REMOTE SENSING OF CONTAMINATION USING GEOPHYSICAL ELECTROMAGNETIC METHODS

by

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ABSTRACT

The use of geophysics in the petroleum and mining industries is common, its use is increasing on geotechnical, hydrogeologic, and contamination projects. The major advantage of the inclusion of geophysical methods on projects is lowered drilling costs; yet in many cases information obtained from geophysical methods is prohibitively expensive to obtain by other means.

The use of electromagnetic data for remote sensing of contamination is an innovative technique which relies on the electrical resistance change caused by the introduction of a contaminant into groundwater. The technique requires that the contaminant appreciably alter the resistance of groundwater beyond the background level changes due to varying lithology or fill materials. The level of contaminant required to achieve this threshold level can be calculated for specific sites and can be substantially lowered by rejecting resistance changes caused by near surface fill materials, or clays. Considering these factors, it is especially important that the contaminant specialist consultant be a geophysicist experienced in contamination projects, and he or she is contacted preferably during planning stages.

Electromagnetics is used to highlight contaminated areas initially. This information is used to locate drill holes in the areas of highest contamination, saving a substantial number of test holes. By the correlation of electromagnetics to drilling data, gross volumes of contaminants can be calculated, and their thicknesses mapped in plan view. This paper outlines these techniques and provides field examples.

Keywords: contamination, correlation, electromagnetic, geophysical, inductive electromagnetic resistivity, permeability, porosity, remediation, resistivity, range of detection, skin depth, very low frequency resistivity.

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INTRODUCTION

Remediation of sites that have had former industrial usage, or contain landfill sites, is a large and growing vocation for many firms and individuals. Geophysics has not established itself in this relatively new profession, although it has great potential for utility in it. Contamination experts have generally had little exposure to geophysical techniques, and tend to use drilling, soil and water sampling, and gas detection. Geophysicists have for the most part not become proficient in geophysical methods relating to the contamination industry. This situation is presently changing, allowing an expansion in the abilities of the environmental sciences.

The objective of this paper is to present electromagnetic methods for the remote sensing of contaminants. For projects where contamination concentrations are generally low, semi-quantitative methods are described which model the response of an electromagnetic survey. This can tell the contaminant expert if an electromagnetic survey will work on his or her project, and to what concentrations of contaminants, for given lithologies.

Methods will be shown which can negate the effects of very near surface fill materials, soils or clays. The correlation of drill hole data and electromagnetic data is discussed with field examples shown.

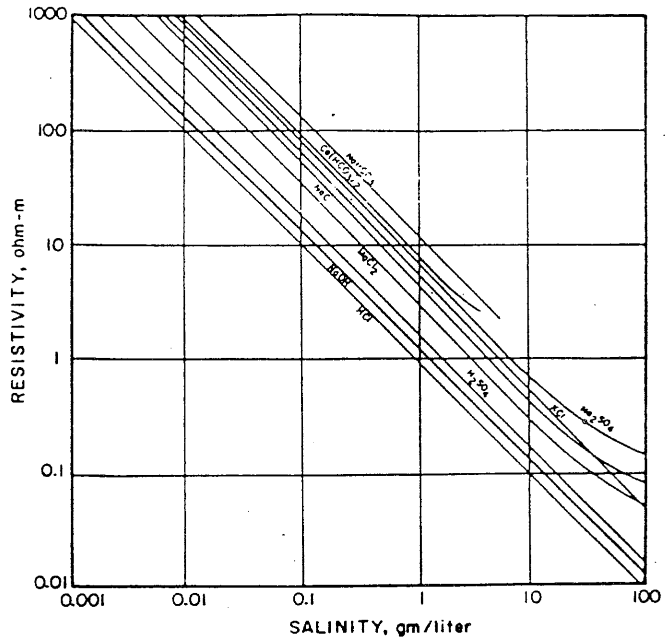
A stress will be placed on the physical contrasts being measured, to give the reader a better feel for what is actually being perceived by the electromagnetic data.

