



Direct-push multilevel sampling system for unconsolidated aquifers

Pascale Ducommun · Xenia Boutsiadou · Daniel Hunkeler

Abstract An economical multilevel groundwater monitoring system has been developed that can be rapidly installed with a direct-push machine, yet is suitable for sampling across large permeability contrasts. This sealed multiport sampling (SMPS) system consists of up to five lengths of PVC tubing (12mm OD), each with a screen at a specific depth created by drilling 2.5-mm holes. Above and below each screen, round elastomer pieces, with peripheral holes (to clip in the sampling tubes) and a central hole (to hold a discontinuous piece of central tubing at the height of the screen), are emplaced. Cement-bentonite grout is injected via a tremie tube inserted through the discontinuous centre tube into each interval between the sampling screens. The elastomer pieces and central tube prevent grout from reaching the screened interval. A textile wrapped around the system holds the arrangement in place and at the same time serves to filter the groundwater at the level of the sampling screens. The SMPS system was tested at a tetrachloroethene (PCE) contaminated site. The seals effectively separated the sampling intervals even in heterogeneous formations. Furthermore, concentration profiles agreed well with a reference system. The system should be suitable for a wide range of hydrogeological conditions.

Keywords Groundwater monitoring · Multilevel sampling · Chlorinated hydrocarbons

Introduction

Dissolved contaminant plumes downgradient of nonaqueous-phase liquid (NAPL) source zones commonly show strong concentration gradients especially in the vertical direction (Anneser et al. 2008; Cunningham and Fadel 2007; Einarson et al. 2010; Guilbeault et al. 2005; Schulmeister et al. 2004). This is due to a number of factors, including geological

heterogeneity, spatial and temporal variability in contaminant mass input, activity of bacteria responsible for biodegradation and aquifer recharge; therefore, the measured concentrations strongly depend on the sampling installations and sampling methods (Parker 1994).

Conventional site characterization methods based on monitoring wells are often ineffective to sufficiently resolve the spatial distribution of dissolved contaminants in aquifers (Charette and Allen 2006; Einarson and Cherry 2002). The use of multilevel sampling techniques for collecting depth-specific groundwater samples makes it possible to obtain detailed vertical concentration profiles. Several systems for multilevel groundwater monitoring are commercially available for permanent or one-time sampling. Available technologies include nested piezometers and cluster wells, a variety of methods for fully screened wells such as multi-packer methods, and specialized multilevel monitoring systems (Einarson 2006; Lerner and Teutsch 1995; Schirmer et al. 1995). However, common multilevel systems have some limitations. Multiport sock samplers (Jones et al. 1999; Schirmer et al. 1995) require a larger diameter borehole implying elevated costs. Furthermore, in unconsolidated aquifers they can only be installed within screened boreholes with a high risk of vertical circulations in the annual space. Several systems consist of multiple narrow stainless steel (Delin and Landon 1996) or PVC (Martin et al. 2003) tubes within a PVC casing of 4–5 cm diameter. Sealing relies on the collapse of the formation or the emplacement of alternating sand and bentonite layers around the PVC casing, which requires again a costly larger diameter borehole. Bundle wells consisting of a series of tubes reaching different depths installed with a direct-push machine is a widely used cost-effective alternative (Cherry et al. 1983; Mackay et al. 1986; Reinhard et al. 1984). This method has mainly been used in sand aquifers, where the formation collapses after retrieving the casing, sealing the annular space around the tubes. With the availability of stronger direct-push machines, similar multilevel wells can also be installed in coarse gravel aquifers. Unfortunately, in such aquifers, the formation will not collapse completely around the multilevel well. Furthermore, in other formations with high clay content, only limited collapse might occur. An incomplete collapse around a multilevel system is particularly problematic when sampling in highly heterogeneous formations as water from a high-permeability zone might be drawn in when sampling in low-permeability layers. There is a particular need for multilevel sampling in such formations because the heterogenous

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permeability distribution might often be associated with steep concentration gradients (Cunningham and Fadel 2007; Schirmer et al. 2001; Topinkova et al. 2007; Ucanus and Unlu 2008). In these cases, seals between monitoring zones are required.

The goal of this study was to develop a multilevel monitoring system that can be rapidly installed with a direct-push method while ensuring a proper sealing between intervals, also in situations where only an incomplete collapse occurs. The concept is based on small-diameter PVC tubes packed into a single unit. The key element of the new system is cement-bentonite seals installed in well-controlled locations to separate the various monitoring zones. The seals make the system suitable for non-collapsing sediments. This article describes the newly developed permanent multilevel monitoring system, presents test results for demonstrating the performance of the seals and compares the obtained concentration profiles with profiles from a reference system.

