Detecting a landfill leachate plume using a DUALEM-421 and a laterally constrained inversion model

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Abstract
Water-based solutions derived from the decomposition of solid waste products (leachates) pose a serious health risk to the community and environment when they enter the groundwater system. Traditionally, geotechnical investigations such as piezometer installation have been employed to determine the extent of the leachate emanating into water courses. To facilitate rapid data collection, geophysical techniques are increasingly being used to better discern the location and extent of existing leachate plumes. The principle aim of this study is to demonstrate how a DUALEM-421 can be used to detect a leachate plume associated with a series of decommissioned municipal landfill sites located in or adjacent to Astrolabe Park in Daceyville, Southern Sydney. Inversion of the apparent conductivity (σ_a) measured in the horizontal (HCP) and perpendicular co-planar arrays (PRP) of the DUALEM-421, characterised the Quaternary Aeolian sands and indicate the location and extent of a leachate plume and a shallow groundwater Table across the study area. A 1-D inversion algorithm with 2-D smoothness constraints is employed to invert the DUALEM-421 σ_a data, to predict true electrical conductivity (σ).Results compare favourably with the stratigraphy of the Tuggerah soil landscape unit, local hydrology, and results of a previous geophysical survey and water chemistry of the leachate plume.

Key Words
Leachate plume, electromagnetic (EM) induction, DUALEM-421, inversion.

Introduction
The primary problem of waste management is that virtually all solid refuse comprises a complex mixture and is usually subjected to indifferent storage conditions resulting in deterioration (Hamer 2003). Consequently, the production of solid waste poses a serious health risk to the community and environment particularly when it is disposed of inadequately (Soupios *et al.* 2007). To assess the impacts on public health and local ecology, we require knowledge of waste constituents and an understanding of the regional and local geological setting.
Traditional investigations, involving geotechnical methods such as borehole drilling and piezometer installation (Jankowski *et al.* 1997), have been employed to determine the extent of the leachate emanating into local groundwater systems. However, this type of approach is time consuming and labour intensive (Zume *et al.* 2006) and has led to the development of instruments and systems which collect data much more rapidly. In this regard geophysical techniques have been used to identify leachate plume including dc-resistivity; Benson *et al.* (1997), Abu-Zeid *et al.* (2004) and with EM induction Buselli *et al.* (1991).
The primary advantage of the non-invasive EM induction is the speed and accuracy with which lateral changes of the apparent soil electrical conductivity (σ_a) can be measured (as well as vertical variations, through extension of intercoil spacings). Many authors have successfully employed such a method to investigate the nature of landfills. This includes the use of an EM31 to determine lateral boundaries and composition of a landfill in Switzerland (Green *et al.* 1999), to map the Burwood coastal landfill in New Zealand (Nobes *et al.* 2000) and to characterize the largest waste disposal site on the island of Crete (Soupios *et al.* 2007). The principle aim of this study is to assess the effectiveness of a DUALEM-421 to identify the presence and location of a leachate plume originating from a decommissioned landfill.

Materials and methods
The study site is within highly permeable Quaternary Aeolian sands in Daceyville, Sydney. Prior to its use as a local sports field, it was used as a landfill throughout various stages of the 20th century. Of significance to the transect discussed in this study, is the landfill from the World War II era. This particular survey line was chosen as it has been the site of previous research by Jorstad (2006) who used the direct current (dc) resistivity method and cross-borehole tomography to characterise the leachate plume. The present

geophysical survey was conducted using a DUALEM-421, carried at 0.30m above the ground surface. The instrument has been designed in a way that enables σ_a to be collected at six depths of exploration (DOE) simultaneously; due to the multiple coil spacings (4, 2 and 1 m) and two orientations (i.e. HCP - horizontal co-planar and PRP – perpendicular arrays). The DUALEM-421 σ_a data is inverted to estimate the true electrical conductivity (σ) using a smooth inversion technique (Monteiro Santos *et al.* 2009). The method allows the construction of a global image of the subsurface distribution of σ that can be useful in the interpretation of routine survey σ_a data. Additionally we compare the σ values achieved against the known stratigraphy of the Tuggerah soil landscape (Lavitt *et al.* 1997) unit, local hydrology of Astrolabe Park, and the results of previous geophysical research of the leachate plume. The results are also interpreted using historical water chemistry data.

