Integration of geophysical, geochemical, and direct push methods for the detection of leachate plumes



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ABSTRACT

An integrated multidisciplinary aquifer characterization program was carried out around the St-Lambert-de-Lauzon landfill. The study aims to integrate multiple sources of data using geostatistical tools to better characterize the aquifer, delineate leachate plumes, and guide a study of the natural attenuation of the plumes. Five characterization methods were combined and took advantage of fully-screened wells: hydrogeological (direct push with CPT/SMR; hydraulic testing), geophysical (surface GPR; geophysical logging) and geochemical (fluid logging). Initial results define the spatial variability of materials and groundwater geochemistry, and indicate the likely extent of landfill leachate.

RÉSUMÉ

Un programme de caractérisation multidisciplinaire d'un aquifère a été réalisé autour du site d'enfouissement de St-Lambert-de-Lauzon. L'étude vise l'intégration de sources variées de données grâce à la géostatistique pour mieux caractériser l'aquifère, délimiter les panaches de lixiviat, et guider une étude sur l'atténuation naturelle du lixiviat. Cinq méthodes de caractérisation ont été combinées et on pris avantage de puits entièrement crépinés : hydrogéologiques (méthodes par enfoncement avec CPT/SMR; essais hydrauliques), géophysiques (géoradar de surface; diagraphies) et géochimique (profils du fluide). Les résultats initiaux révèlent la variabilité spatiale des matériaux et de la géochimie de l'eau souterraine, et indiquent l'étendue probable du lixiviat.

1 INTRODUCTION

Description of aquifer heterogeneity is an important challenge facing hydrogeological research (De Marsily et al. 2005). Aquifer heterogeneity is an important control on contaminant migration, and failure to adequately consider heterogeneity is a common cause of remediation failure. Yet, a capability gap has developed between the numerical simulators, which now can integrate dense information of aquifer heterogeneity, and the still insufficient data provided by conventional hydrogeological characterization methods. Conventional methods involve adding more boreholes as hydrogeological conditions or contamination get more complex. Such an approach is inefficient and generally unaffordable, thus more efficient approaches are needed.

Description of heterogeneity has to rely on more than "direct" hydrogeological data. "Indirect", but spatially continuous data are required to be used as proxy for hydrogeological parameters, especially hydraulic conductivity (K). Such proxy data could be geological, geophysical or geochemical. Ouellon et al. (2008a) present a study where often neglected borehole logs were used to define the spatial distribution of hydrofacies (materials with distinct K). Proportions of hydrofacies were used to estimate a heterogeneous and anisotropic 3D distribution of K. Rubin and Hubbard (2005) have also shown the potential for the emergent field of hydrogeophysics to characterize aquifer heterogeneity. Finally, geochemical tracers can provide independent data, which can complement hydraulic data, to fully constrain numerical model and thus rigorously calibrate



Figure 1. Multidisciplinary characterization and variable source geostatistical data integration approach

and validate these models to obtain a more realistic representation of groundwater flow with reliable predictive capabilities.

The objective of the study documented in this paper is to develop a methodology that integrates multiple-source of data using geostatistical tools to better characterize an aquifer, delineate leachate plumes emitted by a former landfill, and guide a study of the natural attenuation of the plumes. The project relies on a range of approaches providing continuous 1D, 2D or 3D data: direct push methods, full-screened wells, borehole geophysics, surface geophysics and geochemical profiling. Figure 1 shows the interrelation between project components. "Integration" of multidisciplinary team members and different source of data is a major challenge of the project.