Material and methods

Description of the system

The new system, denoted as a sealed multiport system (SMPS), consists of five polyvinyl chloride (PVC) tubes (10 mm inner diameter ID, 12 mm outer diameter OD). Depth-discrete screens are created by drilling holes of 2.5 mm diameter into the single PVC tubes. Stagnant water in tubes below the screens is hydraulically isolated by plugging the tubes a few centimeters below each screen with conical rubber stoppers. Since the standard length of the PVC tubing is 5 m, for longer systems, several tubes are glued together with PVC connectors using Tangit PVC-U glue (Henkel, Germany). This glue, which is certified for drinking-water applications, contains tetrahydrofuran, methyl ethyl ketone and cyclohexanone, and does not interfere with VOC analyses. The PVC tubes are then assembled in one unit by custom-made nitrile butadiene rubber (NBR) elastomer pieces (Fig. 1) attached above and below each screened interval. In the centre of the system, short sections of PVC tubes (13.6 mm ID, 16 mm OD) are placed at the

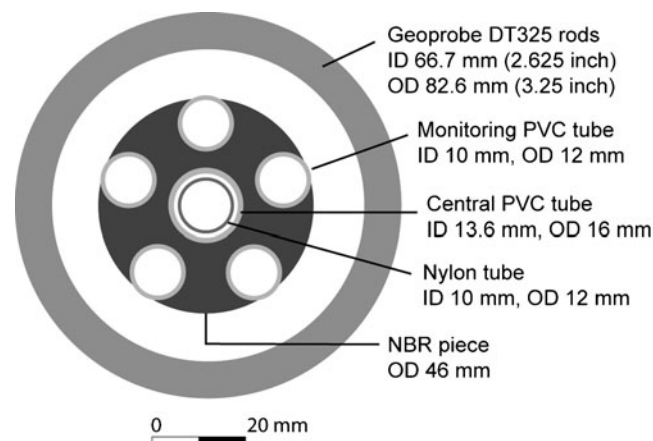


Fig. 1 Horizontal cross section of the SMPS system with five PVC sampling tubes. *ID* internal diameter, *OD* outside diameter, *NBR* nitrile butadiene rubber

height of the screened intervals. A nylon tube (10 mm ID, 12 mm OD) is inserted across the central sections for injection of a cement-bentonite grout using a conventional tremie method. The short sections of PVC tubes allow installation of reliable seals at an exact position between the monitoring zones. The central tube and the NBR pieces at either end of the screened intervals prevent grout from reaching the screened intervals. Finally, the entire unit is packed into a tubular polyamide (NITEX) mesh textile (80 μ m mesh opening) fastened to the elastomer pieces with Cellpack No. 62 (Behr Bircher Cellpack, Switzerland) self-amalgamating tape. The tape is based on ethylene propylene rubber that is not soluble in water and does not interfere with VOC analyses. The mesh textile prevents fine sand from entering the monitoring ports. Furthermore, openings in the mesh are sufficiently small to keep the cement-bentonite grout within the mesh and yet large enough to allow some of the bentonite to squeeze through the mesh as the bentonite swells. The diameter of the tubular mesh is large enough to fill the whole borehole after expansion of the cement-bentonite mixture yet small enough to easily fit inside of the casing during installation.

Installation procedure

The SMPS system was designed for installation in unconsolidated sand and gravels formations. For that purpose, it can be installed using direct-push technology (DPT, Geoprobe Systems), which is cost efficient, compared to traditional drilling methods. The method consists of ramming a steel drive casing with a metal tip to the target depth (Fig. 2a). Before installation of the system, the steel drive casing is filled with water to prevent sediments from entering inside the steel drive casing during its retrieval. The system is inserted into the drive casing. The drive casing is then pulled out while pushing the system down with a piece of rigid tubing to knock out the metal tip and keep the system in place (Fig. 2b). A cement-bentonite slurry is injected by a hand injection pump (HVP10, Comdrill GmbH, Germany) via a tremie pipe (Nylon tube) to ensure the separation of the sampling intervals from each other. Previous studies have shown that cement-bentonite grout is the most universally applicable material for successfully backfilling borehole instruments (Mikkelsen 2002). The percentage of cement and bentonite in the mixture was determined based on literature values (Mikkelsen 2002) and numerous injection tests with the hand pump varying the consistency of the mixture. The optimal composition of 1 L of the cement-bentonite mixture includes 0.9 L of water, 0.32 kg of cement, and 0.12 kg of bentonite. The injection volume necessary to completely fill the intervals between the screens is calculated based on the dimensions of the system. The injection procedure is as follows. The nylon tube is connected to the hand injection pump with a Swagelok connector. The calculated volume of cement-bentonite grout is prepared on site and directly injected through the nylon tube, which is pulled up successively to fill the intervals between the screened ports. The remainder of the hole is completely filled with cement-bentonite grout to the ground surface to prevent

