2014

Geophysical Investigation of the Clay Cap at a Closed Landfill in Southwestern Ontario, Canada

Janet Hart
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Geophysical Investigation of the Clay Cap at a Closed Landfill in Southwestern Ontario, Canada

By

Janet Hart

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Earth and Environmental Sciences
in Partial Fulfillment of the Requirements for
the Degree of Master of Science
at the University of Windsor

Windsor, Ontario, Canada
2013
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Geophysical Investigation of the Clay Cap at a Closed Landfill in Southwestern Ontario, Canada

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November 28, 2013
DECLARATION OF ORIGINALITY

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ABSTRACT
At a closed mixed waste landfill in southwestern Ontario, concerns have been expressed about rainfall infiltration, possibly resulting from a non-contiguous landfill cap, and the potential for leachate leakage at the southern edge of the landfill. This study examines the application of geophysical methods to investigate the contiguity of the landfill cap and to assess for leachate leakage outside the landfill.

DC resistivity profiles were measured using an ABEM Terrameter. Analysis indicated that the cap thickness ranged from 0-3 meters and was not consistent, likely allowing the infiltration of precipitation into the refuse mound. The DualEM 2S/4S was used to map apparent conductivity in and near the problematic area, with values ranging between 2-570 mS/m. Higher conductivity values occurred in the northwestern and central area, while linear areas of midrange values extended from within the landfill to outside the landfill, suggesting leachate leakage.
ACKNOWLEDGEMENTS

This project could not have been completed without the assistance and expert advice from a number of individuals. Foremost, I would like to express my sincere gratitude to my supervisor Dr. Maria Cioppa and co-supervisor Dr. Jianwen Yang for their patience, motivation, constant support and expert advice to successfully complete my studies. I would also like to thank my external committee member Dr. Edwin Tam (Department of Civil and Environmental Engineering) and my internal committee member Dr. Joel Gagnon (Department of Earth and Environmental Sciences). Thank you to both Mr. S. Joshi and Mr. J. Hoyle for their exceptional support and assistance during my field work as well as Mr. Beiraghdar and Mr. Glendenning for all their knowledge and patience. Also thank you to Mr. Reiser and Dan Van Horn from EWSWA for giving me permission to work on the site and providing me with important information about the landfill. I would also like to thank Mrs. Horne for her help and sense of humor in helping me complete all the necessary requirements for the master’s program. Finally, I would like to thank my husband and children for their unconditional love and support throughout my education. This project was funded by an NSERC Discovery Grant to MTC.
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LIST OF ABBREVIATIONS

σ_a = Apparent conductivity (mS/m)
ω = Angular frequency (Hz)
μ_0 = Permeability of free space
s = Intercoil spacing (m)
H_p = Primary field
H_s = Secondary field
ρ_a = Apparent resistivity (Ω*m)
ΔV = Change in voltage (Volts)
I = Current (Ampere)
R = Resistance (Ohms)
G = Geometric factor dependent on electrode arrangement
CHAPTER I

AN INTRODUCTION TO WASTE DISPOSAL AT LANDFILLS, LEACHATE AND GEOPHYSICAL METHODS
1.0 INTRODUCTION

Population and industrial growth are major contributing factors in the ever increasing amount of waste produced worldwide, and landfills are still the most common method of solid waste disposal (Scott et al., 2005; El-Fadel et al., 1997). Worldwide, up to 95% of solid waste is deposited in landfills (EPA, 2012, Scott et al., 2005; Gendebien et al., 1992; Bingemer and Crutzen, 1987; Cossu, 1989). Although landfills are the most economical means of waste disposal (El-Fadel et al., 1997; Carra and Cossu, 1990; Rushbrook, 1988; Thompson and Zandi, 1975), they have not always been well managed (Scott et al., 2005; Stanton and Schrader 2000; Cossu, 1989). As there were often no restrictions upon the type of waste dumped in landfills in the past, industrial, household and sometimes toxic wastes were often mixed together in the same landfill, with no clear record of exactly what was disposed of in the landfill (Scott et al., 2005; Stanton and Schrader, 2000). There have been instances where serious environmental pollution has been caused by landfills, including pollution of air and groundwater by hazardous emissions emitted from the landfill biodegradation (Scott et al., 2005; Schmoll, 2006; Christensen et al., 1989).

However, greater public awareness and the need for additional environmental precautions due to changes in the amount and type of waste being generated have resulted in significant modification of landfills in recent years (Schmoll, 2006; Scott et al., 2005). One of the earliest changes was the development of the sanitary landfills by the United States in the 1930s. In these landfill, the refuse was deposited in layers, compacted, and then covered daily by soil to alleviate concerns over health issues that might occur from having the waste exposed (Scott et al., 2005). Most countries, including Canada, the United States and Australia, have implemented strict governmental regulations regarding the use, design and monitoring of modern landfills in order to avoid negative socioeconomic and environmental impacts (Scott et al., 2005).
A major source of ground water pollution is the liquid generated within landfills, known as leachate, which is derived from liquids that acquire various contaminants as they percolate through the landfill waste (Schmoll, 2006; Scott et al., 2005; Christensen, 2000). There are two main approaches to designing landfills in order to prevent contamination of groundwater resources from landfill leachate (Allen, 2001). The first is attenuation, originally known as dilute and disperse which takes advantage of natural processes, e.g. filtration, biodegradation and dilution/dispersion to reduce the concentration of the contaminants (Gray et al., 1974). The dilute and disperse principle of Gray et al. (1974), relied on natural low permeability and attenuation through a natural geologic barrier (e.g. clays). Thus the leachate is allowed to flow outside the landfill into the surrounding soil and bedrock in order to attenuate the leachate contaminants.

Modern attenuation is based on dilute and disperse model but with some modifications. The main difference between modern attenuation and the older dilute and disperse approach is that modern attenuation requires 1) the presence of a natural attenuation barrier to attenuate the leachate, 2) ongoing monitoring and 3) active management; whereas the original dilute and disperse approach did not require the attenuation layer and relied on passive dilution and dispersion processes within the subsurface (Schmoll, 2006). The attenuation approach’s active management component involves ongoing monitoring of down gradient ground water quality near the landfill until the landfill reaches a “stabilized state”. Such a state occurs when emissions from a closed landfill are reduced to the point where monitoring and treatment are not necessary (Christensen 2000; Christensen, 1994). Christensen estimated the process of reaching a stabilized state will normally take several decades but may last hundreds of years, depending on site conditions. Although it was eventually determined that dispersion and dilution alone may not protect groundwater, recent studies support the modern attenuation approach that requires an attenuation barrier to be present. However, not all sites are suitable for the attenuation method (Schmoll et al., 2005; Christensen, 2000; Batchelder et al., 1998; Christensen et al., 1994; Williams, 1999).
In the 1980s, both the dilute and disperse and attenuation approaches were replaced by the containment strategy. The main purpose of containment is to minimize leachate production by enclosing the waste in order to prevent the infiltration of precipitation or surface runoff into the landfill and to stop the migration of leachate outside the landfill (Scott et al., 2005). This strategy resulted in the development of engineered landfills in the 1990s (Figure 1), which normally include an impermeable underlying liner and overlying cap, together with collection and treatment systems for liquid and gaseous emissions (Schmoll, 2006; Scott et al., 2005).

The liners and cap(s) can be composed of high density polyethylene (geomembrane), clay or a composite of both clay and geomembrane (Schmoll, 2006; Scott et al., 2005). Most modern landfill caps and liners are composite liners (Cossu, 1995; Seymour, 1992). The liners’ main purpose is to prevent the movement of polluted water (leachate) through the sides and bottom of the waste cell into the surrounding soil or groundwater (Scott et al., 2005). The landfill cap is designed to isolate solid waste from the surrounding environment and minimize the percolation of water from the surface through the waste in order to inhibit the generation of leachate and consequently groundwater pollution. Post-closure landfill capping is especially important at unlined landfills (Depountis, 2009; Daniel, 1994).