THEORY

Contaminants change the electrical resistivity of the material they are contained in by altering the resistivity of the groundwater contained in the material. The degree of resistance change of water with the addition of a soluble contaminant is quite large. This is illustrated by a graph of electrical resistivity versus concentrations of various salt solutions, Figure #1, page 3. Dissolved metals have a similar effect on the resistance of water, increasing concentrations give lower resistivities. Table #1, page 4, has an example of resistivity values for a dissolved metal.

Hydrocarbons have the opposite effect on electrical resistivity, they make a material more resistive with increasing hydrocarbon content. Their density is variable, some hydrocarbons are less dense than water, and hence float on the water table. Since geophysical methods beyond shallow electromagnetics are outside the scope of this paper, discussions will be limited to these lighter fractions.

Figure #1: Electrical Resistivity versus Salinity



(CRC Handbook of Physical Properties of Rocks, 1982.)

The theory of electromagnetic resistivity instruments are described in detail by other authors (McNeill, 1980) (Keller & Frishknecht, 1966). Briefly, two main types of electromagnetic resistivity instruments are theoretically explained, namely VLF (Very Low Frequency) Resistivity instruments, and Inductive Electromagnetic Resistivity instruments.

A VLF Resistivity machine measures the intensity of Ex, the Electric field (V/m) and the intensity of Hy, the perpendicular Magnetic field (A/m), yielding an apparent resistivity p, the resistivity of an equivalent uniform earth, in ohm·m. (Parasnis, 1979)

$p = 1/(2\pi f\mu) |Ex/Hy|^2$ (ohm·m) (1)

where μ = permeability of free space (4·10 exp -7 H/m)
f = frequency of electromagnetic field

The depth of exploration of the VLF Resistivity instrument is governed by the skin depth δ (m), which is the depth of penetration which causes the electromagnetic wave to drop in amplitude by 1/e (37%). This value is considered to be the effective exploration depth of an electromagnetic wave. (Telford, 1976)

$\delta = 500 \sqrt{(p/f)}$ (m) (2)

parameters previously defined

Thus, this VLF Resistivity method has a variable exploration depth, greater for lower frequency electromagnetic waves, and greater for higher ground resistivities. The exploration depth sensing ability of this instrument is unknown unless a ground resistivity value for the project area is known. The transmitters used for this and other VLF systems are naval marine navigation stations located worldwide.

The second type of instrument, the Inductive Electromagnetic Resistivity instrument, measures the ratio of the primary magnetic field intensity Hp (A/m) created by the transmitter portion of the instrument and the secondary induced magnetic field Hs (A/m) measured at the receiver. The apparent resistivity (p) is then calculated by: (McNeill, 1980)

$$p = \tfrac{1}{2}\pi f \mu s (Hp/Hs) \quad (\text{ohm}\cdot\text{m}) \quad (3)$$

where s = transmitter to receiver spacing (m)
all other parameters previously defined

This machine has a varying depth sensing ability by changing the separation of the transmitter to receiver distance, as well it has a better exploration depth ability in areas of conductive subsurface conditions. (McNeill, 1980)

DISCUSSION

The application of electromagnetic resistivity surveying is site specific. The contaminant present in the groundwater must create a measurable change in resistivity of the groundwater, and the aquifer must occupy an appreciable amount of the zone of detection of the electromagnetic system employed. (Greenhouse & Harris, 1983) Thus, planning is of upmost importance.

Changes in lithology or water table levels will create differing electrical resistivities. Hence, the natural background level must be less than the contrast created by the contaminant, or these two factors must be separable in some way. (Kledstad, 1975)

These factors may seem insurmountable, but in fact novel methods of electromagnetic surveying, and the integration of methods has proven to be effective for many projects. Some examples are to follow, in the field cases section (text, pages 8-12).

Since electromagnetics is site dependent it is very important to calculate the electromagnetic response for contaminants suspected at a site, and for the specific lithologies present at that site. The following is a sample calculation of the technique used to approximate the electromagnetic response of a contaminant.

Consider a sand/gravel aquifer with a 30% porosity, contaminated by

Cupric Sulphate of various concentrations. If we use Archie's Law (Keller & Frischknecht, 1966) to calculate the aquifer's resistivity, the values below are found, Table #1, page 5. Archie's law is an empirical relationship which gives the ratio of a subsurface material's total resistivity to that of the material's fluid resistivity, based on its porosity. It assumes clay free lithologies, and total fluid saturation of the pore space.