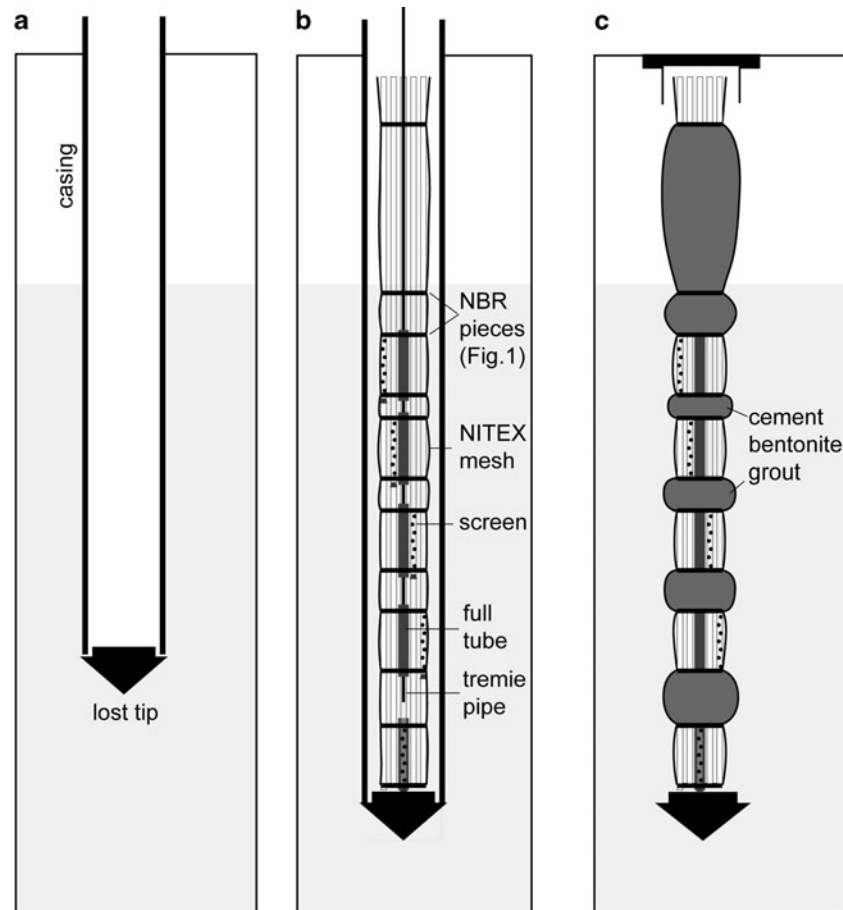


Fig. 2 Vertical cross section illustrating the different steps of installing the SMPS system. **a** Ramming the casing with the metal tip into the ground. **b** Introducing the system through the metal casing and pulling out the metal casing. The cement-bentonite grout is injected via the central tube in *black*. **c** Final view of the SMPS system with cement-bentonite packers and equipped with a flush mounted well cover

rainwater from percolating towards the water table. After installation, the tubes are cut off at the ground surface and a wellhead protection cap is installed (Fig. 2c). This method of installation is very rapid and is particularly well suited to DPT. The assembly of a 10 m SMPS system takes two people approximately 1 h with a further half an hour required for installation.

Sampling procedure

Groundwater samples can be collected using small pumping devices including peristaltic pumps and inertial lift pumps (Waterra, UK). Because of the small internal diameter of the tubing, no commercially available bladder, double-valve or submersible pumps currently exist.

For purging and sampling, the low flow approach is used to minimize disturbance of both well hydraulics and quality of water samples (Barcelona and Helfrich 1986; Barcelona et al. 1994, 2005; Gibs and Imbrigiotta 1990; Kearn et al. 1994; Keely and Boateng 1987; Varljen et al. 2006). In this study, groundwater samples are collected using a hand-operated inertial lift pump (Waterra SS-10 Pump, 6 mm OD, stainless steel) to avoid degassing. Samples are taken via a

polytetrafluoroethylene (PTFE) riser tube (4 mm ID, 6 mm OD) at flow rate of 50 ml/min. Before sampling, the tube is purged using a peristaltic pump at flow rate 150–200 ml/min (Eijkelkamp, the Netherlands). The internal volume for each sampling port is <100 ml/m of tubing, which minimizes the volume of purge water that needs to be removed prior to sampling. Two to three volumes are replaced corresponding to the point of stabilisation of the water-quality indicators monitored in a Sheffield in-line flow cell (Waterra, UK).

In order to remove residual contamination, sampling materials are decontaminated between each sampling point by pumping through the whole sampling line (foot valve pump, PTFE tube and peristaltic pump) successively ethanol (one system volume equivalent to 100 ml) and deionised water (three system volumes; Keely and Boateng 1987; Parker and Ranney 2000, 2003).

Validation of system

The performance of the SMPS system under field conditions was evaluated at a former dry cleaning site in Switzerland (Fig. 3). The SMPS systems were installed in a well characterized part of the aquifer with high vertical

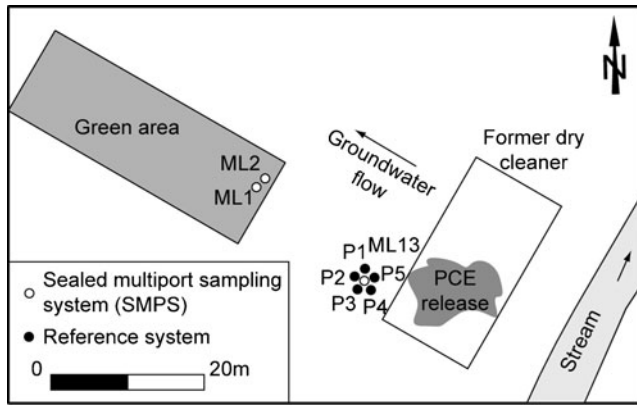


Fig. 3 Plan view of the study site, showing location of SMPS systems and reference systems. PCE is tetrachloroethene

geological and geochemical contrasts, which represents a challenge in obtaining representative groundwater samples. Release of tetrachloroethene (PCE) resulted in the development of a contaminant plume with PCE and degradation products. The geology consists of a sequence of unconsolidated Quaternary fluvio-glacial sediments overlying Tertiary fine sand (Molasse). The total thickness of the Quaternary deposits ranges from 2.5 to 25 m. The unconsolidated material consists of sandy gravel (5–25 m) with a high hydraulic conductivity (10^{-3} – 10^{-4} m/s) which is overlain by flood plain deposits consisting of clayey-silty sand rich in organic matter—about 2.5–5 m below ground surface (bgs)—with a low hydraulic conductivity (10^{-5} – 10^{-6} m/s). The site is bordered on the east by a river which is at the origin of the flood plain deposits unit. Groundwater flows from the river towards the west–northwest. The groundwater level is situated between 2 and 2.3 m bgs within the flood plain deposits. SMPS systems were installed using the methods described previously. Two types of tests were carried out: artificial tracer tests to evaluate if the sampling intervals are sufficiently isolated, and a comparison of the obtained concentration profiles with those obtained using a reference system.