Although containment is the method most widely used today, little is known about the long term stability and function of the liner materials as most have only been in use since the 1990s and some degradation can be expected (Allen, 2001). It has been noted that stress, cold conditions, failure of seams, damage from objects under the liner, heavy equipment and even poor installation can all cause cracking of the liner material and may lead to its eventual failure (Rowe, 2002; Averesch, 1995; Surmann et al., 1995; Thomas et al., 1995; Thomas and Kolbasuk, 1995;
Rollin et al., 1991). It has also been noted that some contaminants can diffuse through the liners (Rowe, 1994; Potter and Yong, 1993). Similarly, the cap is also subject to degradation from a number of causes including erosion, cracking from freeze thaw cycles, settlement and damage due to burrowing animals. As an added means of protection, a soil/vegetative layer is placed on top of the cap to reduce degradation of the cap, maximize evapotranspiration. The vegetative layer is also important to aesthetics of the landfill (Misgav, 2001). Additional monitoring and research is required to evaluate the long term function of these caps and liners (Scott et al., 2005).

The potential for eventual failure of the liners used to isolate landfill refuse leads back to the problem of leachate production and migration of contaminants outside the landfill (Rowe, 2002). Thus, despite the effective improvements in landfill construction, there are still many environmental concerns and the landfills must be carefully monitored (Rowe, 2002; Kjeldsen et al., 2002).

Landfill monitoring has traditionally relied on direct sampling techniques, such as water samples from wells in and around the landfill and solid sampling from boreholes into the landfill. Not only are these techniques expensive, but they also only provide point source information. It is often necessary to extrapolate between points to interpret the information, a practice that could lead to incorrect or incomplete understanding of the site (Zume et al., 2006; Loke, 1999; Benson, 1998). In contrast, non-invasive geophysical methods provide a fast, effective way to obtain detailed, but sometimes ambiguous, information about landfill sites (Soupios et al., 2007; Saltas et al., 2005; Orlando and Marchesi 2001; Loke, 1999; Greenet al., 1999; Lanz et al., 1994; Beres and Haeni 1991; Davis and Annan 1989). Successful geophysical studies have delineated landfill boundaries, defined cell boundaries within a landfill, assisted in determining refuse extent/thickness, and found evidence for the migration of leachate outside landfill borders (De Iaco et al., 2003; Aristodemou, 2000; Bernstone 2000, El-Fadel, 1997; Carpenter 1991). Some of
the geophysical methods used include seismic refraction tomography, gravity, ground-penetrating radar, electrical resistivity imaging, induced polarization, and frequency-domain, time-domain and very-low frequency (VLF) electromagnetism. These methods are discussed in detail in many papers (Orlando and Marchesi, 2001; Bernstone, 2000; Atekwana et al., 2000; Loke, 1999; Reynolds; 1998; Sharma; 1997; Lanz et al., 1994; Ulrych et al., 1994; Carpenter 1991; Telford et al., 1990).

DC resistivity and EM-methods have proven particularly successful for the evaluation of mixed waste landfills (Bavusi et al., 2006; Binley and Kemna, 2005; Loke; 1999; Fenning and Williams, 1997). DC resistivity and electromagnetic (EM) surveys are used for similar purposes, to assess the flow of electrical current in the subsurface; however, the measurements are made in different ways. Subsurface resistivity is a function of the soil/rock type, porosity and conductivity of the fluids that fill pore spaces. Conductivity is the reciprocal of resistivity and is therefore also dependent of the same subsurface parameters. Both conductivity and resistivity are governed by Ohm's Law which deals with the correlation between voltage and current in a conductor. The law states that across a conductor, the potential difference (voltage) is proportional to the current through it (Burger, 2006). Ohm’s Law is generally written as V=I/R, where V is the potential difference (volts), I is the electrical current (amps) and R is resistance (Ohms).

Both resistivity and conductivity methods can be used to map natural (and anthropogenic) variations in subsurface conductivity (Nielsen, 2005; Telfore et al., 1982; Benson et al., 1982). The success of these electrical methods at landfill sites is based on the highly conductive nature of landfill leachate when compared to the natural background values. Thus, variations in conductivity within and surrounding a landfill can provide insight into leachate flow pathways as well as the spread of contamination plumes outside the landfill (Soupios et al., 2005; Dawson et al., 2002; Stanton and Schrader 2001; Karlik and Kaya 2001; Bernstone et al., 2000; Aristodemou
Direct current (DC) resistivity surveying measures the electrical potential (in volts) of the ground near current-carrying electrodes and is thus dependent on the resistivity/conductivity of the underlying materials (Loke, 1999). In this technique, electrodes are in direct contact with the ground, an electrical DC current is introduced into the ground between two electrodes and the difference in potential voltage between two non-current-carrying electrodes is measured (Figure 2). The presence of good or poor electrical conductors can be detected by the distortion of normal potentials (EPA, 2001). There are two variations of DC resistivity surveys: 1) the resistivity sounding method, which is used to detect vertical changes in resistivity by increasing the electrode separation systematically (Sharma, 1997) and 2) the resistivity profiling method, which has four electrodes in a specific geometric formation and is useful for detecting lateral changes in resistivity. The detection of lateral (horizontal) variations in resistivity assists in delineating vertical features in the subsurface such as faults or landfill waste cell boundaries (Loke, 1999, Sharma, 1997).
Figure 1 Cross section of engineered landfill (including processes that affect leachate formation) (Vesilind, 2011).

Figure 2 Resistivity method with a Wenner array of four electrodes: two current electrodes ($c_1$ and $c_2$) and two potential electrodes ($p_1$ and $p_2$) (Murad, 2012)
In contrast, the EM conductivity technique does not rely on direct contact with the ground surface. In this technique, a primary EM wave is generated by a transmitter just above the ground’s surface and the properties of the response or secondary wave measured by a receiver are then compared to the primary wave. Such properties include variations in phase angle, amplitude and intensity. The comparison between the primary and the secondary waves allows detection of changes in subsurface conductivity, and the results can be used to infer the presence of good or poor subsurface conductors (DualEM User manual, 2006; McNeill, 1980). Conductivity surveys are generally less expensive and more rapid than DC resistivity profiling, due to the set-up time and equipment necessary for the DC method (Bevan, 1983).

Despite the success of geophysical methods, there are limitations. Geophysical methods rely on contrasts between physical properties (e.g. conductivity, density etc) within different materials in the subsurface. In cases where there are small or negligible differences in these properties, interpretation of results can be problematic. Modeling of geophysical data may also be hindered by the problem of "non-uniqueness" – that is, a number of different subsurface models could result in the same set of geophysical data and conversely, one set of geophysical data could be interpreted in many different ways. For this reason, it is necessary to have as detailed knowledge of the study area as possible. This knowledge can then be used to determine model constraints and may reduce the non-unique effect (Loke, 1999). Due to the subjective nature of geophysical surveys and their interpretation, it is often necessary to combine more than one technique (e.g. electric and seismic methods) in order to obtain accurate results from the data (Steeples, 2001).
1.2 Objectives of Research

Growth in population and housing density are increasingly requiring location of landfills in populated areas or alternatively, locations of housing developments near pre-existing landfills. These situations create more demand for proper monitoring and remediation of the landfill sites in order to avoid contamination of soil and ground water surrounding the landfill (Kaplan 1997; Misgav, 2001, Kumar, 2005). This study examines a mixed waste landfill located in Lakeshore, Ontario, which has been closed and monitored since 1997. This area has seen significant economic development in the last decade, and the landfill itself is under consideration for recreational green space. However, in a 2005 post closure monitoring report, concerns were expressed that infiltration of precipitation into the refuse, which stemmed from possible defects in the landfill cap, was occurring. Geophysical techniques, specifically the two electrical methods discussed above, were chosen to assess the landfill site because the techniques are widely used, have been proven successful in similar studies and provide a non invasive method to assess this landfill.