Table #1: Cupric Sulphate Concentrations, Solution Resistivity, and Solution Saturated Sand/Gravel Resistivity

Concentration (ppm)	Solution Resistivity (ohm·m)	Saturated Sand/Gravel Resistivity (ohm·m)
5.0	3.45	30.0
10.1	1.85	12.3
20.4	1.08	7.2
52.6	0.53	3.5
104.6	0.32	2.2
217.1	0.21	1.4

(CRC Handbook, 1973)

If we compare the contaminated saturated sand/gravel values with values for lithologies having appreciable permeability (the ability to transmit fluids) (Table #2, page 5), we find that materials having the ability to allow contaminant migration are at least one or more orders of magnitude more resistive than even a relatively dilute 5 ppm solution of Cupric Sulphate.

Table #2: Resistivities of Near Surface Permeable and Impermeable Lithologies

Lithology	Resistivity range (ohm·m)
Permeable	
Clayey Soils	100 - 800
Sandy Soils	8000 - 10,000
Loose Soils	1000 - 100,000
River Sand & Gravel	100 - 8000
Impermeable	
Clay	1 - 100
Glacial Till	10 - 8000

(Culley, 1975)

Thus, this Cupric Sulphate contamination would be clearly discernable from various lithologies of permeable materials. The only common lithologic units found above the consolidated layer which could be confused with a conductive contaminant plume are clays, or less likely, glacial tills.

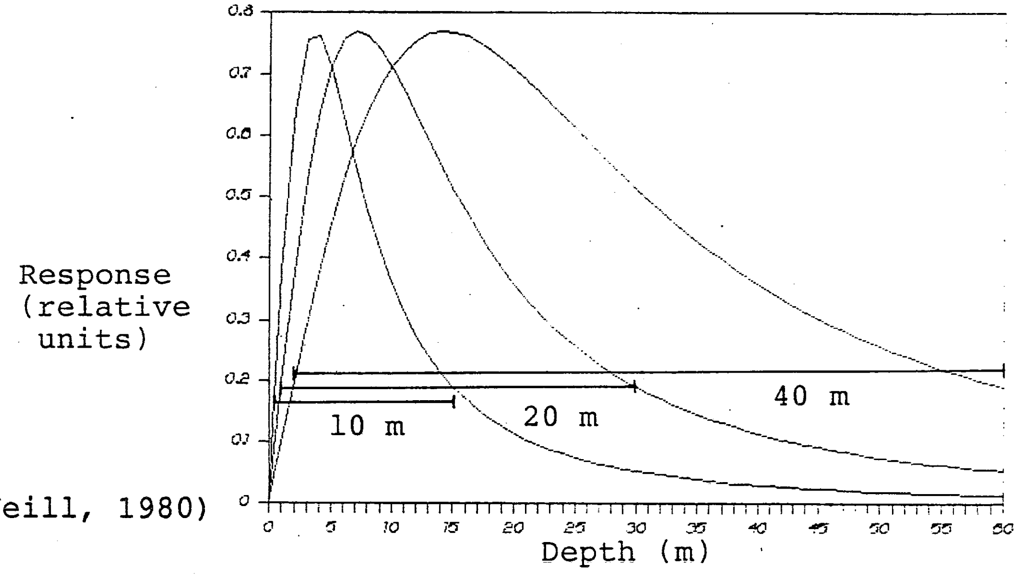
If we consider the general concentric shape of a contamination plume (Figure #5, page 9) it is unlikely to confuse these impermeable materials with contamination. This is especially true if we trace a contaminant from source, such as a surface occurrence, or from a drill hole contamination intersection. As well in some instances a clay lens near surface can create a perched water table of contaminated fluid. (Personal conversation, Mike Fink, 1990)

In urban areas storm sewers, hydro lines, and telephone cables appear on electromagnetic surveys as linear conductive zones, which are rejected from survey data since this conductive zone would not extend in orthogonal directions.

