Hydrogeophysical characterization of an unconfined aquifer at the sub-watershed scale

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ABSTRACT
The goal of this study is to improve the understanding of an unconfined aquifer in terms of structure, geometry and composition at the scale of a sub-watershed, by integrating multiple geophysical and hydrogeological data in three dimensions. The site under study is a former unlined landfill located in the municipality of St-Lambert-de-Lauzon, Canada. In addition to the conventional hydrogeological data acquired on 25 wells (slug test, water conductivity, water levels, etc…), three types of geophysical surveys were done: surface 2D electrical tomography, surface ground penetrating radar (GPR) and cone penetration tests (CPT). The proposed integration method allows a better global understanding, makes the interpretation easier and helps developing a high-resolution numerical groundwater flow and transport model of the aquifer.

RÉSUMÉ
Le but de l’étude est d’améliorer la compréhension d’un aquifère non confiné en terme de structure, de géométrie et de composition en intégrant en trois dimensions plusieurs données géophysiques et hydrogéologiques. Le site de l’étude se trouve aux alentours d’un ancien site sanitaire situé à Saint-Lambert-de-Lauzon au Canada. En plus des données hydrogéologiques conventionnelles acquises sur 25 puits (slug test, conductivité de l’eau, niveau de l’eau, etc…), trois méthodes géophysiques ont été utilisées : l’imagerie électrique 2D de surface, des levés de géoradar et des essais de pénétration au cône. La méthode d’intégration en 3D permet une meilleure vision globale, facilite l’interprétation et permet de développer un modèle numérique d’écoulement et de transport de plus haute résolution.

1 INTRODUCTION

The shallow subsurface of the earth is an extremely important geological zone as it yields much of our water resources, supports our agriculture and ecosystems, and influences our climate. Unfortunately, this zone also serves as the repository for most of our municipal, industrial, and governmental wastes and contaminants, intentional or otherwise. Safe and effective management of our natural resources is a major societal challenge. Contaminants associated with industrial, agricultural, and defense activities in developed countries, the increasing use of chemical pollutants resulting from the technological development of countries with evolving market economies, the increasing need to develop sustainable water resources for growing populations, and the threat of climate change and anthropogenic effects on ecosystem all contribute to the urgency associated with improving our understanding of the shallow subsurface. Many agencies and councils have recently described the pressing need to more fully develop tools and approaches that can be used to characterize, monitor, and investigate hydrogeological parameters and processes in the shallow subsurface at relevant spatial scales and in a minimally invasive manner (e.g., the National Research Council, 2000; U.S. Department of Energy, 2000; U.S. Global Change Research Program, 2001, National Plan on Regional Groundwater Management in Quebec). However, it is now well accepted that conventional groundwater characterization techniques fail in defining the spatial heterogeneity of the hydrogeological parameters at the appropriate scale and that this heterogeneity is the main driver of groundwater contaminant transport (de Marsily, 2005). In petroleum and mining industries and more recently in groundwater studies, the use of continuous indirect data (such as geophysical data) has proved to be very efficient to constrain the spatial modeling of the heterogeneity of the parameters of interest measured at few sparse locations (Goovaert, 1998). Following this approach, this paper presents a part of a non conventional characterization program of an unconfined aquifer located in a former landfill integrating indirect and hydrogeological data for groundwater flow and contaminant transport modeling. The studied site covers a 12km^2 area located in Saint-Lambert-de-Lauzon, 35km southeast of Québec City (Figure 1). In addition, a proper environmental management of St-Lambert landfill requires the understanding of the phenomenon of the natural attenuation and of the path of the potential leachate plume. Because the plume attenuation and way path depend on multiple elements such as physical and chemical heterogeneities, groundwater flow conditions and the variety of chemicals present, a high resolution characterization program is required in order to appropriately numerically represent the aquifer conditions (Paradis et al., 2009). To assess the appropriate resolution, many direct and indirect data were combined in a geostatistical framework. The dataset consists in high resolution Digital Earth Model (DEM), multi-level slug test, flowmeter, multi-level geochemical sampling, core, CPTu/SMR soundings, surface GPR and electrical imaging and electrical and GPR tomographies (Tremblay et al., 2009). First, the study area is presented. Then, the data acquisition and the data itself are described. Finally, the data fusion is presented.