Previous studies at the site have included the collection of water chemistry data. These can be used to validate the results achieved using the EM method. Using Archie's law; $\sigma_b = \sigma_w Ø^m$ and known electrical conductivity (EC) values of both contaminated and uncontaminated water at the site, previously determined porosity (Ø of 0.36 and the cementation factor (m) for the formation of 1.51 (Kelly, 1994) it is possible to determine the value of bulk conductivity (σ_b) of the formation. Using averaged values of EC for the leachate plume and uncontaminated sands it was possible to determine that σ_b should be in the vacinity of 32 mS/m and 3 mS/m respectively for the inverted DUALEM-421 σ data.

Figure 1a. shows the results achieved by Jorstad (2006) using the dc-resistivity method along a small (160 m) transect within the area known to have been used as a municipal waste site during World War II. This was performed through the installation of 64 steel electrodes spaced at 2.5 m intervals in a Wenner array. The electrodes were connected to the ABEM SAS4000 resistance metre and linked to a LUND ES 464 electrode controller. Bulk electrical conductivity is shown in milliseimens per meter (mS/m). The area thought to be contaminated with the leachate plume has a σ value of 36.4 mS/m. Conversely, the area below the plume has a much lower value of < 4 mS/m, this is thought to be the uncontaminated water Table associated with the clean sands. Results of cross-borehole tomography also performed by Jorstad (2006) are shown in Figure 1b. Values obtained for the sands containing the leachate plume are >60 mS/m. The area below the plume, in the clean sands, have σ values of < 4 mS/m. The two methods produce slightly different spatial distribution of σ despite being in the same location. Figure 1b appears to show a plume that diffuses out in the vertical plane, whereas Figure 1a illustrates a plume that is very much restricted to within the top 5 m below ground surface level and changes abruptly below this. This is to be expected given the first method involves the surface insertion of probes whilst the second involves additional data that is collected from probes inserted at depth.

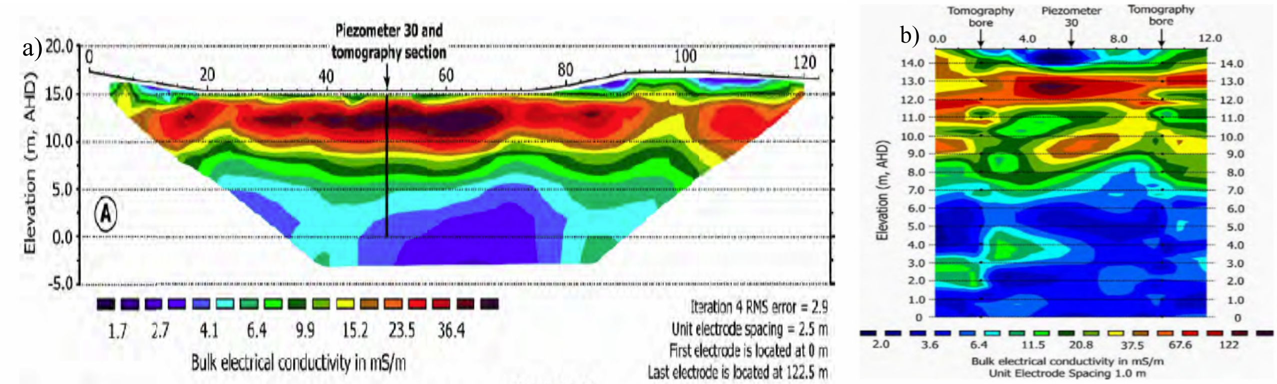

Figure 1. Spatial distribution of true electrical conductivity (σ - mS/m) estimated using an (a) ABEM SAS4000 resistance metre linked with LUND ES 464 electrode controller and (b) Conductivity section produced using cross-borehole tomography (after Jorstad 2006).