Another potential difficulty encountered by electromagnetic surveying is the masking effect of low concentration water born contaminants by near surface materials. This is commonly the result of a clay zone below the humus; or as seen in urban areas, fill materials of an unknown resistivity which occupy the top metre or few metres at sites.

The best approach to these problems is to negate the effect of this unwanted surficial background from the electromagnetic data. Consider the graph below (Figure #2, page 6) which illustrates the response of an inductive electromagnetic resistivity survey done with 10 m, 20 m, and 40 m transmitter to receiver coil separations. (McNeill, 1980).

Figure #2: Response of an Inductive Resistivity Instrument



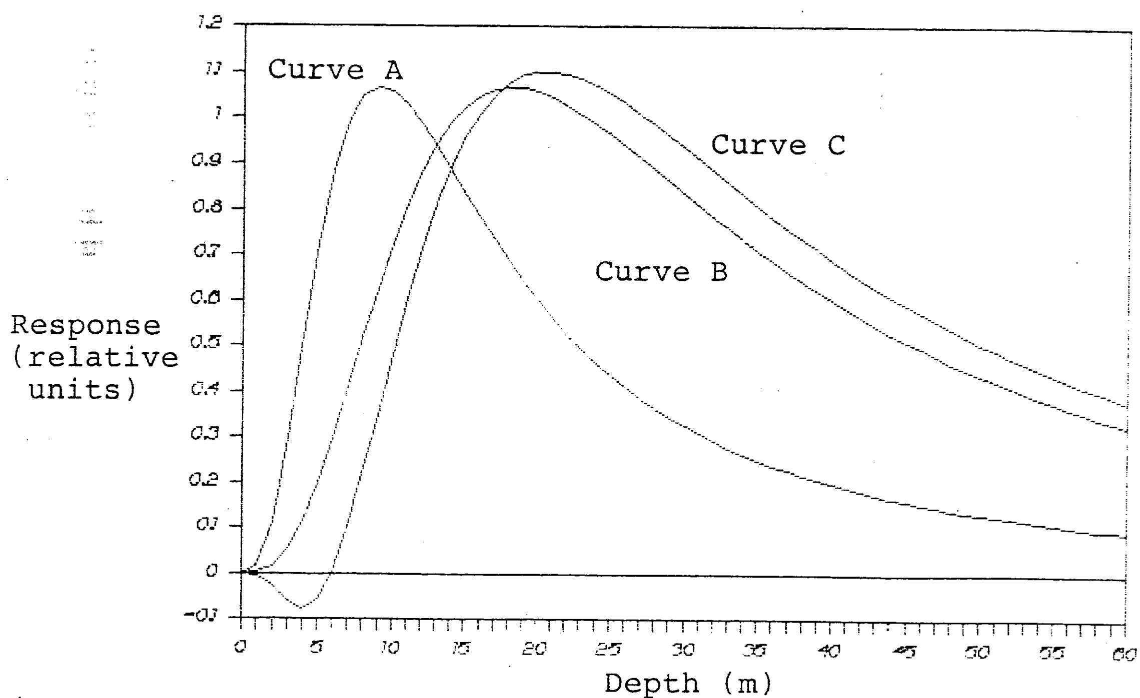
(McNeill, 1980)

These curves represent the amount of response from the instrument from various depths, referred to in text as the range of detection. The horizontal lines show the effective detection zone of the instrument for the three coil separations.

By perusing these curves, a problem presents itself; the range of detection zone includes too much surficial materials, prone to containing clays or fill materials which hamper contamination sensing.

The next figure, (Figure #3, page 7) shows some examples of methods used to negate near surface material. The new range of detection zones are calculated by simple arithmetic operations done on the electromagnetic data from 10 m, 20 m, and 40 m coil separations. Curve A is computed by doubling the 20 m values minus the 10 m values. Curve B is computed by doubling the 40 m values minus the 20 m values. (McNeill, 1980) Curve C is computed by a proprietary method developed by the author.