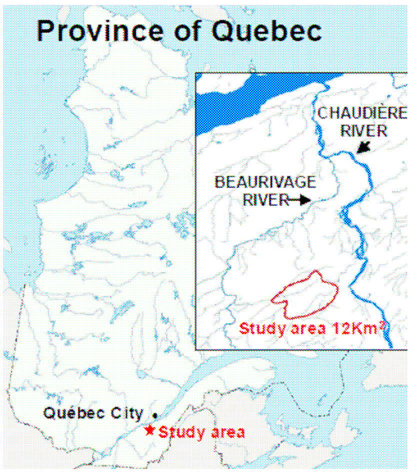

Figure 1 Location map of the study area (from Tremblay et al., 2008)

2 STUDY SITE

The study area is 4 km EW by 3 km NS, located in the municipality of Saint-Lambert-de-Lauzon, 20 km South of Québec city (Figure 1). The study zone is in the Beaurivage River watershed. The hydrological boundary delimitation is based on the groundwater divide line between the Chaudière River watershed on the East, the Beaurivage River watershed on the West and on the hydrological physiology of the surrounding creeks. The topography is relatively flat and natural streams influence the groundwater flow. Primary and secondary roads as well as forestry roads makes the site easily accessible. A landfill owned by the Régie intermunicipale de gestion des déchets des Chutes-de-la-Chaudière is located in the middle of the study area (Figure 2). It has been exploited from 1974 to 1997 and has received waste from municipal, agricultural and industrial sources (Régie Intermunicipale de gestion des déchets des Chutes-de-la-Chaudière, 2006). In 24 years, 900 000 tons of waste were buried in the old landfill of Saint-Lambert-de-Lauzon. The wastes were buried directly in the 10m thick sandy unconfined aquifer overlying impermeable unit of clayey silt and till. Because of this situation, leachate is produced as water percolates through the waste in decomposition and it reaches the leveling water table. The contamination is mixed with the groundwater and flows in the direction of the groundwater pathway (Fetter 2001). Leachate was detected in the surrounding creeks before the site closure and previous to capping the old site (Géoroche 1985). The contamination is naturally attenuated (Tremblay et al., 2008) due to the fast and important geochemical transformations between the leachate (reductive) and the aquifer (oxidant in unconfined condition). The only way the leachate is managed on the St-Lambert site is by natural attenuation. However, this method has not been validated and this its efficiently efficiency still must be confirmed.

As previously mentioned, the characterization program includes a large amount of three-dimensional data from very different types. A three-dimensional integration approach needs to be taken at the start of the project in order to handle the huge database. Because of its accessibility, its a friendly user interface and its 3D capacities, gocad was chosen to integrate the data. In addition, a geostatistical approach (Routin et al., 2008) was used to estimate the aquifer surfaces boundaries such as 1) the surface topography, 2) the top of the aquifer and 3) the bottom of the aquifer delimited by an uneven rock.

Figure 2 General context of the study area

2.1 Geology and hydrogeology

The unconfined aquifer is hosted in a 10 to 15 meter thick heterogeneous sand layer. The uneven bedrock is overlaid by a sequence of quaternary sediments (till and sill) that plays the role of an aquitard for the unconfined aquifer. The rock is principally of sandstones, friable schist, limestone and conglomerates (Landry 1983). Many glaciations contributed to the erosion of this bedrock to its actual elevation. The sea level fluctuations following the last glaciation are responsible for the deposition of marine, deltaic and fluvial sediments at the studied site (Bolduc 2003). At the maximum level of Champlain Sea, a silt unit was deposited as the sea submerged the site. This unit is present sparsely over the till. The sand, which formed the unconfined aquifer, is a relic of a delta deposited during the regression of the Champlain Sea at the Chaudière River outlet. Champlain Sea tides and currents as well as the Chaudière River current and sediment supplies controlled the system at that time. The

heterogeneity of the aquifer materiel is due to the complex depositional environment (Parent et al 1999). Since then, the depositional environment was controlled by fluvial erosion and organic sedimentation.
The studied zone is located near the groundwater divide in the groundwater basin of the Beaurivage River. The water table is close to the surface and can be above the ground in certain area. The groundwater flows from the highest elevation of the landfill to the regional study zone in a radial manner. It is to be noticed that the landfill is located at the highest topographic point (Figure 2).