Artificial tracer tests

The principle of the SMPS system is to separate the various monitoring zones by cement-bentonite seals. The main objective of the artificial tracer test is to prove that these seals ensure a sufficient isolation of the sampling intervals and no short cuts between the sampling intervals occur. For that purpose, fluorescent tracer tests were carried out using two different SMPS systems installed in the contaminant plume (Fig. 3). The two SMPS systems share the same design but the cement-bentonite seals were only emplaced in one of them (ML2, Fig. 4). The principle of these experiments was to inject tracer in a screen (injection screen) and to pump in screens situated below and above the injection screen. In each injection screen, 300 ml of tracer solution (5,000 $\mu\text{g/L}$) were injected with a syringe via a PTFE tube (4 mm ID, 6 mm OD) inserted inside the PVC

tube, followed by injection of 100 ml deionised water to flush out the tracer solution remaining in the tube. To avoid cross-contamination between the tests, two different tracers were used: Duasyn and sulforhodamine B. Additionally, two peristaltic pumps connected to PTFE tubes were used to take groundwater samples in the extraction screens at low flow rates (150–200 ml/min) equivalent to the purging conditions used for sampling in the SMPS system. Groundwater samples were collected during the experiment in both extraction screens until a total volume of 5–7 L was extracted. All samples were analysed in the CHYN laboratory (Neuchâtel, Switzerland) with a Perkin Elmer LS50B spectrofluorometer (Perkin Elmer, USA).

Comparison with reference system

To investigate if the SMPS systems provide reliable vertical concentration profiles, concentration data from the SMPS system were compared with those obtained from a reference system installed in proximity of the SMPS system (Fig. 5). The comparison was carried out close to the source zone where the highest concentrations were measured in previous sampling campaigns (Fig. 3). The reference multilevel system consists of a cluster of five piezometers (P1–P5) constructed with commercially available pre-packed screens and seals. The pre-packed screens consist of slotted PVC pipe of 0.75 m (AMS, USA) or 0.90 m (Geoprobe, USA) length surrounded by a sand layer that is held in place by a stainless steel mesh. The inner diameter of the tube is 19 mm (0.75 inches, in) and the outer diameter of the whole system is 36 mm (1.4 in). Immediately above the screen, a tube with a quick seal bentonite sleeve (AMS, USA) was attached followed by PVC tubes. The assembled pre-packed piezometers were installed by advancing 54 mm (2.125 in) OD by 38 mm (1.5 in) ID probe rods with a Geoprobe machine to the selected depths. The systems were lowered through the rod, attached to an expandable anchor point and the rods were retracted. After installation, the quick-seal bentonite sleeve expands preventing a vertical flow of groundwater towards the screened section. The SMPS system ML13 (Fig. 3) was designed with five sampling ports with screen lengths of 50 cm. The screens are separated by cement-bentonite seals of variable lengths such that the screens of the SMPS system (ML13-1–ML13-5) are at the same depth as those of the reference system (P1–P5). Samples were taken in both reference and multilevel systems following the sampling protocol described previously. Concentrations of chlorinated ethenes and redox sensitive species were compared. Dissolved oxygen, electrical conductivity, temperature and pH were measured in the in-line flow cell. Once these parameters were stable, groundwater aliquots for analysis of dissolved Fe(II), Mn(IV) and major anions and cations, as well as chlorinated hydrocarbons, were sampled. For cations and anions, 60 ml of groundwater was filtered through a 0.45- μm filter and collected separately in two 30-ml polypropylene bottles. Groundwater aliquots for cations were stabilized with 10 % (v/v) HNO_3 . Major anion and cation concentrations were determined with an ion chromatograph (Dionex DX-120) with a detection limit of