Figure #3: Range of Detection Response Curves



(McNeill, 1980)

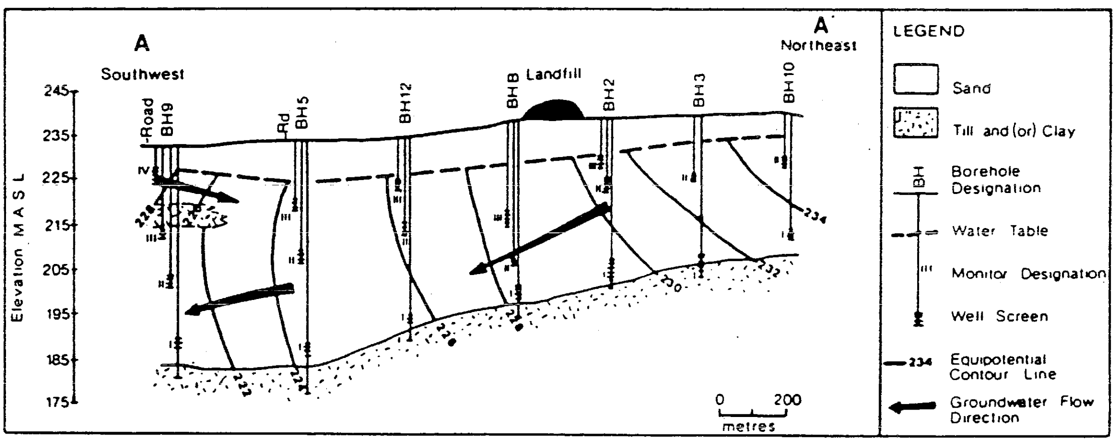
These methods give the electromagnetic survey a much better contaminant resolution, by making them partially separate from site conditions. In areas of complex geology, multiple contamination zones, or deep seated contamination (deeper than 60 m) other electromagnetic and/or seismic techniques are better suited, which are beyond the scope of this paper.

FIELD EXAMPLES OF ELECTROMAGNETIC CONTAMINATION SENSING

LANDFILL SITE CASE

This case involves a landfill waste site near Midland, southern Ontario. The site accepted solid and liquid waste since 1966. In 1981 a hydrogeology study found that contaminants had drifted beyond site, so an integrated geophysical, hydrogeology and geochemistry study was conducted in 1983. (Greenhouse & Slaine, 1986) A drilling derived cross section is shown below (Figure #4, page 8).

Figure #4: Drilling Derived Cross Section of Midland Site

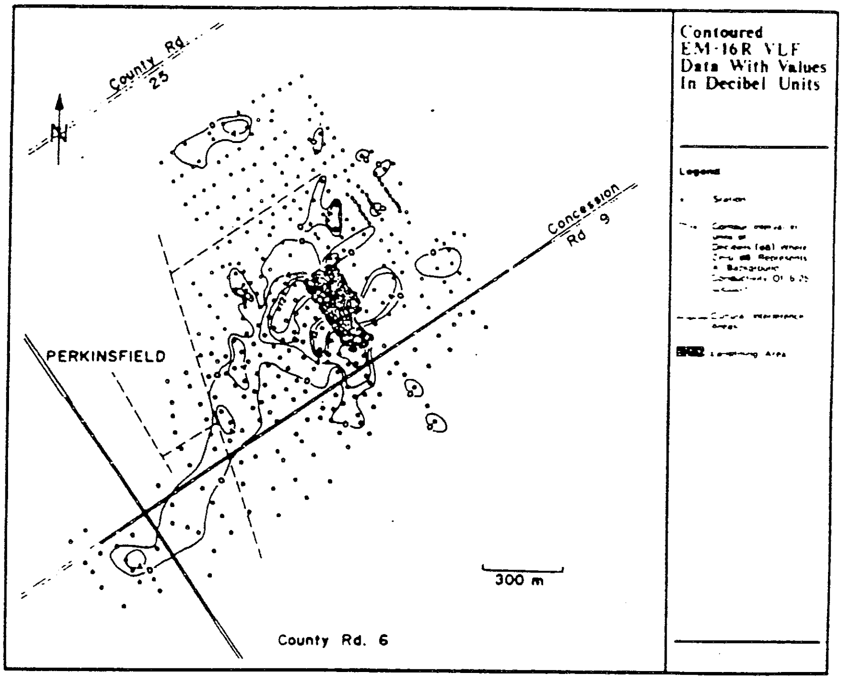


(Greenhouse & Slaine, 1986)