3 DATA ACQUISITION AND ANALYSIS

3.1 Surface ground penetrating radar (GPR)

Ground penetrating radar is a method that images the subsurface using radio frequency electromagnetic pulses. A transmitting antenna sends an electromagnetic short pulse in the ground. When the pulse hits an interface between materials having different electrical properties a part of the transmitted energy is reflected toward the surface and eventually, a receiving antenna records a part of the returning signal. An acquisition unit records the measurements, named traces, at every transmitter-receiver locations usually moved along straight profiles.
About 20km of GPR survey was done on the studied site. Surveyed profiles are shown in green lines in Figure 2. The 100Mhz antenna was retained because they offered the best ratio between resolution and investigation depth.

The data processing consisted in 1) dewow filtering, 2) static correction, 3) manual gain (the gain function was adapted to each profile in order to get the best image as decided by the user, but the gain was kept constant for all traces belonging to a same profile), 4) bandpass filtering, 5) background removal. The GPR profiles done in this region portray the lithology and the sediment deposition mode. When the rock is not too deep or when the attenuation is low, it is possible to follow a clear reflector representing the interface between the aquifer and the bedrock (Figure 3). This reflector is usually not very regular. Also, zones showing strong attenuation are relevant in this case because they may coincide with region where leachate is found. Tests on the water from those areas confirmed this hypothesis. The groundwater with leachate is more electrically conductive, so the GPR signal is more easily dissipated in the ground.
Figure 3 shows two typical profiles. Depending on the conductivity of the first layer, the profiles show varying resolution of the structure within the sandy aquifer. Indeed, the deposition mode is clearly visible in Figure 3B. However, the interface between the aquifer and the bedrock below appears clearly in almost all the profiles, as show the blue circles. This information is crucial, as it will constrain the aquifer bottom surface interpolation to complement the few well measurements. Also visible in Figure 3B is the upwelling of the rock at the right end of the profile. In addition, two zones seem to be more conductive (GPR signal attenuation is higher) between 120-200 m and 290-390 m. Unfortunately, the GPR data do not allow to say if this attenuation is due to a subsurface strong reflectivity interface or if it is due to the internal change of the material or fluid electrical properties. CPT and electrical imaging will be deployed in this specific area to answer this question. Besides, *ArcGIS* has been used to map each GPR lines. The mapped lines allow their sampling in the same number of points than the number of traces that constitute each profile. Thus, it is possible to associate a position to each single trace of the GPR. After all these manipulations, each profile is imported into *Gocad* where the topographic correction is performed.

A)
B)