The first goal in this study was to test the feasibility of using geoelectrical methods to assess the continuity of the clay cap. Resistivity/conductivity surveys were used because clay has a low electrical resistivity which should allow differentiation of the clay from the underlying refuse. The second goal is to assess for leachate leakage outside the landfill. Due to the high conductivity/low resistivity of leachate electromagnetic methods can be used to trace preferential water pathways and detect anomalies due to increased leachate within the waste mass.
2.0 METHODS

In order to obtain the spatial and vertical distribution of geophysical properties within the area of interest, a sequence of 8 parallel (east to west) survey lines of approximately 760 m length were laid out for the study; six within Area C and two in the field south of the landfill (Figure 5). The ends of each line were geo-referenced using a GARMIN Model GPS60 GPS. The survey lines within the landfill were spaced 20 m apart, and were numbered sequentially from south to north. Line 1 is near the base of the refuse mound (near ground level), and the numbers increase to Line 6 near the top of the refuse mound. N-S lines were laid out at 60 m intervals across Lines 1-6, in order to form a grid pattern and to provide better spatial distribution of measurements.

The E-W lines outside the landfill were spaced 10 m apart, and were in a 20 m buffer zone between the landfill and the adjacent farmer’s field; however, the tenant farmer used this buffer zone for crop production (this will become important later on). Conductivity and resistivity surveys were conducted over the length of the E-W lines within the landfill; however resistivity profiling was not conducted on the lines outside the landfill, as permission could not be obtained from the tenant farmer to conduct detailed resistivity measurements in the field. Finally, a single resistivity survey line was completed over Area A1 within in the northern part of the landfill (Figure 3). This line was done as a reference and baseline for the cap depth as the cap is presumed to be intact in this area (Cascadden, pers comm., 2010). It was not possible to obtain a baseline for the local sediments outside of the landfill due to negative public perception of the landfill by the local residents.
There are a number of features that could interfere with the geophysical measurements. There was an iron fence between the landfill and the buffer zone / farmer’s field; this fence has recently been relocated further to the south. Several features from the leachate monitoring system are within close proximity to Line 1 of the survey as noted in Figure 6A. These include groundwater monitoring wells, leachate collection pipes, drainage ditches, storm water monitors, and landfill gas monitors. In addition, a gas pipeline is located just to the south of the landfill border in the eastern third of the area of interest. The conductivity survey lines outside the landfill pass directly over this pipeline.

2.1 Conductivity Surveys

A DualEM conductivity meter was used for the conductivity measurements, and each survey was run twice: once with a 2 m boom and once with a 4 m boom, thus providing four separate data sets for depths of exploration (DOEs) of 1.0, 2.2, 2.8 and 5.8 m.

The conductivity data was downloaded from the DualEM meter and converted to MS Excel files for use with ESRI’s ArcGIS software (Esri, 2010). The individual measurements with each data set were then georeferenced using the GPS data obtained from the GARMIN, and the final georeferenced data was imported into ArcGIS. Within ArGIS, the geostatistical tool Spatial Analyst was used to construct maps of the conductivity distribution for each DOE. Several different methods for contouring were used to investigate the distribution, and inverse distance weighting (IDW) was used to generate the final maps, as this took the distribution of the data points into account when extrapolating between the points. In their final form, the conductivity scales for all four of the maps are identical, in order to allow easier comparison.
2.2 Resistivity

Resistivity surveys were conducted using an ABEM TerraMeter (SAS 4000) with 40 stainless steel electrodes. The surveys used a Wenner-α array with 2 meter probe spacing, for a total single measurement sequence length of 80 m. In order to complete the full length of each line within Area C, it was necessary to conduct a run-along survey. Each line required 16-20 jumps, and a total time of approximately 20 hours. As mentioned previously, no resistivity measurements were done in the field south of the landfill. The reference North Line did not require a run-along survey, as the single 80 m length was considered sufficient to characterize the cap thickness. All models are missing data due to a probe malfunction, and although this does not affect the model evaluation process it may make data in this area slightly less reliable (Loke, Geotomo, pers. comm., 2013)

The resistivity data required two separate programs. The data was downloaded and imported into Erigraph, in order to convert the raw data to a .dat file that could then be imported into the RES2DINV analysis inversion software (Geotomo, 2006). RES2DINV was used both to produce an image of the vertical profile (pseudosection) of each line, as well as to calculate a subsurface model of the resistivity distribution. Within the program, the subsurface is divided into blocks, which are then assigned a resistivity value. These values are followed by upwards modelling, calculation and plotting of the surface resistivity (ρc) that would result from the given model values, which could then be compared to the measured apparent resistivity. The root mean square (RMS) error, which is the difference between the measured apparent resistivity values and the calculated apparent resistivity values, was then calculated. This process was then repeated until the RMS error reached either a minimum (ideally < 5%) or a constant value. The software manual for the RES2DINV program indicated that high RMS values were acceptable if the change in RMS values were minimal (ideally <3%).
2.3 Cap thickness determination

In order to determine the cap thickness, a two step process was followed. The initial work, and methodology, were developed using the North Line data and profile. As the cap was considered to be intact in this area (EWSWA, pers. comm., 2011), the values calculated for the upper four meters of the subsurface model were evaluated, and the estimated resistivity values for the cap were determined to be 18-50 Ω.m, which is consistent with the known values for clay. The subsurface model was then overlain by a 2m grid and the depth to which the predetermined cap values extended was recorded for each grid point. That depth was considered to be the base of the cap.

Using these values and procedure, this process was then repeated for the full length of each line within Area C; with a total of approximately 375 points evaluated per line. Where the surface apparent resistivity was either above or below these values, or where the determination of a specific depth was not possible due to high near surface variability, the data point was classified as either having high surface resistivity (> 50Ω.m), low surface resistivity (< 18 Ω.m), or unknown, respectively. The individual determinations of cap thickness were then georeferenced using the GPS data obtained from the GARMIN, and this georeferenced data was imported into ArcGIS. Within ArcGIS, the geostatistical tool Spatial Analyst and the IDW technique was used to construct a map of cap thickness for Area C. In order to assess whether conductivity could be used as a proxy for cap thickness, the conductivity map constructed for the DOE of 2.8 m was then compared to the map of cap thickness.
BIBLIOGRAPHY


DualEM manual (2006), DUALEM Inc. Milton, ON, Canada


CHAPTER II
GEOPHYSICAL INVESTIGATION OF A CLOSED MUNICIPAL LANDFILL IN SOUTHWESTERN ONTARIO
1.0 INTRODUCTION

Increasing amounts of waste are being produced due to rising population and industrial growth. Landfills are the most common means of disposal of solid waste (Al-Jarrah, 2006; Scott, 2005; Hamer, 2003; Lema, 1988). Despite the major changes in landfill technology that have occurred, including sanitary and engineered landfills, there remains significant concern over the effects of landfills on environmental safety and public health (Heaney, 2011; Hamer, 2003; Dolk, 1998). Engineered landfills are designed to enclose waste so as to prevent the infiltration of precipitation into the landfill waste, and reduce the leakage of contaminated fluids (leachate) outside the landfill (Traynham, 2012; Heaney, 2011; Scott, 2005). The production of leachate at landfill sites depends on several factors, including the type of waste, the age of the landfill, and the amount of evapotranspiration and precipitation; however, infiltration of precipitation is usually the major contributing factor to leachate production (Simon, 2004; Allen, 2001; Johannessen, 1999). It is therefore paramount that the landfill cap and liner, which enclose the waste, be intact and impermeable in order to avoid any contamination moving outside the landfill (Simon, 2004, Meegoda et al., 2002).

The application of geophysical methods has become an important tool in the assessment and characterization of landfills (e.g. Carpenter et al., 1990; Beres and Haeni 1991; Davis and Annan 1989; Green et al., 1999; Heitfeld and Heitfeld 1997; Lanz et al., 1994; Orlando and Marchesi 2001; Soupios et al., 2005a, b, c; Saltas et al., 2005). For example, gravity data has been used to delineate the bottom depth of landfill refuse (Silva et al., 2009; Roberts et al., 1990). Electrical resistivity tomography (ERT), electromagnetic terrain conductivity (EM)
surveys and seismic surveys have all been used to map the sediments outside the landfill and landfill boundaries (Soupious et al., 2007; Hutchinson and Barta, 2000; De Iaco et al., 2003; Nyquist, 2001). Ground penetrating radar (GPR) has been used successfully to delineate internal landfill structures (Splajt et al., 2003) as well as external leachate plumes (Pujari and Nanoti, 2006; Bernstone et al., 2000). Carpenter et al. (1990) successfully mapped internal landfill structures (cells), leachate mound elevation levels, and waste type and volume using DC resistivity surveys. Bernstone and Dahlin (1997) used magnetometry, electromagnetic and DC resistivity surveys to assess the location of waste metals at a closed landfill.