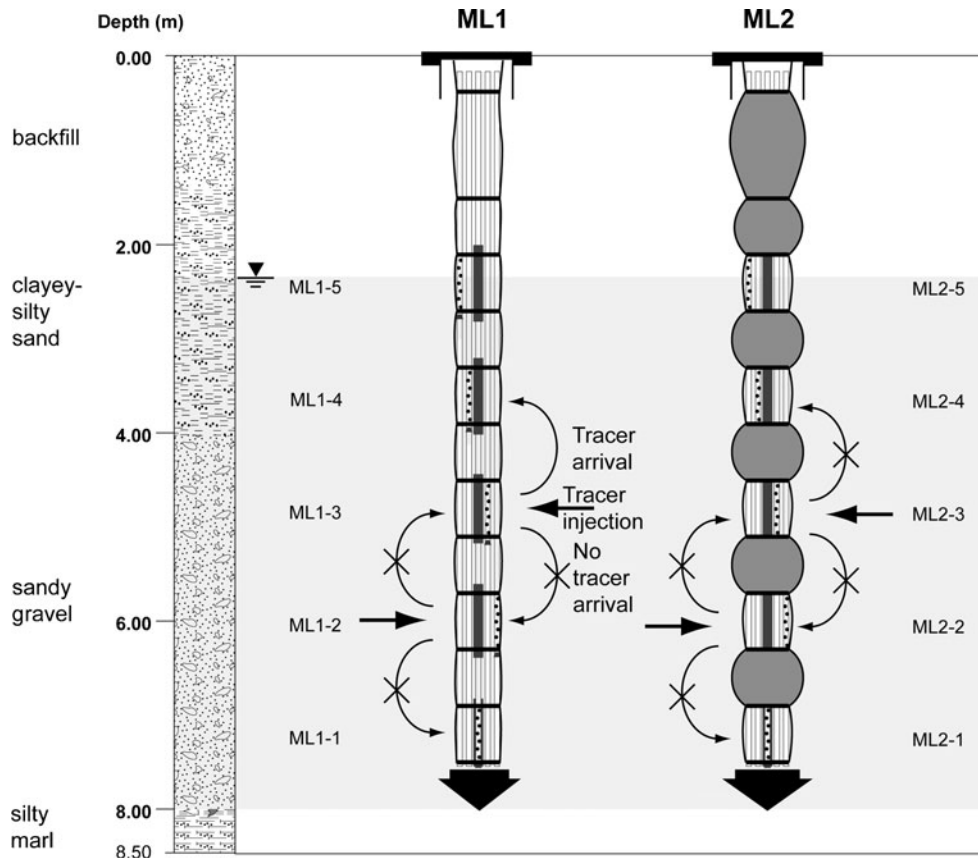


Fig. 4 Vertical cross section of the two SMPS systems used for artificial tracer tests. *On the left* is the geological cross section of the studied area. *ML1* is the SMPS system without cement-bentonite packer and *ML2* is the tubing-multilevel systems equipped with packers. The **bold arrows** show the tracer injections. The **curved arrows** show the possible circulations between the ports after tracer injection when sampling in the port above and below. Connections were observed between ports *ML1-3* and *ML1-4*, while no circulations were observed between other ports

0.1 mg/L and an uncertainty of $\pm 5\%$. For quantification of Fe(II) and Mn(II), 20 ml of groundwater were filtered and stabilized with 0.25 ml of 10% (v/v) HNO₃ in 20 ml vials. The amount of Fe(II) was measured colorimetrically following the phenanthroline method with a detection limit of 0.05 mg/L and an uncertainty of $\pm 5\%$. Mn(II) was determined following the formaldoxime (FAD) method (Goto et al. 1962) with a detection limit of 0.01 mg/L and an uncertainty of $\pm 3.5\%$. Groundwater samples for VOC analysis were collected in 40-ml glass vials that were completely filled without any air bubbles and sealed with Teflon-lined plastic caps. VOC concentrations were determined using a purge and trap (P&T) system (VSP 4000, IMT Innovative Messtechnik GmbH, Germany) coupled to a Varian CP-3800 gas chromatograph (Varian, USA) equipped with a plot fused silica capillary column (RT-QSPLOT, 30 m, 0.32 mm, 10 μ m, RESTEK) and a FID detector. For PCE, trichloroethene (TCE), cis-1,2-dichloroethene (cDCE) and vinyl chloride (VC), the detection limit is 0.5 μ g/L. Concentrations of ethene, ethane and methane were determined by headspace (HS) analysis using a Varian CP-3800 gas chromatograph (Varian, USA) equipped with plot capillary column (CARBOPLOT 15 m, 0.32 mm, 1.5 μ m,

Agilent) and a FID detector. For ethene, ethane and methane the detection limit is 2.5 μ g/L. The uncertainty of the analytical method is $\pm 9, 11, 10$ and 8% for PCE, TCE, cDCE and VC, and $\pm 12\%$ for ethane, ethane and methane.

Results and discussions

Artificial tracer tests

In the SMPS system without seals (ML1), tracers were injected at two depths in two separate experiments and samples taken in the intervals above and below the injection point (Fig. 4). After injection of tracer in ML1-2, no tracer was detected at both extraction screens ML1-1 and ML1-3. The tracer concentration at the end of the experiment was 143.4 μ g/L at the injection screen ML1-2 after pumping 100 ml. The injection and sampling ports are all situated in the sandy gravel part of the aquifer characterized by a high hydraulic conductivity. After injection of tracer in ML1-3, tracer was detected in the upper extraction screen ML1-4. After purging of only 100 ml, a concentration of 217 μ g/L was measured at ML1-4 which decreased subsequently. In contrast, at the lower screen, ML1-2, the tracer was not