2 STUDY AREA

2.1 Context of the St-Lambert Study

This paper documents the initial phase of an integrated multidisciplinary aquifer characterization program carried out in a 12 km² area of the subwatershed surrounding a former landfill. The former landfill is located in Saint-Lambert-de-Lauzon, 35 km south-east of Québec City (Figure 2). The former Saint-Lambert-de-Lauzon landfill was operated from 1974 to 1997. During those 24 years, 900 000 tonnes of waste from municipal, agricultural and industrial sources was buried (Régie Intermunicipale de gestion des déchets des Chutes-de-la-Chaudière 2006). The wastes were placed directly on a 10 m thick sandy unconfined aquifer overlying clayey silt and till units. As water percolates through decomposing waste, leachate is produced: this brings high concentrations of organic and inorganic contaminants to the water table, which mix with groundwater and forms a plume migrating with groundwater flow (Fetter 2001). Prior to the former St-Lambert site closure and its capping, leachate was detected in the surrounding creeks (Géoroche 1985). A modern sanitary landfill presently operates besides the former closed site. In this new site, waste is placed on basal liners and it is capped as landfilling progresses.

The contrast of the redox conditions between the leachate (reductive) and the aquifer (oxidizing under unconfined conditions) brings fast and important geochemical transformations, which contribute to its natural attenuation. Chemical, physical and biological reactions occurring within water and sediments help break down some contaminants found in leachate. Natural attenuation processes are dependent on the chemical and mineralogical composition of the aquifer and on the importance of the contamination source (Christensen et al. 1994). Leachate emission at the St-Lambert former landfill is solely managed by natural attenuation, without previous validation of its efficiency. This is a quite common practice for a large number of old landfill sites that did not use basal liners, and are thus likely to release contaminants to the environment, and represent a serious risk to groundwater (Fetter 2001).

To ensure rigorous environmental management of the St-Lambert former landfill, natural attenuation processes must be studied and understood. Such an evaluation is complex, as attenuation depends on many conditions: site dimension, physical and chemical heterogeneity, groundwater flow conditions, and types of chemicals present in leachate. Many analytical techniques must be combined in order to characterize these processes in time and in space (van Breukelen 2003). In this study, novel field methods are developed and are tested to characterize the aquifer and the leachate plume in the subwatershed of the landfill.



Figure 2. Location of the study area

2.2 Geology and Hydrogeology

The landfill is located in the Beaurivage River watershed (Figure 2). The study area was delimited based on the groundwater divide between the Chaudière and Beaurivage Rivers watersheds, and the hydrological network of surrounding creeks (Figure 3). The area is accessible through primary, secondary and private forestry roads. In this relatively flat area, natural streams as well as agricultural and forestry drainage networks influence groundwater flow. The landfill is surrounded by forested peatland and agricultural fields. Stratigraphy of the aquifer can be observed in a few gravel pits located in the area.



Figure 3. General context of the study area



Figure 4. Geological cross-section A-A' (Fig. 3)

Figure 4 presents a geological cross-section based on existing borehole logs (Gauthier et al. 1993) (location A-A' on figure 3). From top to bottom, the stratigraphy includes a 10 to 15 m thick unconfined aquifer composed of heterogeneous sand overlying silt, till and bedrock. Bedrock comprises Appalachian sandstones, friable schist, limestone and conglomerates, and its topography shows high variability (Landry 1983).

In the study area, late Quaternary marine, deltaic and fluvial sediments result from sea level changes following the last glaciation (Bolduc 2003). A silt unit sparsely covering the till was deposited at the maximum Champlain Sea, as the site was submerged. The delta, which deposited the unconfined aguifer sand, was formed during regression of the Champlain Sea at the Chaudière River outlet in the sea. At the time, the system was controlled by sea tides and currents, as well as by Chaudière River current and sediment supplies. This depositional environment is responsible for the heterogeneity of the aguifer material (Parent et al. 1999). Subsequently, the depositional environment of the study area was controlled by fluvial erosion and organic sedimentation.

Hydrologically, the study area is located in the basin of the Beaurivage River and the site is located very near the groundwater divide. The water table is close to the surface and above ground in certain areas. The waste piles at the landfill remodelled the topography of the area and groundwater flows from the highest elevation of the landfill to the regional study zone in a radial manner.