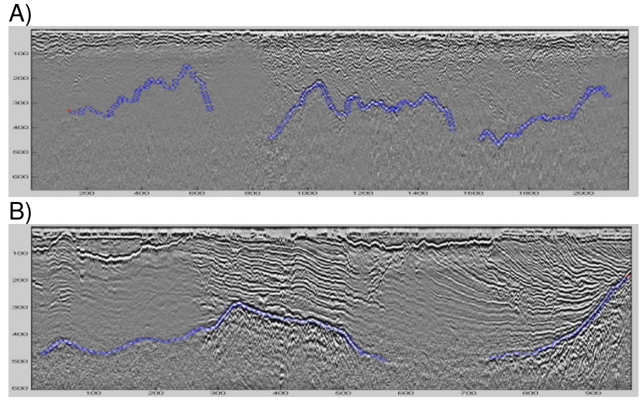

Figure 3 Comparison of two GPR profiles

3.2 Surface 2D electrical tomography

Electrical tomography is a geophysical technique that measures the near surface resistivity. The basic principle consists in applying a current between two electrodes hammered in the ground, while the difference of potential is measured between two other electrodes placed generally on the same line. The apparent electrical resistivity is then calculated for each combination of electrodes, resulting in a pseudo-section, which represent the distribution of the apparent resistivity in terms of pseudo-depth (Figure 5-A1). A numerical analysis called inversion has to be applied on the apparent resistivity in order to transform the pseudo-section in an image of the "true" ground resistivity (Figure 5-A2 et A3). The results of inversion depend on parameters chosen by the user, and special attention has to be taken with respect to this process.
A total of 2 km of resistivity profile was measured at our site, over five different profiles. The location of the resistivity profiles was driven by the GPR and CPT soundings and by the hydrogeological context. The inversion of the data has been carried out using *Res2dinv* by Geotomo Software. To respect the topography witch influences the inversion results, each electrical survey line was imported in *ArcGIS*. They were divided in the number of electrodes used on each profile. Then, it was possible to assign a position of the electrodes in three dimensions. Elevation values were imported in *Res2dinv* to run the inversion. The best results were obtained after five iterations with standard smoothing constraint. The default damping factor was kept because its variation did not sensibly improve the RMS error. Besides, many inversions

parameters were tested in order to validate the final image and to confirm that the resulting resistivity profile was mainly supported by the data and not by the inversion parameters. Figure 5A shows a resistivity profile measured directly at the output downstream of the landfill site. The processed resistivity image (Figure 5-A3) shows low resistivity anomalies associated to conductive water, which is typical for contaminated water. Figure 5B shows a resistivity profiles measured upstream of the landfill at the same location than the GPR profile shown in Figure 3B. The resistivity image shows low resistivity contrasts compared to Figure 5A, indicating the presence of highly resistive uncontaminated water. Also, it seems to confirm the low resistivity zone at 290-390 m location and suggest that the strong attenuation in the GPR profile in Figure 3B is due to change in the aquifer electrical property itself. Well installation permitted to measure the water conductivity and confirmed an increase in mobile ions in solution. Also, the resistive upwelling of the bedrock is visible at 400 m location.

3.3 Cone penetration tests including resistivity and permittivity logs (CPT)

Cone penetration test is a technique that measures mechanic and electrical properties which describes soils properties and stratigraphy as it is pushed or hammered in the ground. A cone tip is pushed into the ground at a controlled rate of 2 cm/s until it hits a compact layer or the rock. Others instruments are installed in the first rod, such as electrode rings and relative pressure indicator. The drill machine used is a *Geotech 605*, which is small and easy to move because its platform rose on tracks. The parameters measured in this study are tip resistance, fluid pressure, global resistivity, water content, friction and the dielectric constant. In coarse materials, pore pressure is low because pores are bigger. On the other hand, pore pressure is high for fine grain materials. Also, when tip resistance and friction on the rod is high, material is usually fine. In addition, the instrument allows the easy installation of wells. In this condition, well installation does not require back filling and screen wells were installed on the entire aquifer width. More than 30 CPT sounding were done at the site. It is to be noticed that the CPT location was decided after the results of the geophysical surveys. The analysis of the surface geophysical data permits to define zones with varying physical properties. Hence, CPT soundings were mainly done in area showing strong contrasts of physical properties. Figure 5 shows 16 CPT electrical soundings. This figure illustrates a clear increase in the electrical conductivity from well P14 (upstream from the landfill) to well P12 in the lower left part. This suggests the extend position of the leachate.