Electrical methods have been found to be particularly suitable for the assessment of landfill internal structure, leachate mound height and leachate migration pathways, as most landfill contaminants are relatively conductive in contrast to the surrounding areas (Belghazal, 2013; Suski et al., 2006; Soupious, 2005; Naudet et al., 2004; Guérin et al., 2004; Bernstone 2000). Therefore the electrical geophysical method DC resistivity and EM conductivity were selected to evaluate environmental problems at the study site, which is a closed landfill in southwestern Ontario. More specifically, the goals of this study were to determine the contiguity of the landfill cap and to assess for leachate leakage outside the southern landfill perimeter.

The landfill site is a mixed waste landfill containing household and light industrial waste (EWSWA, 2001). Leachate produced from these waste materials is expected to have high conductivity/low resistivity due to the amount of dissolved ions that are typically present. This should allow the assessment of leachate migration pathways both within the waste cells
and outside the landfill border, using EM methods. Likewise these methods would be ideal to assess the electrical properties of the clay cap. The clay cap material also should show high conductivity allowing differentiation of the cap from the wastes with dissimilar conductivity.

1.1 Site Description

The study site is a closed mixed waste landfill located in Lakeshore, Ontario. Since its closure in 1997, the post closure maintenance reports (EWSWA, 2005) have contained concerns about the potential for rapid infiltration of precipitation. Concerns were also expressed regarding possible leachate leakage in the southernmost area (Area C) of the landfill (Figure 2) (Cascadden, pers comm. 2010). An earlier geophysical study (Joshi, 2009) was done in 2009, and investigated portions of the study area. This smaller study did suggest both the possibility of leachate leakage into the field and inconsistencies in the thickness of the clay cap (Joshi, 2009). As the continuing, expanded investigation of these concerns, this study has been undertaken to assess the integrity of the clay cap across the whole of the area of concern, in addition to investigating the possible leakage of leachate into the nearby fields to the south.

Landfill 3 was established in 1970 and includes an older landfill that was in operation for several decades before that. The landfill has a total area of 100 ha with 88.5 ha containing waste. A land buffer of 30 meters is present on the south and west sides. In the area of concern, the thickness of the refuse is a maximum of 18.3m, while the nearby older landfill has a refuse thickness of ~3.5m. The refuse extends between 2 and 7m below the natural ground surface.
Figure 3 Landfill site map with wells with elevated leachate (Cl or B noted. (Black circles indicate wells with an elevated leachate mound, yellow circles are wells showing elevated Cl, green circles indicate elevated B, and black line in area A1 represents North Line)
Several of the biannual site reports prepared by Essex Windsor Solid Waste Authority (EWSWA) make note of the local geology. As stated in these reports, the landfill is located within the St Clair clay plain region, which can be divided into six stratigraphic units with an overall average thickness of approximately 30m (Figure 4A). The bedrock is interbedded limestone and shale from the middle and lower Devonian Hamilton Group, and the upper 2 meters of the bedrock are fractured. This fractured bedrock and the lower parts of the overlying till comprise the local bedrock aquifer. The local groundwater flow system consists of 4 parts (Figure 4B). The shallow flow system (including liquid through refuse and brown zone) is within the upper 1-6m of weathered clayey soil; the upper aquitard consists of 4-12m of unweathered clayey soil and a transition zone with fractured/weathered soil; the interbedded zone is a 6m thick layer of clayey soil including some silt to sand (refuse likely extends into this zone); and the bedrock aquifer consists of the upper fractured part of the local bedrock which extends from a depth of 36-43 meters (EWSWA, 2011, 2007, 2001).

At the study site, the leachate collector system consists of a network containing a perimeter leachate collector system with refuse finger drains, underdrains, and a groundwater interceptor system. The leachate collection perimeter system around Areas A1, A2, A4 and C (Figure 3) collects leachate from finger drains in these areas, as well as from underdrains in Areas A5, B1 and B2. The perimeter leachate collector system in Areas A5, B1 and B2 postdates the refuse mound, and was structured so that the leachate within the refuse flows into the collection system and then to the holding ponds. However, in the older part of the landfill, leachate flows radially outward towards the perimeter collection system and the nearby woodlot (EWSWA, 2001).

Groundwater monitors are located at four locations around the perimeter of the landfill; the northwest corner of A1 (monitor 80), just north of Area A1 (monitor 81), to the west of Area C (monitor 82), and just south of Area C (monitor 83). Groundwater generally moves from the refuse towards the collector system, and the surface water runoff is discharged into a network of
drains and ditches. To the west of Area C, the groundwater flow is in an easterly direction (towards the landfill) due to the underdrain system and similarly in areas to the south, and outside the landfill, the ground water flows northwards. Groundwater movement in the local flow system is essentially vertical downward except for the bedrock aquifer where vertical movement of groundwater is not possible due to the overlying lower aquitard. Although the water quality is poor in the interbedded zone and bedrock aquifer, no landfill leachate has been noted at this depth during monitoring (EWSWA, 2011).

In order to assess for leachate contamination and levels, chloride and boron concentrations are commonly used as leachate indicator parameters due to their elevated concentration in leachate and mobility in groundwater (EWSWA, 2010, Clark and Piskin, 1977). These are the parameters that have been used at the study site for leachate assessment. Boron is used as an indicator for metals and chloride is used as an indicator for inorganic chemicals (EWSWA, 2011). Chemical concentrations within the leachate fluctuate with precipitation levels but generally fall within the concentration ranges seen since closure of the landfill (Table 1). Most leachate elevations (height of leachate within the refuse mound) appear to have stabilized since 2000; however the 2005 post closure site report states that leachate elevations from wells L5 and L6 in Area C, L12 in Area A2 and L28-V1 in Area A1 show increases over time (Table 2 & 3). Leachate elevations are highest centrally within Area C near L5 and decrease towards the perimeter leachate collection system. In June 2010, a leachate spring was observed, and was reported as subsequently repaired, on the west side of Area C. There have been continual site improvements since 2004, including several upgrades of the landfill cover and drainage systems in order to reduce the influence of precipitation on landfill leachate levels; however the precipitation amounts are still affecting the leachate elevations within the landfill (EWSWA, 2011).
Figure 4 A) Geologic cross section of study area showing stratigraphic units, B) Stratigraphic units of the groundwater system below study area.
Table 1 Wells with increasing Cl, B or leachate levels noted on 2010-2011 post closure site report.

<table>
<thead>
<tr>
<th>Shallow zone:</th>
<th>Wells showing elevated chloride</th>
<th>Wells showing elevated boron</th>
</tr>
</thead>
<tbody>
<tr>
<td>North of landfill</td>
<td>55v-elevated but decreasing Cl</td>
<td></td>
</tr>
<tr>
<td>North of area A1</td>
<td>47-II elevated Cl</td>
<td></td>
</tr>
<tr>
<td>Area C</td>
<td>L22A-II–Cl increased till 2008 now decreasing</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interbedded zone:</th>
<th>Wells showing elevated chloride</th>
<th>Wells showing elevated boron</th>
</tr>
</thead>
<tbody>
<tr>
<td>West of landfill</td>
<td>29, 84-III, 86 (area c) elevated Cl</td>
<td>84-III elevated B</td>
</tr>
<tr>
<td>Between refuse areas</td>
<td>34-II elevated Cl</td>
<td></td>
</tr>
<tr>
<td>Below refuse</td>
<td>L28-III elevated Cl</td>
<td></td>
</tr>
<tr>
<td>Leachate elevations within the refuse</td>
<td>L5, L6, L12 and L28-VI increasing leachate elevations</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Location of Active Monitors, modified from post closure site report (EWSWA 2010-2011).