3 METHODS AND FIELD PROCEDURES

3.1 Characterisation Approach and Methods

The characterisation methodology used in our study integrates hydrogeological, geophysical and geochemical techniques to better identify the geological materials, determine their hydraulic properties and define the leachate plume emitted by the former landfill. Following a coarse to fine characterisation approach, the initial phase of the program focused on a regional hydrogeological and geochemical characterisation using extensive surface and downhole geophysical surveys. Five approaches were combined: 1) surface ground penetrating radar (GPR); 2) direct-push methods, including a) cone penetration tests (CPT) with soil moisture resistivity (SMR) that measured electrical permittivity and conductivity as well as usual mechanical parameters (tip stress, sleeve friction and pore pressure), b) soil sampling including the preservation of some samples in oxygen free environment to preserve the prevailing redox conditions of the sample, and c) installation of full-screened observation wells; 3) fluid logging in boreholes involving multilevel measurement of geochemical parameters (temperature, pH, Eh, conductivity, dissolved oxygen DO); 4) borehole geophysical logging, including water electrical conductivity, natural gamma, and magnetic susceptibility; and 5) high resolution hydraulic tests with borehole flowmeter profiles while pumping and between packers.

3.2 Field Procedures

Based on available data, a preliminary conceptual model was developed and 17 test sites were selected in the study area. Data available from private consultant reports and the physiographic disposition of the site were used to determine the location of GPR surveys. These surveys were carried out to optimise the installation of 17 CPT and wells (Figure 5). The sites were selected to be representative of geological facies and hydrofacies of the study area, as well as to detect the leachate emitted from the landfill. These surveys will guide further work on the detailed delineation and characterisation of leachate plumes.



Figure 5. Field survey location

First, GPR surveys were carried out on many secondary and private forestry roads in the study area. 20 km of GPR surveys were used to define the base of the aquifer, its stratigraphy and guide the positioning of observation wells. Using GPR sections directly in the field, CPT/SMR locations were selected in order to help and guide GPR data processing and CPT section interpretation. These operations used INRS' GeoTech 605D rig and the approach described by Fauveau et al. (2005). Figure 6 shows an example of the real-time data provided by CPT/SMR soundings in the field. Mechanical data identifies materials types, whereas lateral variability of electrical parameters can be an indicator of the potential presence of leachate where conductivity is high for a given material.



Figure 6. Vertically continuous CPT/SMR data available in real time in the field

At the same direct push location, 5-foot soil cores were taken adjacent to CPT soundings across the various types of soils shown by CPT data. Since cores are taken by hammering down the core taker, soil cores could also be collected beyond the total depth reached by CPT soundings that are strictly pushed down. A sub-sample was preserved for each core in oxygen free environment for further geochemical analysis.

Also based on the CPT/SMR data, a full-screened observation well was installed at each of the 17 survey sites. These wells generally span the entire thickness of the surficial sandy aquifer. Wells were installed by first hammering down a 7.6 cm (3 in OD) steel casing with a sacrificial point tip, and then inserting a conventional 5.1 cm (2 in ID) PVC screen over most of the saturated zone. Retrieving the steel casing allowed natural soil to come in direct contact with well screen by filling the small annular space between the PVC and steel casing. A short blind PVC casing was placed in the unsaturated zone and the top meter of casing and the protective tubing were sealed with bentonite to prevent preferential infiltration. In order to insure the direct comparison of CPT/SMR data with subsequent measurements made in the wells, they were installed directly in the location of CPT soundings.

After their installation, each well was systematically developed by swabbing using a Waterra pump and a development disk. The lower valve was moved in one metre increments across the entire screened interval. Slug tests were run prior to and after development to ensure its completeness and guarantee good contact between screens and soil.

Borehole geophysical logging was carried out in each well. This also included borehole flowmeter profiles while pumping, to evaluate the vertical distribution of *K*. Finally, fluid logging was carried out to measure geochemical parameters and obtain profiles of fluid properties (temperature, pH, redox potential, conductivity, dissolved oxygen) with a TROLL 9000 WQP-100 as well as with an YSI 556-MPS. Measurements were taken from the top of the screened well, lowering the probe at 1 or 2 m intervals all the way to the bottom of the screens. The probe was stabilize at each depth and measurements were recorded after all parameters had stabilised.