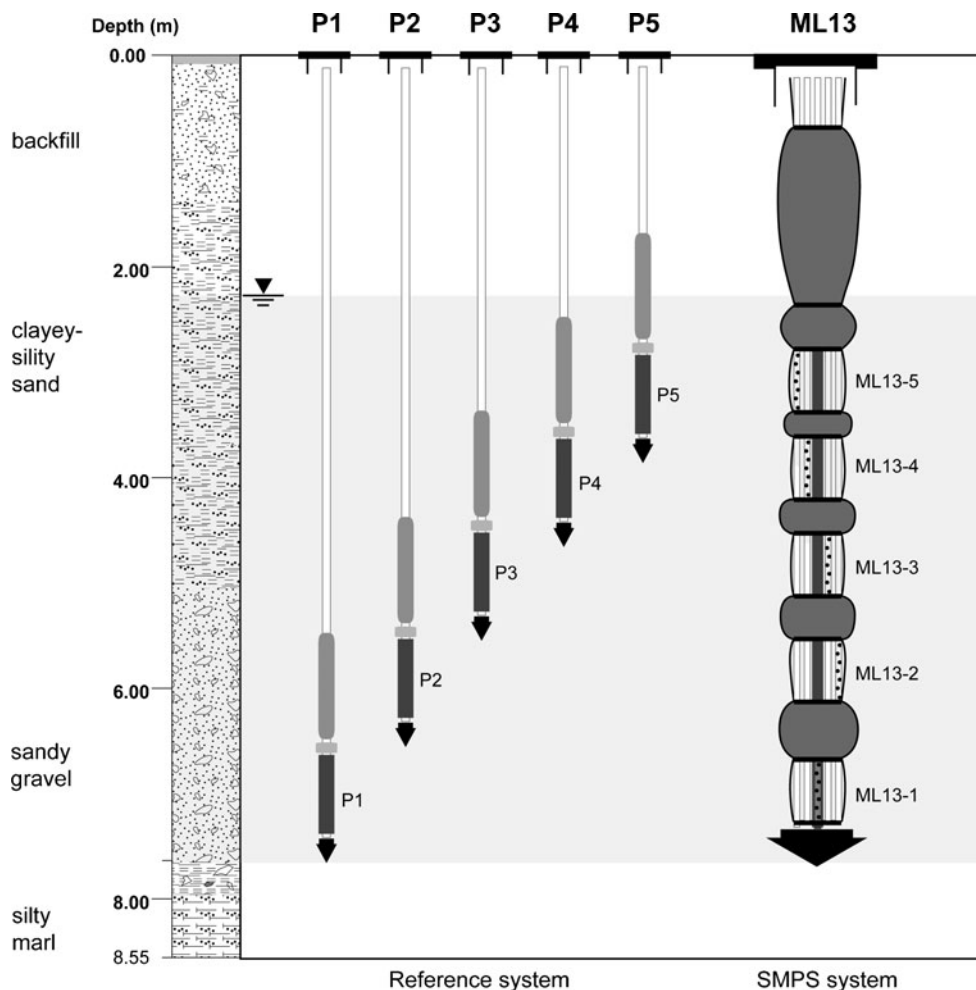


Fig. 5 Vertical cross section of the reference systems and SMPS system used for the validation tests comparing the concentrations profiles. *On the left* is the geological cross section of the studied area

detected. The lower extraction screen ML1-3 is likely situated in the sandy gravel part of the aquifer, while the upper extraction screen ML1-4 is located in the clayey silty sand part of the aquifer with a low hydraulic conductivity.

In the SMPS system with seals, tracers were injected in analogous depths (ML2-2 and ML2-3) as in the system without seals. In both cases, no tracer was detected in the sampling ports above and below the injection points during purging of 6 L. At the end of the experiment, tracer concentrations at the injection screens ML2-2 and ML2-3 were 94.8 and 124.3 $\mu\text{g/L}$, respectively, after pumping 100 ml.

The tests demonstrate that the multilevel system without seals is susceptible to cross-contamination. When pumping in the low-permeability horizon, water is pulled up from the high-permeability zone. The very rapid breakthrough of the tracer suggests that the tracer migrated along the axis of the SMPS system likely because the clayey material did not fully collapse around the system. In contrast, in the system with seals no cross-contamination occurred when sampling in the lower-hydraulic conductivity zone. These results

demonstrate that the cement-bentonite seals effectively separated the sampling intervals even in heterogeneous formations.

Comparison with reference system

Concentration profiles for the SMPS and reference system are illustrated in Fig. 6. Unfortunately, it was not possible to sample P5 and ML13-5 due to clogging. Strong gradients in contaminant concentrations were observed with both systems. Both systems showed a maximum PCE concentration at level 3 (4.85 m bgs), while TCE was also elevated at the level above (level 4). Concentrations of cDCE, VC, ethane and ethane showed the highest concentrations in the uppermost sampling point (3.95 m bgs). While the concentration patterns of chlorinated ethenes and degradation products agreed well between the systems, some deviations in actual concentrations occurred, especially for cDCE and ethane. The general trend of the redox parameters was similar for the two sampling systems as well, while the actual values deviated slightly between the two systems especially for dissolved oxygen and nitrate at level 3 (4.7 m bgs). The