The aquifer containing the contaminant is 25 to 50 m thick, with a glacial till below this zone acting as an aquitard. (Slaine, 1984) A VLF Resistivity survey was conducted of the area taking 385 measurements in 36 man hours. The data was corrected using a technique developed by Greenhouse & Slaine, 1986. This method involves taking resistivity measurements near the site in a non-contaminated area. This ascertains the background resistivity, which is due to the site conditions. This background resistivity value is assumed to occur over the whole site, using this method. The ratio of the area values over the background values was calculated, then plotted in contour using the decibel as a contour interval value. This method successfully illustrated the contamination plume. Figure #5 page 9 shows this contour map. (Greenhouse & Slaine, 1986)

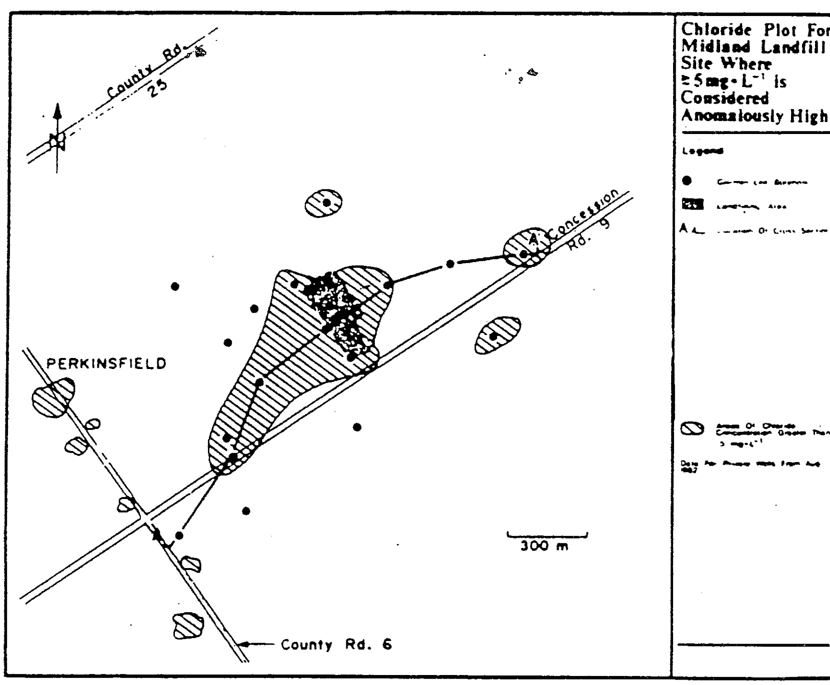
A contour plot was also made from the down hole samples taken from the drill data. Areas shown shaded, (Figure #6, page 9) are zones with chloride values of 5 ppm or greater. (Greenhouse & Slaine, 1986) These figures (Figures #5 and #6) both clearly show the contamination plume and correlate well to each other. The electromagnetic values are much more cost effective.

Figure #5: Electromagnetic Contamination Contour Map



(Greenhouse & Slaine, 1986)