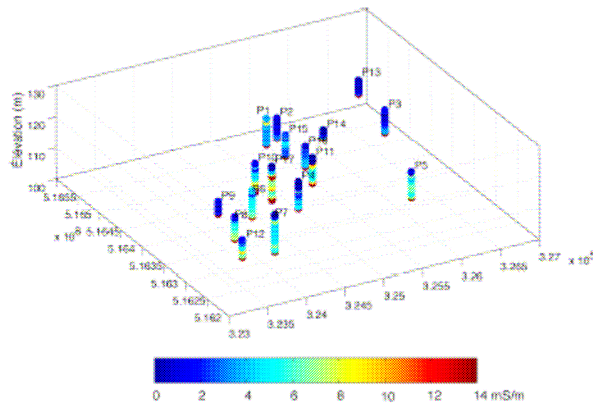

Figure 4 Distribution of CPT

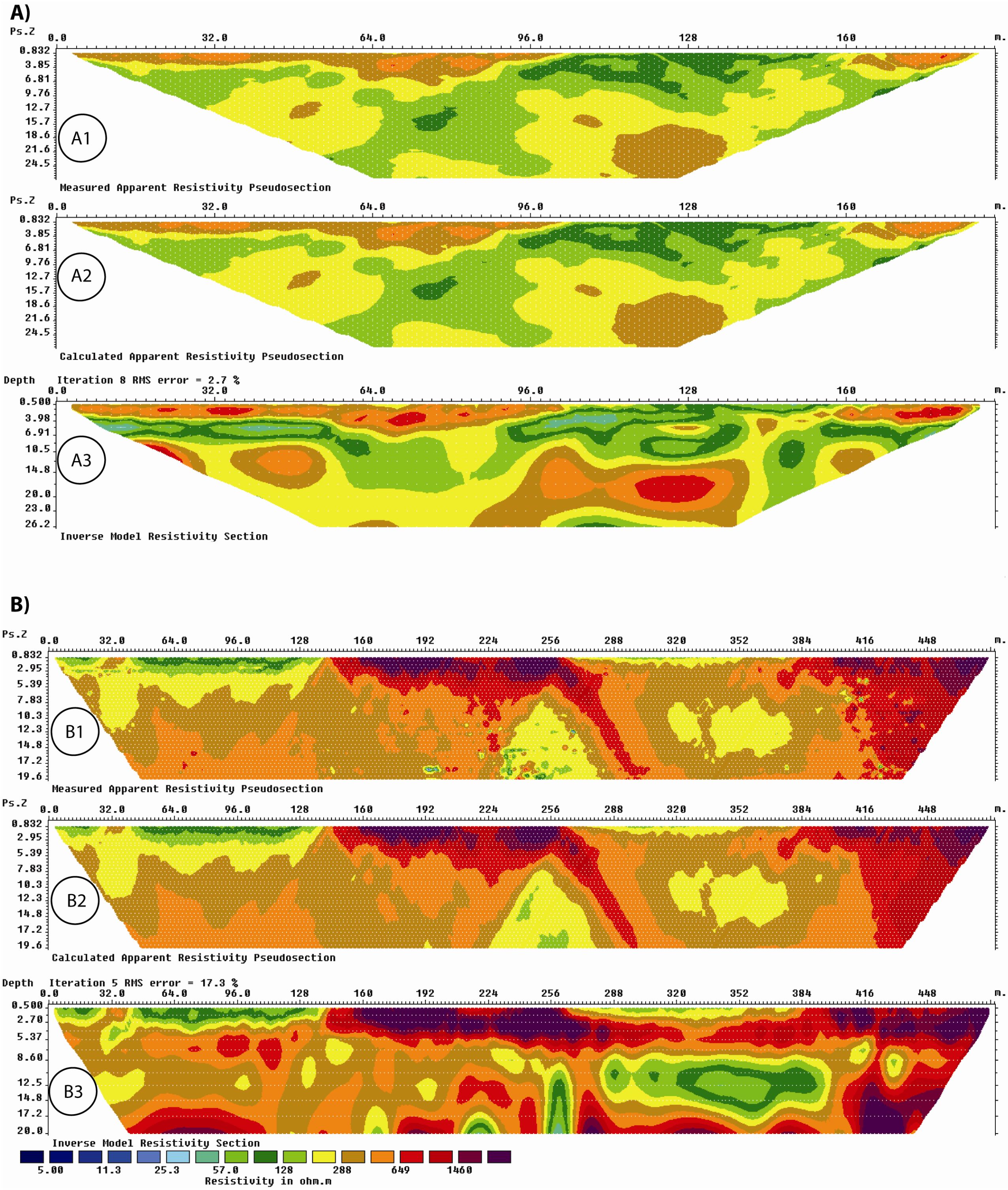

Figure 5. A) Electrical survey over the landfill. B) Electrical survey outside the landfill (same location as GPR profile in Figure 3B). A1: measured apparent resistivity; A2: computed apparent resistivity leading to A3; A3: inversed "true" resistivity. B1: measured apparent resistivity; B2: computed apparent resistivity leading to B3; B3: inversed “true” model.

4 INTERPOLATION OF AQUIFER BOUNDARIES

One of the first steps of groundwater flow modeling consists in interpolating the main interfaces of the aquifer. In the absence of indirect data, those interfaces are usually guessed or interpolated under careful user control. A geostatistical approach was devised from known techniques in the petroleum industry, where few wells are available but where extensive indirect measurements are (Chiles and Delfiner, 1999). The sandy aquifer being fairly homogeneous, three surfaces must be interpolated: the topography of the air-soil interface, the water level and the bottom of the aquifer.

Interpolation of topographic surface: First, the topography of the ground surface elevation was cokriged using measured high precision GPS elevations and a freely available Digital Elevation Model (DEM). As it is prevalent to georef the study site in today's application, DEM, which gives ground surface elevation on a regular grid, is an easily obtainable information that could be efficiently used with water-well measurement. The DEM allows constraining the interpolation the sparse measured GPS data at unsampled location. The chosen algorithm was the collocated cokriging as it proves to be numerically efficient and stable when the secondary data are oversampled (Comeau et al., 2009, Desbarats et al., 2002, Routin et al., 2008) and as it requires only the modeling of the secondary oversampled data variogram (Goovaerts, 1998).