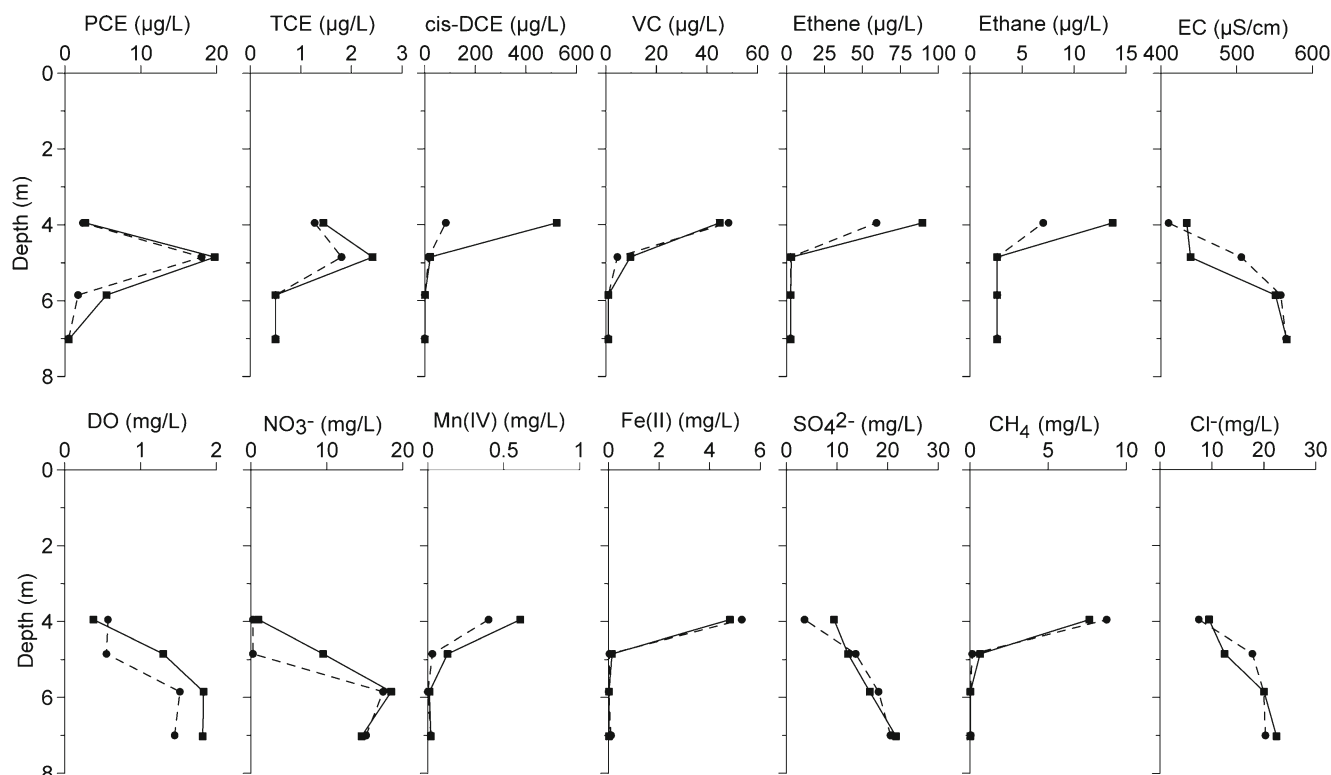


Fig. 6 Profiles of the SMPS system (dash line) and reference systems (solid line)

two systems were not installed exactly at the same location and the concentrations in the low-permeability zone may show considerable spatial variations due to small-scale geological heterogeneities. In addition, the screens do not have exactly the same length in the two systems.

Both systems clearly reveal that the upper part of the aquifer was under strongly reducing conditions (absence of oxygen, nitrate, sulphate and presence of Fe(II), Mn(II) and methane), while the lower part was under oxic conditions (presence of oxygen, nitrate and sulphate; absence of Fe(II), Mn(II) and methane). The redox conditions are consistent with the distribution of different chlorinated ethenes. In the upper part of the aquifer, reductive dechlorination occurs and cDCE was the dominant compound, while in the lower oxic part only PCE and traces of cDCE occurred. Hence, the low-permeability zone favoured reductive degradation of the PCE trapped in this zone. These results confirm that the SMPS system can provide detailed insight in the variability of contaminant distribution and geochemical conditions in aquifers even across zones with large permeability contrasts.

Conclusion

The results of this study demonstrate that plausible concentration profiles of individual chlorinated compounds and redox sensitive parameters can be obtained across

contrasting lithologies with a system installed using a direct-push method. The design of the system offers flexibility with respect to vertical spacing of sampling intervals. In addition, the construction ensures that the screens and seals are situated at precisely defined depths, which is sometimes not met with a conventional multilevel system when sand and bentonite pellets, respectively, are poured from the surface. Due to the low interval volume of the system, purging volumes are small and sampling is rapid. While results suggest that the system has a great potential for application in groundwater-quality monitoring, it has also some limitations. The sample volume is limited because of the small diameter of the tubes. However, the sampling volume is sufficient for classical analysis of chlorinated compounds and redox-related parameters. Furthermore, the installation depth is limited to 15–20 m because of the direct-push installation method and the system construction. While in this study a system with 46-mm OD diameter was used that requires a 83-mm OD diameter rod, the system can be adapted for 55-mm OD diameter rods. Smaller rods penetrate coarser deposits more easily and a greater depth can be reached. However when using a smaller diameter only 3–4 sampling intervals are possible instead of 5–6. Given the successful application of the SMPS system at a site with a large permeability contrast, the system should be suited for a wide range of hydrogeological conditions.