<table>
<thead>
<tr>
<th>Location of Active Monitors</th>
<th>Active Monitors</th>
<th>Conductivity shallow flow system (mS/m)</th>
<th>Conductivity upper aquitard (mS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2010</td>
<td>2011</td>
<td>2010</td>
</tr>
<tr>
<td>East of Area C</td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>121.6</td>
</tr>
<tr>
<td>Northeast of Area C</td>
<td>11</td>
<td>116.7</td>
<td>899</td>
</tr>
<tr>
<td>South of Area C</td>
<td>18</td>
<td>Dry</td>
<td>885</td>
</tr>
<tr>
<td>South of Area C</td>
<td>19</td>
<td>86.6</td>
<td>77</td>
</tr>
<tr>
<td>South of Area C</td>
<td>20</td>
<td>70.4</td>
<td>74</td>
</tr>
<tr>
<td>South of Area C</td>
<td>21</td>
<td>71</td>
<td>71</td>
</tr>
<tr>
<td>South of Area C</td>
<td>22</td>
<td>209.1</td>
<td>174</td>
</tr>
<tr>
<td>West of Area C</td>
<td>27</td>
<td>140.1</td>
<td>130</td>
</tr>
<tr>
<td>Northwest of Area C</td>
<td>28</td>
<td>88.5</td>
<td>113</td>
</tr>
<tr>
<td>Northwest of Area C</td>
<td>30</td>
<td>60.6</td>
<td>59</td>
</tr>
</tbody>
</table>

29
Table 3 Leachate elevation trends over time modified from EWSWA 2010-2011.

<table>
<thead>
<tr>
<th>Monitor Designation</th>
<th><strong>LONG TERM TREND</strong></th>
<th>(includes historic data)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Constant</td>
<td>Decreasing</td>
<td>Increasing</td>
</tr>
<tr>
<td><strong>AREA A1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L18</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>L20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L23</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>L27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L28-VI</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>L29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L30</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>L31</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td><strong>AREA A2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L12</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>L14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AREA C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>L5</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>L6</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>L7</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td><strong>AREA B1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L32</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>L33</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>AREA B2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L34A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>OLD M. LANDFILL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1-II</td>
<td></td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

Note: Leachate elevations can show more than one trend.
2.0 METHODS

2.1 Field Organization

A sequence of 8 parallel (east to west) survey lines were laid out for the study; six within Area C and two in the field south of the landfill (Figure 5). The latter two were designed to evaluate the possibility of leachate leakage outside the landfill. The survey lines within the landfill were numbered sequentially from south to north. Line 1 is near the base of the refuse mound (near ground level), and the numbers increase to Line 6 near the top of the refuse mound. Conductivity and resistivity surveys were conducted over the length of the lines within the landfill; however resistivity profiling was not conducted on the lines outside the landfill, as permission could not be obtained. Conductivity surveys were also made at 60 m intervals in a north-south direction across Lines 1-6 in order to form a grid pattern and provide better spatial distribution of measurements. Finally, a single resistivity survey line was completed over Area A1, in the northern part of the landfill (Figure 3). This line was done as a reference and baseline for the cap depth as the cap is presumed to be intact in this area (Cascadden, pers comm., 2010). It was not possible to obtain a baseline for the local sediments outside of the landfill due to negative public perception of the landfill. Several features from the leachate monitoring system are within close proximity to Line 1 of the survey as noted in Figure 6A.
Figure 5 (A) Site map and outset of Area C, (EWSWA, 2001). (B) NS cross cut of Area C waste cell (Dillon 1986), Survey lines 1 to 6 (left to right) shown in black.
Figure 6 (A) Features from the leachate collection system in close proximity to Line 1. These features could interfere with results from the geophysical surveys of Line 1 (approximate position of Line 1 denoted by dashed line). Black lines represent gas pipeline. (B) Topography Area C.
2.2 Conductivity

2.2.1 Instrumentation

A DualEM conductivity meter was used for conductivity measurements. The dual geometry of this instrument incorporates a transmitter coil with horizontal windings with both a horizontal and a vertical receiver coil. This arrangement of the coils results in a horizontal co-planar (HCP) and a perpendicular (PRP) geometry. This allows conductivity measurements to be made simultaneously at two distinct depths (Dual EM Manual, 2006). By varying the transmitter-receiver separation, the depths of exploration (DOE) can be altered. The DOEs are determined by transmitter/receiver separation and height of the instrument above ground level, using the following equations: (PRP) 0.6 x the transmitter-receiver separation – carrier elevation, and (HCP) 1.5 x the transmitter-receiver separation – carrier elevation. In this study, four DOEs were obtained using two transmitter-receiver separations (2m and 4m), with a carrier elevation of 20 cm. Thus, the DOEs for the PRP configuration were 1m and 2.8m, and 2.2m and 5.8m for the HCP configuration.

2.2.2 Data Processing

The conductivity data was downloaded from the DualEM meter and converted to MS Excel files for use with ESRI’s ArcGIS software (Esri, 2010). Within ArcGIS, the geostatistical tool Spatial Analyst was used to generate maps of apparent conductivity, through the Inverse Distance Weighting (IDW) process, which uses a ‘nearest-neighbour’ approach to extrapolation of values between known points. Scales for all apparent the conductivity maps were set to be equal for easier comparison.
2.3 Resistivity

2.3.1 Instrumentation

Resistivity surveys were conducted using an ABEM TerraMeter (SAS 4000) and 40 stainless steel electrodes. The surveys used a Wenner-á array with 2 meter probe spacing, for a total single measurement sequence length of 80 m, and a continuous run-along length of 700-750 m on each line. The surveys were conducted on the elevated area of the refuse cells, however only part of the overall DOE shown in the pseudosections from Lines 1, 2 and 3 delineates refuse. As mentioned previously, no resistivity measurements were done the field south of the landfill.

2.3.2 Data Processing

The resistivity data was imported into the RES2DINV inversion software (Geotomo, 2006), and used to produce two-dimensional vertical profiles (pseudosections) showing the apparent resistivity (ρm) of the subsurface. An initial model of subsurface resistivity was produced using Geotomo’s default settings, followed by calculation and plotting of the surface resistivity (ρc) that could then be compared to the measured apparent resistivity. The root mean square (RMS) error, which is the difference between the measured apparent resistivity values and the calculated apparent resistivity values, was then calculated. This process was then repeated until the RMS error reached a minimum. All models are missing data due to a probe malfunction, and although this does not affect the model evaluation process it may make data in this area slightly less reliable, but not unusual (Loke, Geotomo Software, Pers. Communication 2013).

2.4 Cap thickness determination

In order to determine the cap thickness, a two step process was followed. The estimated resistivity values for the cap (18-50 Ω.m) were determined from the North line (Area A1), as the
cap in this area was presumed to be intact (EWSWA, pers comm., 2011). The subsurface model for each resistivity profile was overlain by a 2 m grid and the depth at which the predetermined cap values extended was recorded for each grid point. The depth to which these values extended was considered to be the base of the cap. If, at a specific location along the line, the surface resistivity value was either higher than 50Ω.m or lower than 18 Ω.m, that location was not considered to have a measureable cap depth, and was classified as either having high surface resistivity, low surface resistivity, or unknown.

3.0 RESULTS

3.1 Conductivity Values

The conductivity values range from -2 to 570 mS/m (Figure 8). The conductivity maps for all depths of exploration show similar patterns (Figure 8). In the northwestern portion of the survey area (along Lines 5 and 6), the conductivity values are highest, and decrease towards the south and somewhat less towards the east. The shallowest DOE map shows several linear midrange conductivity fingers extending south of the refuse mound towards the southern landfill border and adjacent field. These are more abundant in the eastern third of Area C. South of the survey lines in the field outside the landfill, there is a localized area of higher conductivity. There is also a similar feature just south of the fence line in the eastern/central region (Figure 9). The high conductivity features cover more area on the 2.8m DOE map and are the least extensive on the 5.8 m DOE map. The majority of the conductivity readings outside the landfill are <20mS/m.
Figure 7 Apparent Conductivity values. A) Line 1, 4 meter HCP, B) Line 2, 4m HCP
Figure 8 Subsurface apparent conductivity of Area C and nearby field at all DOEs. (DOEs: 2m PRP=1m, 2m HCP=2.2m, 4m PRP=2.8, 4m HCP=5.8m)
Figure 9  Apparent conductivity features located in the field south of the landfill. See section 3.1 for more details. (Red line represents approximate position of landfill border).