Results

Electromagnetic induction

Figure 2a-c show the spatial distribution of σ_a measured by the DUALEM-421. At a Northing of less than 6244125, two peaks in σ_a lie within 25 m of each other. Another pair is evident at 6244125 and 6244200. These peaks fall within the WWII landfill area. In addition, this is where the remodeled landscape is lowest along. The same pattern is repeated a short distance further to the north, between 6244225 and 6244275. The peaks in σ_a delineate the swale of the remodeled mid-1970's landfill landscape. In addition, measured

1mHcon and 2mHcon σ_a are generally larger than the equivalent Pcon σ_a. Given the shallower measurements are larger along transect 2, this suggests the true conductivity (σ) is larger in the near-surface than in the subsoil. A 2-dimensional model of σ obtained by inversion of the DUALEM-421 σ_a has been created (Figure 2d). The results along this transect and between the Northings of 6244125 and 6244175, compare favourably with Figure 1a and b. In particular the values of σ are comparable. As discussed for the DC-resistivity method above, the contaminated sands had σ values of >35 mS/m and the uncontaminated sands had σ values of <4 mS/m. Figure 2d shows the spatial distribution of σ, with clear delineation and location of the leachate plume. Values of σ in the leachate plume are >30 mS/m. In addition, the uncontaminated groundwater has σ values of <15 mS/m. these results are equivalent to those obtained with the dc-resitivity and bore-hole tomography methods.