4 RESULTS

4.1 CPT Mechanical Response

Figure 7 shows the log-log scale of the CPT sleeve and tip stresses data in an Eslami-Fellenius profiling chart to correlate the mechanical response with the type of material (Fauveau 2006). Classes of materials in the chart can be adjusted based on soil cores taken at each of the 17 test sites. Once the material is identified and correlated to the mechanical response, the stratigraphy for each survey can be obtained (Figure 8).

Eslami-Fellenius Profiling Chart - St-Lambert CPT Soundings



Figure 7. Eslami-Fellenius profiling chart for the log of the tip stress (kPa) on the log of the sleeve stress (kPa)

Figures 7 and 8 illustrate the spatial variability and heterogeneity of the aquifer material in the study area is confirmed. Coarser sand is mostly found in the center of the study area, while finer sediments such as silt and clay dominate along the edges of the area. Material type having different permeability will influence groundwater flow and leachate migration. According to Christensen et al. (2001), most of the information on leachate plume originates from plumes in sandy aquifers.



Figure 8. Material distribution in the study area based on CPT (yellow is sand, green is silt and brown is clay)

4.2 GPR and CPT Electrical Response

At the studied site, GPR reflexions indicate contrasts in soil water content. Combination of GRP and CPT measurements can enhance their respective interpretation. Figure 9 shows the superposition of relative permittivity from a GPR survey and CPT soundings. Gloaguen et al. (2008) have developed a new geostatistical approach to the velocity analysis of sandy aquifer based on the CPT permittivity and conductivity data. The first consists in scaling the GPR radargram to maximize the correlation with the logs. Then, collocated cokriging of electrical permittivity and conductivity and the scaled radargram data is computed. The cokriged fields are converted in velocity field using classical low loss EM hypothesis and the time to depth conversion of the original radargram is then applied using the inferred velocity field.

Electrical measurements from CPT/SMR soundings were used to identify sediment characteristics such as porosity and water content. These measurements also provide global conductivity (material and water). Leachate contains a large amount of ions in solution and its presence in groundwater can be detected by higher conductivity values.

In the GPR section shown in Figure 9, attenuated portions of the radargram were found to be due to the presence of more saline groundwater as indicated first by the CPT/SMR lower resistivity and later proven by fluid conductivity obtained from borehole fluid logging. The combination of surface GPR and CPT/SMR data thus has the potential to image the variation in the distribution of both materials and the fluids they contain.



Figure 9. Relative permittivity of 2D GRP survey combined with CPT relative permittivity 1D profiles (Gloaguen et al. 2008). Depths of CPT profiles are converted into travel times using low-loss assumption.



Figure 10. Distribution of fluid logging geochemical parameters measured in wells: dissolved oxygen versus fluid conductivity (top) and pH (bottom)

4.3 Geochemical Profiles

Fluid logging was carried out across the long-screened sections of observation wells. Among the parameters measured, Figure 10 shows graphs of dissolved oxygen versus fluid conductivity and pH for measurements made in all of the 17 wells. Measurements span a wide range of all three parameters, and values are distributed between two groundwater geochemical end-members. Wells P02, P03 and P09 represent one end-member, with oxidizing, acidic and low conductivity groundwater. Wells P10, P06 and P08, among others, represent the other end-member, with anoxic, alkaline and high conductivity groundwater.

These two geochemical end-members respectively represent natural conditions and those related to leachate release in the aquifer. Inferred natural geochemical groundwater conditions in St-Lambert are somewhat peculiar. Very resistive waters (20-40 μ S/cm) are found at sites P02 and P03, which represents the lowest range of conductivities for natural water quoted in the literature. These natural groundwaters are also quite acidic.