3.2 Resistivity

In this and the following sections, all references to meters along the survey lines are noted from the eastern end of the lines, extending westward.

3.2.1 North line, Area A1

The resistivity survey (Figure 10) in the north cell of the landfill (Area A1) was conducted to serve as a baseline for identifying the landfill cap from the resistivity data. The data on this line shows relatively high values (18-77 Ω.m) near the surface, which should represent an intact clay cap (EWSWA, pers. comm. 2010). These surficial values are within normal resistivity ranges for clay (Christiansen, 2006). Below the surface high resistivity zone, the resistivity values are quite
low (<9 Ω.m) in the eastern section, but somewhat higher in the western section (18 to 85 Ω.m). There is a small superficial high resistivity feature (>160 Ω.m) between 37 and 40 meters.

![Resistivity survey](image.png)

**Figure 10** Resistivity survey within Area A1, north area of landfill. The estimated cap thickness (see section 1.0) is denoted by black line.

### 3.2.2 Resistivity Surveys, Area C

**Line 1**

The subsurface model of Line 1 (Figure 11A) shows several surficial (< 4 meters depth) high resistivity areas (>31 Ω.m) between 200 to 300 meters and from 520 to 700 meters. All other surficial resistivity values are < 30 Ω.m. The apparent resistivity of the underlying layer(s) is also less than 30 Ω.m from 0 to 515 meters. Beyond 515 meters, the apparent resistivity increases, and remains relatively high (>31 Ω.m) at depth.

**Line 2**

The root mean square (RMS) error calculated by the inversion software for this line could not be reduced below 44%, due to the heterogeneous measurements of resistivity. Despite these high values, the data is usable, as the change in RMS value was < 3% (Loke, Geotomo Software, pers...
comm. 2013) Most of the pseudosection shows low to moderate apparent resistivity values (50 \( \Omega\cdot m \)), with the exception of several surficial high resistivity (> 120 \( \Omega\cdot m \)) features evident between 364m and 650m, all extending to about 5m depth. One feature (at 510 m from the beginning of the line) extends beyond this depth.

Line 3

The resistivity values from Line 3 (Figure 11C) are <50 \( \Omega\cdot m \) for the entire subsurface model and tend to decrease with depth with the exception of three isolated features. These three features show resistivities of >50 \( \Omega\cdot m \), are located at 64, 120 and 736 meters, and occur at depths of 3-12 meters.

Line 4

On this survey line (Figure 11D); the apparent resistivity pseudosection values measured in the eastern 200 meters of the line are more homogeneous than the remainder of the line. Relatively elevated apparent resistivity values (>15 \( \Omega\cdot m \)) are observed at all depths in this section for the first 200 meters. Towards the west, the high resistivity values are observed only near the surface. The subsurface model is quite variable both horizontally and vertically in the western section, with lower apparent resistivity values (3 - 15 \( \Omega\cdot m \)) interspersed with areas of high resistivity (Figure 11). There are several isolated areas of low resistivity (< 5 \( \Omega\cdot m \)) noted in the subsurface below 4 meters.

Line 5

The subsurface model for Line 5 (Figure 11E) has relatively homogeneous areas that extend the depth of the model in the easternmost (0 to 175 meters) and westernmost sections (680 to 720 meters). The central section of the model is more heterogeneous. Most resistivity values are <40 \( \Omega\cdot m \), with the exception of a few small surficial features (280 meters, 484 meters and several between 640 - 760 meters). A deeper higher resistivity (>40 \( \Omega\cdot m \)) feature is present at 154 meters.
at a depth of 3 to 8 meters. The remainder of the model has resistivity values between 4 to 10 \(\Omega\).m, including several scattered low resistivity areas at <3 \(\Omega\).m.

Line 6

The majority of the resistivity measurement values from Line 6 (Figure 11F) are <100 \(\Omega\).m, with the exception of several isolated very high resistivity features (>1300 \(\Omega\).m) between 154-238 meters, at depths of 0-4 meters. Most near surface resistivity values within the subsurface model range between 7 and 25 \(\Omega\).m, which is consistent with most of the other survey lines. At depths greater than 5 meters, lower resistivity values (<10 \(\Omega\).m) dominate.
Figure 51 Subsurface models of resistivity profiles from Lines 1 (A) to Line 6 (F).
4.0 DISCUSSION

4.1 Conductivity

The four conductivity maps (DOEs of 1.0, 2.2, 2.8 and 5.8 meters) all show similar spatial patterns. Higher conductivity values (>140 mS/m) are apparent to the northwest, which is near the top of the refuse pile. In this area, two monitoring wells have shown higher leachate elevations in the past (EWSWA, 2011, 2007). The higher conductivity areas typically coincide with the flat surface of the top of the refuse mound (Figure 3). One explanation of this correlation is that the presence of leachate in the flatter areas is related to increased infiltration of precipitation as there is less chance of runoff due to the lack of relief in this area. _Phragmites australis_ (Cav.) Trin. ex Steud. was found growing in the northwestern portion of Area C at the top of the refuse mound. As this invasive wetland species prefers areas of standing water (OMNR, 2011); its presence suggests increased moisture in the soil, potentially related to the near-surface leachate mound.

The eastern section of the mapped area slopes gently towards the east (Figure 6B), and is less likely to be affected by infiltration because the topography results in better surface runoff. This area has low to moderate conductivity values at all DOEs (32-50 mS/m), with the exception of the eastern end of Line 2. This area shows slightly higher conductivity than its surroundings (>139 mS/m). In examination of the physical features, this feature is coincident with a drainage ditch, and thus higher moisture and conductivity values would be expected. The western section of the farm field adjacent to the landfill (south) shows conductivity values of <48 mS/m (Figure 12).
Figure 6 Comparison of apparent conductivity values from Line 1 and Lines in field. (The range of conductivity values differ on each graph, however the overall patterns of higher/lower conductivity can be compared from the landfill into the field).
In the eastern section there are several areas with higher conductivity values (50 - 95 mS/m) that extend between the refuse mound and the field south of the landfill border (Figure 9). These somewhat linear features occur more frequently towards the eastern third of the area. There are also two high conductivity features in the field (Figure 9).

Both the features in the field and “finger” features may indicate that leachate has flowed past the border of the refuse mound into the field. However, an alternative explanation could be that the ‘fingers’ are an artifact of the ArcGIS program contouring algorithm. There are two spatially close sources (the landfill itself and the nearby gas pipeline present in the eastern half of the field (Figure 9) that have high conductivity values, and ArcGIS may have combined the two to create a single feature. The high conductivity features observed near the centre of the lines measured in the field coincide with, and are probably caused by, the presence of this gas pipeline as it angles to the southwest (Figure 9). The pipeline is not present in the western section of the map, making it highly unlikely to have caused the finger features in this area (Figure 6A), and thus leachate may indeed be present in the field. Despite the above evidence, there is a significant problem in that the shallow ground water flow direction is supposedly north towards the landfill (EWSWA, 2007), rather than southwards. It is possible that the difference in leachate and groundwater density could have an effect on the direction of flow.