Interpolation of water level surface: Over than a century ago, King (1899) recognized the close relationship between the water-table and the topography and suggested that topography should be used to constrain the water-table elevation. In order to fill the sparse water level data, many studies propose to use the topography as indirect data. The incorporation of indirect data can be accessed through deterministic or probabilistic ways. Hoeksema et al. (1989) appears to be the first who integrates the topography with measurement of groundwater levels in wells for geostatistical estimation of the potentiometric surface. Many authors (Deutsch and Journel, 1992; Goovaerts, 1997; Hoeksema et al., 1989) estimated the water-table surface with ordinary cokriging using water elevations as primary variable and ground surface elevations as secondary variable. These papers show the same outcome, i.e. the water-table cokriging estimation is more accurate than one made with ordinary kriging only if the secondary variable (ground surface elevation) is more densely sampled than the primary variable (groundwater level. Recent papers show implementation of the KED either by using linear function between water-table depth and DEM-derived quantity known as topographic index (Desbarats et al., 2002) or by incorporating linear model of coregionalization and Markov models (Boezio et al., 2006). Interpolation of the bottom of the aquifer surface: Similarly to the previous surfaces, the aquifer width was cockriged using depth to rock and GPR picked at the aquifer rock interface as shown in blue circles in Figure 3. But contrary to the two other surfaces, the indirect data are not available at all interpolation locations. Hence, the chosen algorithm was the full cokriging. This algorithm requires the variograms and cross-variogram to be calculated and modeled. When the cokriged aquifer width is computed, the interpolated widths are substracted from the topographic surface in order to obtaine the aquifer's bottom elevation.

