subsequent deposit in the high security landfill of Madrid Community. The in situ techniques will consist in the soil treatment, the filling of the hole and the soil regeneration by mean of autochthonous plants. The study conducted by the above signatories has shown that more than thirty years since the activity began in the quarry, contamination is confined to the site, has not generated any plume and the lakes around the quarry don't have symptoms of contamination. Moreover, the hydrogeological characteristics of the aquifer reflect that in case of leakage, the groundwater flow would transport contaminants towards the south or southwest affecting several lakes. In these conditions, the cleanup of the site should be especially careful to avoid any contact between the hydrocarbon residues and the more permeable layers of the quaternary aquifer.

LAC MEGANTIC : THE REHABILITATION OF A TOWN FOLLOWING A PETROLEUM LOADED TRAIN EXPLOSION

Michel Beaulieu
MDDELCC, Quebec City, CA

The town of Lac Mégantic, 6 000 inhabitants, is located in the Canadian Province of Quebec south east corner, only 35 kilometers away from the American state of Maine. Build along the lake which gave its name to the city, Lac Mégantic is a major northern transit route for trains circulating from the earth of the continent to the Atlantic seaboard. Petroleum is one of the goods carried over that railway line, increasingly so over the last years. Late on July 5th 2013, a convoy consisting of 5 engines and 72 tankers filled with crude petroleum extracted from the Bakken formation in North Dakota reached the town of Nantes, 13 kilometres uphill from Lac Mégantic. On its way to the St-John's Irving refinery in the neighbouring eastern Canadian province of New Brunswick, it stopped for the night at the top of a slope. Few minutes before 1 o'clock at night, the breaks of the unattended train let go. The convoy started to roll down the 1.2% slope. At 1:16 in the morning, entering Lac Mégantic downtown full speed, the train