Geochemical measurements of groundwater samples from several monitoring wells just to the south of the area mapped (Table 4) have been reported as having high conductivity values (EWSWA, 2011), and these have been compared to the apparent conductivity maps created for this study. Although some of the wells are in close proximity to the linear features seen
extending towards the field on the apparent conductivity maps, the values are not identical, which is to be expected due to the difference in measurement type (direct measurement of groundwater conductivity vs. field measurement of apparent conductivity). The areas in closest proximity to the wells show apparent conductivity values which range between 30-40 mS/m, while the groundwater conductivity from the wells in Area C is much higher (71 -174 mS/m). However there is a strong spatial correlation between the wells whose groundwater samples show high conductivity, and areas of mid to high range apparent conductivity (Figure 13B). Specifically, the linear features noted in the southern and western borders of the apparent conductivity map of Area C are in close proximity to the wells that have higher conductivities.
Figure 73 A) Increased conductivity features in the field south of the landfill (red line represents the division between landfill (north of line) and field (south of line). B) Wells with groundwater having high conductivity.
4.2 Resistivity interpretation and concerns

Prior to discussing the results, it is worth noting that the pseudosections shown in Figure 11 have a vertical exaggeration (VE) of 11.8. This strong exaggeration has created significant vertical elongation of features within the pseudosections. However, the features within the profiles would not be apparent on a 1:1 scale. Figure 14 is somewhat closer to true scale, with a vertical exaggeration of 6.4. It must also be noted that there are several monitoring features in close proximity to Line 1 (Figure 6A) that could potentially affect the readings obtained by the resistivity and conductivity surveys; however, no definite anomalies were evident surrounding these monitoring features (Figure 8). For ease of interpretation, several types of features have been noted and categorized in this discussion.

- **Type A** features are typically small (often related to a single measurement) and surficial with high resistivity values (>90 \( \Omega \cdot m \)). Type A features may be related to poor grounding of an electrode, small void spaces, or near surface non conductive material.

- **Type B** features are characterized by surficial low resistivity values (< 10 \( \Omega \cdot m \)), which may relate to the presence of near-surface high conductivity leachate or a metallic body close to surface.

- **Type C** features are also small and characterized by low resistivity values (<8 \( \Omega \cdot m \)), but occur in the subsurface, and may be due to isolated pockets of leachate or conductive refuse.

- **Type D** features have high resistivity values (> 50 \( \Omega \cdot m \)) and also occur as isolated features in the subsurface. These features may be due to either high resistivity material in the refuse or void spaces caused by features such as monitoring wells.
Type $E$ features are high resistivity (>50 Ω.m), linear and near vertical, extending from the near surface to a considerable depth within the model. While the origin of these features is unclear, some are in close proximity to boreholes dug in 1986 by Dillon Consulting Engineering (Dillon, 1986).

Type $F$ features are large areas of low apparent resistivity values in the subsurface, which may be caused by leachate or saturated refuse.

4.2.1 North Line, Area A1

The North Line, as would be expected from its location and history, has relatively few features. One type A feature is present at ~ 38 m. The near-surface high resistivity layer that represents the intact cap is underlain by type F features, probably due to the presence of leachate. The most likely explanation for the type D feature at the eastern end of the line is a nearby monitoring well.

4.2.2 Resistivity Surveys and Features, Area C

The six parallel resistivity survey lines were laid out to cover areas from the edge of the landfill (Lines 1 and 2), up the slope of the refuse pile (Lines 3 and 4) to the flat top of the landfill (Lines 5 and 6). The underlying glacial till should be visible in the first two lines, but is unlikely to be observed in Lines 5 and 6 as the refuse is likely too thick. Due to the history of the landfill, there are few records of the types of waste present, and thus the refuse could be very spatially heterogeneous.
The subsurface models from both Lines 1 and 2 show a very similar pattern with type A and B features, multiple type D features, and type F characteristics at depth. The type A, B and D features occur centrally in Line 1 and more towards the west in Line 2 (Figure 11). Lines 3, 4, and 5 are considerably more heterogeneous than Lines 1 and 2, with the exception of the eastern areas of lines 4 and 5. Line 6 is less heterogeneous than Lines 3, 4, and 5 (Figure 11).

The top 4 meters of all of the subsurface models have similar apparent resistivity values, although some heterogeneity is present (Line 1: 18-32 Ω.m, Line 2: 18-29 Ω.m, Line 3: 12-50 Ω.m, Line 4: 15-65 Ω.m, Line 5: 15-30 Ω.m, Line 6: 16-6 Ω.m). Based on the similarity to the North line, and the consistency of the superficial resistivity values, this layer is likely to be the clay cap. However, the near-surface A and B features seen on all lines may indicate disruptions in the landfill cap. Thus, differentiation of the cap and refuse is problematic, and the thickness of the cap is often difficult to determine.
Figure 84 Subsurface model of Line 4 (VE= 6.4).
There is a general trend on all pseudosections/models of decreasing resistivity values with depth, with the exception of a few isolated features. The large subsurface areas of low apparent resistivity values are probably indications of saturated zones below the surface. However, in Lines 1 and 2, the low resistivity values most likely delineate the shallow flow system beneath the refuse. In Lines 3, 4, 5, and 6, there are multiple features at varying depths, which is consistent with varying landfill refuse types.

In order to determine whether or not conductivity can be used as a proxy for cap thickness, it is necessary to evaluate the correlation between the conductivity measurements and the resistivity profiles, from which the cap thickness has been determined. The conductivity measurements along each survey line were compared to the near-surface portion of the same line’s resistivity model (e.g. Figure 15 and Figure 16). Reciprocal conductivity values ($\sigma_c$) were calculated from the measured apparent resistivity ($\rho_{am}$) readings. These calculated conductivity values were then compared to the measured apparent conductivity ($\sigma_{am}$) obtained at the study site (Table 5). In this section, we will focus on two lines (Lines 2 and 4) in detail.

Line 2’s conductivity profile for DOE = 2.2 m and resistivity profile for are assess for inverse correlation and shown in Figure 13. As would be expected, there is a strong correlation of high conductivity and low resistivity values. At 650 m, the measured apparent resistivity ($\rho_{am}$) is 20 $\Omega\cdot$m, the measured apparent conductivity ($\sigma_{am}$) is 57 mS/m, and the calculated conductivity ($\sigma_c$) is ~50 mS/m, which closely matches the measured apparent conductivity. However, in other areas, the correlation between apparent resistivity and apparent conductivity is not as good e.g. at
90 m $\rho_{am} = <10 \, \Omega \cdot m$, $\sigma_{am} = \sim 200 \, mS/m$, $\sigma_c = \sim 100 \, mS/m$. There are two possible explanation for the scale differences which are differences in the frequency of measurement (conductivity $\sim 0.8 \, m$, resistivity, 2 m) or linear calibration within the instruments.

Figure 16 shows Line 4’s conductivity profile (DOE = 2.2 m) and resistivity profile. The expected high conductivity / low resistivity correlation is more evident on this line, e.g. at 340 m ($\rho_{am} = \sim 7 \, \Omega \cdot m$, $\sigma_{am} = \sim 137 \, mS/m$, $\sigma_c = \sim 137 mS/m$). Again, there are small areas where the correlation is not as good, e.g. at 400m ($\rho_{am} = \sim 20 \, \Omega \cdot m$, $\sigma_{am} = \sim 110 \, mS/m$, $\sigma_c = \sim 50 \, mS/m$). Once again, this suggests that scale differences such as frequency of measurement may have an effect.

In general, in most areas the conductivity and surficial resistivity data show good inverse correlation (conductivity is the reciprocal of resistivity) with few exceptions. Small high surficial apparent resistivity features may be caused by a lack of proper grounding of the probes, and/or materials such as gravel, poorly conductive refuse or void spaces near the surface, therefore resulting in areas where apparent resistivity and apparent conductivity do not correlate well.

### 4.4 Comparison with 1986 Dillon Site Report

In 1986, an evaluation of the landfill site was carried out by Dillon Consulting Engineers (Dillon, 1986). A series of test pits and boreholes were dug in Area C (Figure 15). Although, the location of the boreholes is not consistent with most features on either the conductivity or resistivity surveys there is one possible exception, which is the linear type E feature evident on the
resistivity model of Line 6 at 318 meters (Figure 11). This feature is in close proximity to borehole 24w-9.75 from the Dillon investigation.

Of note however, is that Dillon sited a possible contact between the waste and the interbedded zone below Area C (the area studied). The interbedded zone consists of silt and sand. The high sand content of this layer would increase the permeability of this zone and could facilitate offsite migration of leachate into the field south of the landfill border. This may be a contributing factor and a migration pathway if leachate is indeed present in the field south of the landfill border.