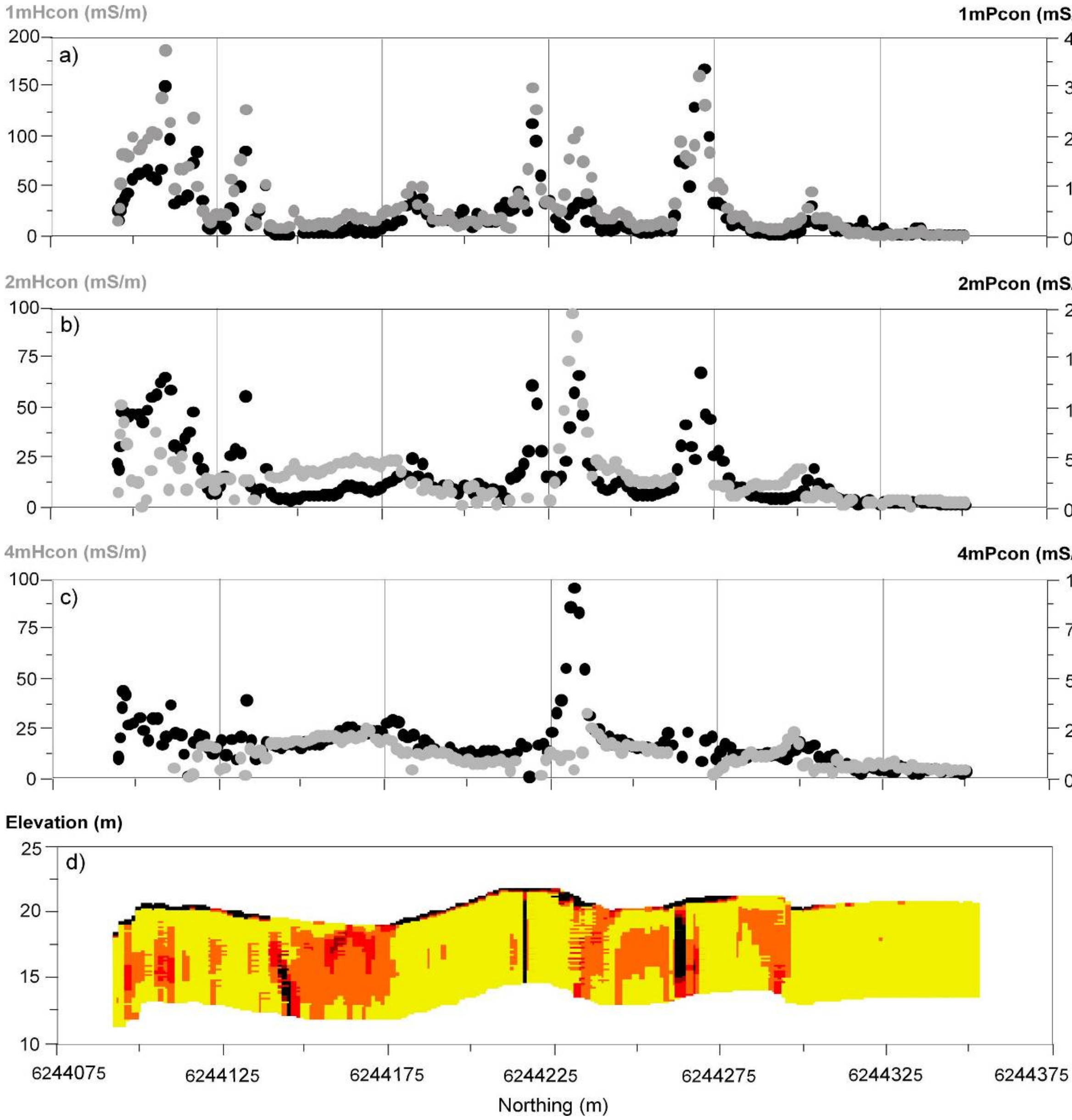

Figure 2. Spatial distribution of apparent soil electrical conductivity (σ_a - mS/m) along transect 2 of DUALEM in horizontal coplanar (HCP) and perpendicular coplanar (PCP) modes of operation and spacing of (a) 1 m; (b) 2 m; (c) 4 m; and, (d) true electrical conductivity (σ - mS/m) estimated using a 1-D inversion algorithm with 2-D smoothness constraints using apparent soil electrical conductivity (σ_a - mS/m) in the horizontal coplanar (HCP) and perpendicular coplanar (PCP) of a DUALEM-421.

Conclusion

A DUALEM-421 was employed to perform a reconnaissance survey and to collect apparent conductivity (σ_a) along six parallel transects on the western edge of two decomissioned landfills within the Daceyville area, with the aim of characterising the pedological, geological and hydrological features present at the site. With respect to the measured σ_a it is concluded that the DUALEM 1mHcon and 1mPcon as well as the

2mHcon and 2mPcon provide information which assist in inferring the likely location of a leachate plume and conductive municipal wastes within 0.5-5 m of the surface of the Astrolabe Park landfill. The inferences are made based on larger Hcon σ_a as compared to the Pcon measurements of equivalent coil spacing, and usually between two peaks in σ_a readings. Conversely, the 2mHcon, 4mHcon and 4mPcon σ_a provide us with information which can be used to infer the location and extent of a local groundwater Table at a depth of 6 m-7 m. The development of a cross-sectional model of σ was made possible through the use of the DUALEM-421 σ_a and a 1-D inversion algorithm with 2-D smoothness constraints (Monteiro Santos *et al.* 2009). The cross-sections confirmed the likely location of near-surface leachate plumes and shallow local groundwater tables. The results in terms of σ, are favourable with calculations of σ_b, derived from Archie's law. Accordingly results are comparable to inverted resistivity data collected by Jorstad (2006) who previously applied dc-resisitivity electrical methods and bore-hole tomography along a small portion of our study transect. Specifically, the estimated value of σ of the highly permeable but uncontaminated groundwater associated with Quaternary Aeolian sand that characterizes the Tuggerah soil landscape is small (i.e. <15 mS/m) and compares favourably with estimated σ achieved by inversion of dc-resistivity and cross-borehole tomography data (i.e. <15 mS/m). Conversely, it is calculated the leachate plume has intermediate (30-45 mS/m) to intermediate-large (45-60 mS/m) σ, which are equivalent to the σ estimated using dc-resisitivity (>23.5 mS/m) and cross-bore hole tomography (>37.5 mS/m).

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