5 3D DATA INTEGRATION

We want to recall here, that the main goal of this study is to integrate all the available information in order to produce the highest resolution numerical flow model possible. But, the large amount of data of different types makes it very difficult to interpret if taken separately. In addition, some 3D GIS allow generating meshgrid that are easily exportable to numerical flow softwares such as FEEFLOW. Hence, building a 3D model directly in 3D softwares will permit to save time and to have a better spatial control on adjacent information when modeling. The 3D integration in *Gocad* is a way to quickly visualize and interpret the data together. With all those parameters in 3D it is possible to follow important interfaces and link them to build surfaces. For example, each reflectors associated to the aquifer-rock interface on the GPR surveys is flagged so as the measured depth on CPT. Combination of both data into geostatistical analysis permits to compute high resolution roc topography surface. Also, 3D visualization allows following the 3D behavior of the very complex stratigraphy. It also permits to validate and compare the different data. For example, Figure 6 shows the GPR profile in Figure 3B and the resistivity profile in Figure 5B. The analysis allows confirming that the GPR attenuation is due to a decrease of the aquifer water resistivity. Also, the strong reflections near the surface are associated to low resistive pools that are typical of peat zones in the studied area. Figures 7 and 8 show different views of the available geophysical data. These data shows clearly a decrease in the electrical resistivity over the landfill area (red anomalies on resistivity profiles). Also, the GPR data shows good potential to identify the internal structure of the different lithofacies. In addition, CPT data (Figure 7 and 8) helps differentiating the lithological and the change in electrical groundwater conductivity, as mechanical data are not sensitive to changes in groundwater condition.