4.5 Cap depth as interpreted from resistivity – discussion and problems

Due to the heterogeneous nature of this landfill and resistivity measurements, it proved to be difficult to determine the depth to the base of the landfill cap / top of the refuse in some areas. Resistivity soundings could not delineate the landfill cap thickness in areas where either very high or low resistivity was present at the surface, or where the resistivity contrasts between the cap and underlying refuse were minor. Cap thickness estimates could be obtained only in areas where no surficial features were present (Figure 16). Lower resistivity surficial features may indicate the presence of leachate near the surface – as was evident near at least one location on Line 4. In order to determine if the conductivity data could provide clues to cap thickness and cohesiveness where the resistivity data could not, the apparent conductivity and cap thickness maps were compared to see if a correlation between the thickness of the cap and surficial high apparent conductivity exists.
Table 4 Conductivity values derived from ground water sampling of wells near Area C. (measurements are in mS/m)

<table>
<thead>
<tr>
<th>Location of Active Monitors</th>
<th>Active Monitors</th>
<th>Conductivity shallow flow system (mS/m)</th>
<th>Conductivity upper aquitard (mS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2010</td>
<td>2011</td>
<td>2010</td>
</tr>
<tr>
<td>East of Area C</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Northeast of Area C</td>
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<td>South of Area C</td>
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<td>West of Area C</td>
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<tr>
<td>Northwest of Area C</td>
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<td></td>
<td></td>
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<tr>
<td>Northwest of Area C</td>
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<td></td>
<td></td>
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</tbody>
</table>

Table 5 Apparent resistivity with reciprocal in calculated conductivity

<table>
<thead>
<tr>
<th>Measured apparent resistivity (pam)Ω.m</th>
<th>Calculated conductivity (σc)mS/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.97</td>
<td>1030.9</td>
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<tr>
<td>1.68</td>
<td>595.24</td>
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<tr>
<td>5.03</td>
<td>198.81</td>
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<td>8.71</td>
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<td>15.1</td>
<td>66.225</td>
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<tr>
<td>26.1</td>
<td>38.314</td>
</tr>
<tr>
<td>45.2</td>
<td>22.124</td>
</tr>
</tbody>
</table>
Figure 95  Apparent conductivity ($\sigma_{am}$) of Line 2 (top) and near surface apparent resistivity ($\rho_{am}$) of Line 2 (bottom)

Figure 106  Apparent conductivity ($\sigma_{am}$) of Line 4 (top) and near surface apparent resistivity ($\rho_{am}$) of Line 4 (bottom)
4.5.1 Comparison of conductivity and cap thickness maps

Using the parameters described above, the cap thickness in the baseline area (Area A1) was determined to range between 0 and ~3 m (Figure 17). The same method resulted in estimates of cap thickness in Area C from 0 to >4 meters. However, as mentioned previously, evaluating the thickness was not possible in all areas. An inverse distance weighted prediction map was constructed using ArcGIS software showing the spatial distribution of the cap thickness variations. This map of estimated cap thickness was then compared with the apparent conductivity maps (Figure 17) to see if the high conductivity areas noted on the maps would correlate with the areas where the cap was thin or missing, and thus to evaluate whether or not the conductivity measurements could be used to extend our knowledge of cap thickness and potentially be used for remediation purposes.

A general correlation between estimated cap thickness and conductivity is apparent. The high conductivity ( >140 mS/m) areas to the northwest of the survey area correlated to cap thicknesses of <1.5 meters, while mid range conductivity values (60-100mS/m, east/central of line 2 and 3) generally correlated with cap depths of 1.5 to 3 meters. Given this pattern, it would be expected that areas of low conductivity would correlate with a thicker cap; however, this did not prove to be entirely true (e.g. most of Line 1). However, many of the areas with low conductivity had highly variable surficial resistivity features where cap thickness could not be determined. (e.g. eastern 1/3 of lines 1 and 6). The correlation between cap thickness and conductivity may have been hindered by the shortcomings in the method of estimating cap thickness. A more accurate estimation of landfill cap thickness may be possible but in this case there were too many unexplained surficial inconsistencies. Increased accuracy could be obtained with a better data set and a different method for picking depths.
Figure 17 Approximate location of Dillon boreholes on 2m PRP with survey lines

Figure 18 High and low resistivity surficial features along survey lines which prevented accurate prediction of cap depth
Figure 119 Comparison of cap thickness (top) and conductivity (bottom).
5.0 CONCLUSIONS

The primary goals of this study were twofold: to assess whether or not the geophysical methods could be used to determine cap thickness, and to determine if there was any evidence for leachate leakage from the landfill into the surrounding area.

The results from the use of the resistivity models were mixed. A comparison of the subsurface models in the problematic area to the baseline North line in area A1 suggests that several areas of the clay cap are compromised. There are additional lines of evidence, such as the presence of *Phragmites*, and liquid, with an oily appearance and chemical smell pooling near the surface near Line 4 which may indicate a possible leachate spring in this area. Efforts at correlation of the cap thickness to the apparent conductivity maps showed higher conductivity in areas where the clay cap was thin (<1.5m) indicating near surface leachate, and may also indicate that the cap has been compromised in these areas. Thus, although there is evidence to support the assumption that the cap is not contiguous, the use of geoelectrical methods to assess cap thickness had limited success, as it was not possible to obtain a measurement of cap thickness in all areas. Other non-geophysical methods, such as boreholes, would be helpful to confirm results.

There is some evidence for potential leachate leakage southwards into the adjacent farmer’s field. The information obtained from the 1986 Dillon report stated that there was likely contact between refuse and the interbedded zone. The sand content in this zone would provide an excellent migration pathway for leachate to flow outside the landfill border. There are also several high conductivity features noted in the field, including linear features of higher conductivity that apparently extend into the field from the landfill. Such linear features occur at intervals along the whole length of the map (Figure 9). However, the presence of a gas pipeline in the eastern half of the field could also have produced high conductivity values that would mask any evidence of leachate leakage. Therefore, while the data suggests that leachate leakage could be occurring, however more research and/or ground truthing is needed to confirm this.
BIBLIOGRAPHY


DualEM manual (2006), DUALEM Inc. Milton, ON, Canada


Geotomo software, 115, Cangkat Minden Jalan 5, Minden Heights, 11700 Gelugor, Penang, Malaysia.


CHAPTER III
SUMMARY AND FUTURE WORK
1.0 SUMMARY

This study focused on delineation of the landfill cap thickness and assessing for possible leachate migration outside the landfill border using non-invasive geophysical methods. Geophysical methods were chosen for their ability to locate leachate, as well as to assess the clay cap. The DualEM 2S/4S conductivity meter was utilized to map variations in subsurface conductivity at the site. Results from the EM terrain conductivity mapping suggested that the northwestern area of the site had higher conductivity values compared to the eastern portion. This difference in conductivity could potentially be due to higher leachate elevations in the northwest area. There are also “fingers” of mid range conductivity values extending beyond the southern landfill border which may indicate migration of leachate into the field south of the landfill border.

The site was further examined by DC resistivity surveys using the Wenner-α array with 2m electrode spacing. This survey was conducted to determine the thickness of the landfill cap. Based on the DC resistivity results, the clay cap is not continuous in the areas covered by the profiles. A few of the resistivity profiles show areas where there is little to no capping material, which would allow the infiltration of precipitation into the landfill. This suggests that the clay cap is susceptible to weathering and deterioration over time, decreasing the effectiveness of the cap in preventing infiltration, and likely increasing leachate production. Due to the numerous surficial features seen on the resistivity surveys, which prevented determination of the base of the cap, it was not possible to assess cap thickness in all areas. Thus, the results of the geophysical surveys suggest that the landfill cap is not contiguous and that it is possible there may be leachate leakage outside the landfill.
2.0 FUTURE WORK

The following are the recommendations for future work:

1) The area south of the landfill should be investigated using both EM conductivity and DC resistivity surveys. This will assist in mapping any contaminants present outside of the landfill.

2) Geo-electrical surveys should be correlated with other geophysical methods, such as GPR or seismic refraction to provide a better overall picture of the site. Correlation of geophysical data with other methods, such as borehole data would improve accuracy and provide confirmation of interpretations.
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