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References

- Anneser B, Einsiedl F, Meckenstock RU, Richters L, Wisotzky F, Griebler C (2008) High-resolution monitoring of biogeochemical gradients in a tar oil-contaminated aquifer. *Appl Geochem* 23:1715–1730
- Barcelona MJ, Helfrich JA (1986) Well construction and purging effects on ground-water samples. *Environ Sci Technol* 20:1179–1184
- Barcelona MJ, Wehrmann HA, Varljen MD (1994) Reproducible well-purging procedures and VOC stabilization criteria for groundwater sampling. *Ground Water* 32:12–22
- Barcelona MJ, Varljen MD, Puls RW, Kaminski D (2005) Ground water-purging and sampling methods: history vs. hysteria. *Groundwater Monit Rem* 25:52–62
- Charette MA, Allen MC (2006) Precision ground water sampling in coastal aquifers using a direct-push, shielded-screen well-point system. *Groundwater Monit Rem* 26:87–93
- Cherry JA, Gillham RW, Anderson EG, Johnson PE (1983) Migration of contaminants in groundwater at a landfill: a case-study. 2. Groundwater monitoring devices. *J Hydrol* 63:31–49
- Cunningham JA, Fadel ZJ (2007) Contaminant degradation in physically and chemically heterogeneous aquifers. *J Contam Hydrol* 94:293–304
- Delin GN, Landon MK (1996) Multiport well design for sampling of ground water at closely spaced vertical intervals. *Ground Water* 34:1098–1104
- Einarson MD (2006) Multilevel ground-water monitoring. In: Nielsen DM (ed) *Practical handbook of environmental site characterization and ground-water monitoring*, 2nd edn. CRC, Boca Raton, FL, pp 807–847
- Einarson MD, Cherry JA (2002) A new multilevel ground water monitoring system using multichannel tubing. *Groundwater Monit Rem* 22:52–65
- Einarson MD, Mackay DM, Bennett PJ (2010) Sampling transects for affordable, high-resolution plume characterization and monitoring. *Ground Water* 48:805–808
- Gibs J, Imbrigiotta TE (1990) Well-purging criteria for sampling purgeable organic-compounds. *Ground Water* 28:68–78
- Goto K, Komatsu T, Furukawa T (1962) Rapid colorimetric determination of manganese in waters containing iron: a modification of formaldoxime method. *Anal Chim Acta* 27:331
- Guilbeault MA, Parker BL, Cherry JA (2005) Mass and flux distributions from DNAPL zones in sandy aquifers. *Ground Water* 43:70–86
- Jones I, Lerner DN, Baines OP (1999) Multiport sock samplers: a low-cost technology for effective multilevel ground water sampling. *Groundwater Monit Rem* 19:134–142
- Kearl PM, Korte NE, Stites M, Baker J (1994) Field comparison of micropurging vs. traditional ground water sampling. *Groundwater Monit Rem* 14:183–190
- Keely JF, Boateng K (1987) Monitoring well installation, purging, and sampling techniques: part 1, conceptualizations. *Ground Water* 25:300–313
- Lerner DN, Teutsch G (1995) Recommendations for level-determined sampling in wells. *J Hydrol* 171:355–377
- Mackay DM, Freyberg DL, Roberts PV (1986) A natural gradient experiment on solute transport in a sand aquifer. 1. Approach and overview of plume movement. *Water Resour Res* 22:2017–2029
- Martin JB, Hartl KM, Corbett DR, Swarzenski PW, Cable JE (2003) A multi-level pore-water sampler for permeable sediments. *J Sediment Res* 73:128–132
- Mikkelsen PE (2002) Cement-bentonite grout backfill for borehole instruments. *Geotechnical Instrumentation News*. BiTech, Richmond, BC, Canada, pp 38–42
- Parker LV (1994) The effects of ground water sampling devices on water quality: a literature review. *Groundwater Monit Rem* 14:130–141
- Parker LV, Ranney TA (2000) Decontaminating materials used in ground water sampling devices: organic contaminants. *Groundwater Monit Rem* 20:56–68
- Parker LV, Ranney TA (2003) An environmentally friendly decontamination protocol for ground water sampling devices. *Groundwater Monit Rem* 23:84–91
- Reinhard M, Barker JF, Goodman NL (1984) Occurrence and distribution of organic chemicals in two landfill leachate plumes. *Environ Sci Technol* 18:953–961
- Schirmer M, Jones I, Teutsch G, Lerner DN (1995) Development and testing of multiport sock samplers for groundwater. *J Hydrol* 171:239–257
- Schirmer M, Durrant GC, Molson JW, Frind EO (2001) Influence of transient flow on contaminant biodegradation. *Ground Water* 39:276–282
- Schulmeister MK, Healey JM, Butler JJ, McCall GW (2004) Direct-push geochemical profiling for assessment of inorganic chemical heterogeneity in aquifers. *J Contam Hydrol* 69:215–232
- Topinkova B, Nesetril K, Datel J, Nol O, Hosl P (2007) Geochemical heterogeneity and isotope geochemistry of natural attenuation processes in a gasoline-contaminated aquifer at the Hnevice site, Czech Republic. *Hydrogeol J* 15:961–976
- Ucankus T, Unlu K (2008) The effect of aquifer heterogeneity on natural attenuation rate of BTEX. *Environ Geol* 54:759–776
- Varljen MD, Barcelona MJ, Obereiner J, Kaminski D (2006) Numerical simulations to assess the monitoring zone achieved during low-flow purging and sampling. *Groundwater Monit Rem* 26:44–52