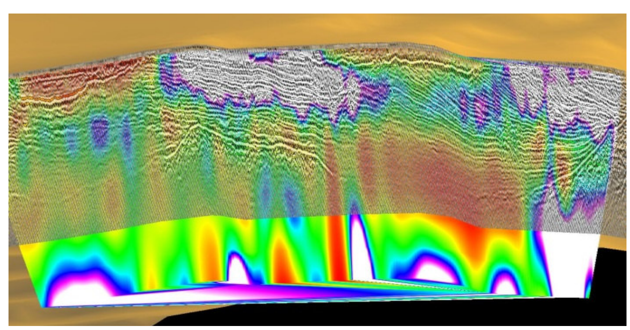

Figure 6 Juxtaposition of Figure 3B and figure 5B in *Gocad*

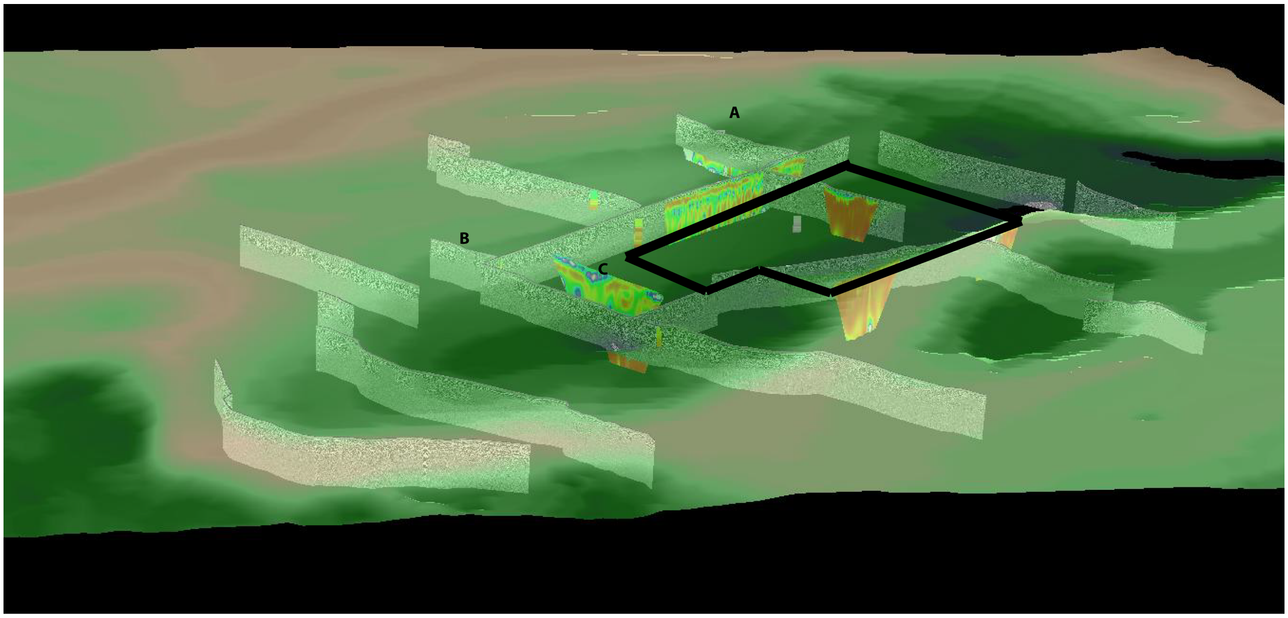

Figure 7. Aerial view of the study area showing the surface topography (green surface), the GPR profiles (in gray), some of the CPT logs and the electrical inversion results. The landfill limits are shown in black lines. A) GPR and electrical surveys shown in Figure 3B, 5B and 6. B) GPR profile shown in Figure 3A. C) Electrical inversion results shown in Figure 5A.

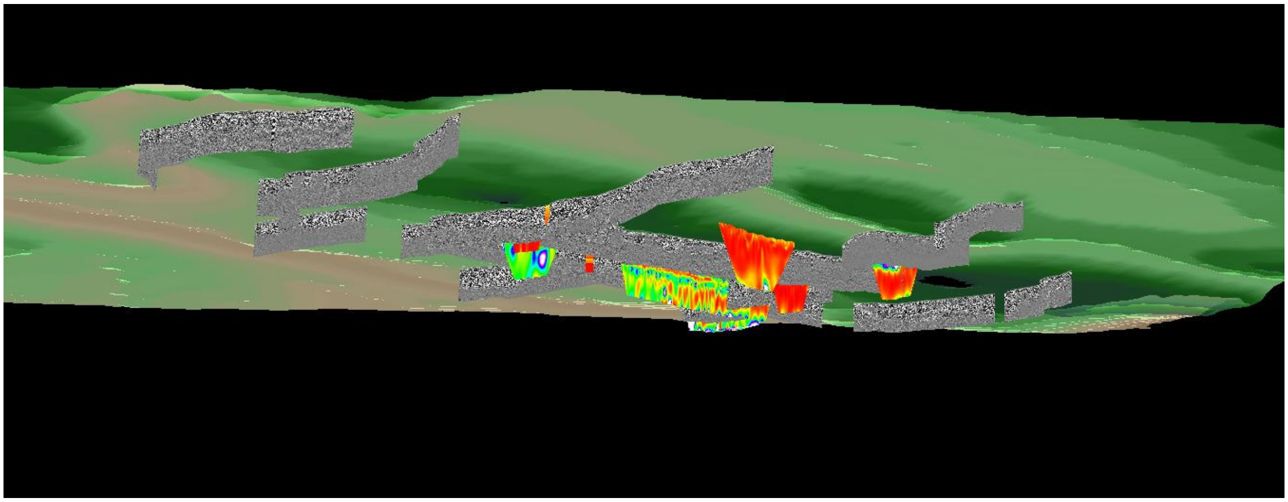

Figure 8. View from below showing the low resistive zone (red colours in electrical profiles) below the landfill site.

6 CONCLUSION

Each type of data supplies different type of complementary information to characterize the leachate plume and to identify the aquifer structural variability. Bringing all those information in the same medium enables a more effective comprehension of the aquifer structure and of the leachate spatial distribution. Data integration in three dimensions makes the interpretation more visual and global and help defining the spatial heterogeneity at high resolution. Actual result shows a lower resistivity near the landfill site, which increases as the distance from the landfill increases. GPR profiles permits delineating attenuation area, which correlates with a decrease in water resistivity. CPT logs help identifying the different reflectors in GPR profiles and the type of soil. Rock contact, aquifer surface and topography was adjusted and integrated in the 3D model. With the different data, it will be possible to join diverse visible structures between them like the leachate plume. All those data will make a complex system where the maximum of information will be gathered. The 3D model will allow an easier vision of the dispersion of leachate phenomena and help to develop the hydrogeologic model of the site.

7 AKNOWLEDGEMENT

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