Groundwaters related to the inferred presence of leachate have a composition depending on geochemical processes acting in landfills. Disposed waste in landfills undergoes a series of decomposition phases (Kjeldsen 2002). The composition of leachate is highly dependent on the degradation stage of the waste. Highly reductive leachate reaching groundwater undergoes a sequence of reactions characterized by different redox zones in groundwater, from the leachate source along the extent of the plume

Typically, methanogenic (highly reductive) and alkaline conditions are found close to the landfill and groundwater progressively becomes more oxidizing and more acidic away from the leachate source. This contrast in redox conditions between the leachate (reductive) and the aquifer (oxidant in unconfined condition) leads to fast and major geochemical transformations, which contribute to leachate natural attenuation. The chemical stability of many compounds depends on redox conditions. Therefore, the extent of natural attenuation processes is dependent in large part on the evolution of redox conditions as the leachate plume migrates through the aguifer (Christensen et al. 2001). It is thus critical to characterize the evolution of redox conditions in space and time through the aquifer to predict the potential efficiency of natural attenuation by chemical reactions. The fluid logging data will guide further characterization of the extent of the leachate plumes and of their internal geochemical conditions, especially redox conditions. Once these zones are drawn, targeted groundwater sampling and analyses for major and minor ions will be carried out to further evaluate the loss of contaminant mass as leachate a plume flows away from its source. These results will guide the assessment of the efficiency of natural attenuation for the environmental management of leachate release from the former St-Lambert landfill.

Combination of soil conductivity measured with the CPT/SMR soundings and fluid conductivity obtained from geochemical fluid logging can be used to do an initial global delineation of the presence of leachate in the St-Lambert aquifer. Figures 11 and 12 respectively show 3D perspectives of measurements from the CPT/SMR and fluid logging for all locations where CPT soundings were made or where boreholes were installed. These graphs show data in views from the south-west to the north-east. For reference, P11 is located right by the landfill.

Figure 11 shows that CPT profiles exhibit an important range of global conductivity that is caused both by the types of sediments and the conductivity of the fluid. Trends of high global conductivity are found to the southwest and north of the former landfill. Higher global conductivities are also generally found in depth, compare to near-surface. Figure 12 shows that fluid conductivity also spans a large range (see also Fig. 10) and is quite variable across the study area. There is a generally good agreement between the spatial trend of high global and high fluid conductivity variations control the changes in global conductivity.

These trends in the general distribution of leachate in the study area are coherent with an initial map of the water table elevation (not shown), and the inferred trends in groundwater flow, as expected (Christensen 2001). The flow patterns are obviously controlled by the larger streams, but variation in total aquifer thickness related to the varying bedrock topography could also exert a certain control on groundwater flow and leachate migration through the study area.

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Figure 11. Global soil conductivity from CPT/SMR soundings (mS/m)



Figure 12. Fluid conductivity from fluid logging in boreholes (μ S/m)

5 CONCLUSIONS

An integrated aquifer characterization program was carried out around the St-Lambert-de-Lauzon landfill. The first phase focused on the subwatershed characterization using five field methods, including hydrogeological, geophysical and geochemical methods, to better identify geological materials, determine their hydraulic properties and define the extent of leachate emitted by the former landfill. Data show spatial variability of material properties and groundwater geochemistry.

The interpretation of the multilevel geochemical parameters, combined with CPT global conductivity data, thus provides a general definition of groundwater geochemical spatial variability, and indicates the likely extent of landfill leachate in the study area. Surface resistivity surveys, combined with CPT/SMR soundings, thus show a very good potential for delineating the extent and internal morphology of leachate plumes in the study area. Such surveys are planned in the upcoming detailed plume characterization phase of the study.

In the next field work phase, induced-polarisation and borehole GPR tomographies will be carried out to fully define the 3D morphology of the leachate plume and characterise its internal variability and geochemical conditions. Geostatistical methods will be used to integrate and interpret the multi-source data set thus obtained.

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