Figure #6: Drilling Derived Contamination Map



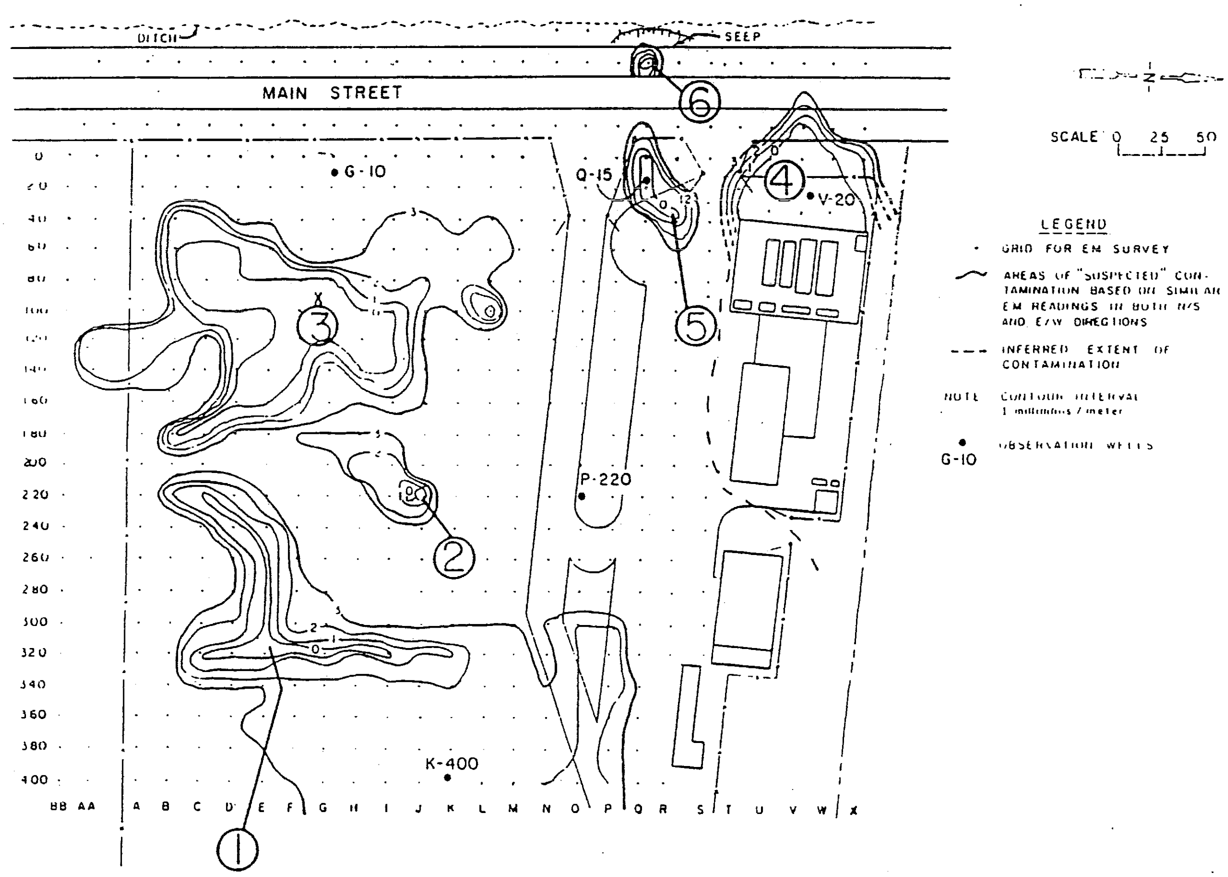
(Greenhouse & Slaine, 1986)

HYDROCARBON SEEPAGE SITE CASE

This project area is presumed to be in Tallahassee, Florida, the authors made no mention of the exact area in text. The project was initiated since a hydrocarbon seepage to surface occurred, proximal to a small chemical mixing plant. A contractor was hired to remove this surface contamination, yet in about a month hydrocarbon contaminant had seeped to surface again. It was now obvious that the contaminant source needed to be located and remediated. (Valentine, 1985)

An inductive electromagnetic survey was initiated over the project area, with readings taken every 20 feet (about 6.1 m). The equidistant dots on Figure #7, page 10 are these data points. The instrument used had a exploration depth of about 6 m. This data was then plotted, with no data processing done on it. (Figure #7, page 10) (Valentine, 1985)

Figure #7: Electromagnetic Hydrocarbon Contamination Contour Map



(Valentine, 1985)

This project made use of electromagnetics prior to drilling, and hence no drill holes were "dry" (didn't encounter contaminants). The source of the contaminant was found, as was a number of other hydrocarbon contaminated zones. These contaminant areas were confirmed by drilling. One area in the survey contained hydrocarbon contamination that was not definitively illustrated by the electromagnetics. This contamination was intersected by drill hole # K-400 at the bottom centre of Figure #7, page 10. This detection was impossible by the survey instrument used, since the contamination depth was below the exploration depth of the instrument. This illustrates the advantage of using variable range of detection zones outlined in the discussion, page 7.

HYDROCARBON DETECTION USING DRILL HOLE CORRELATION

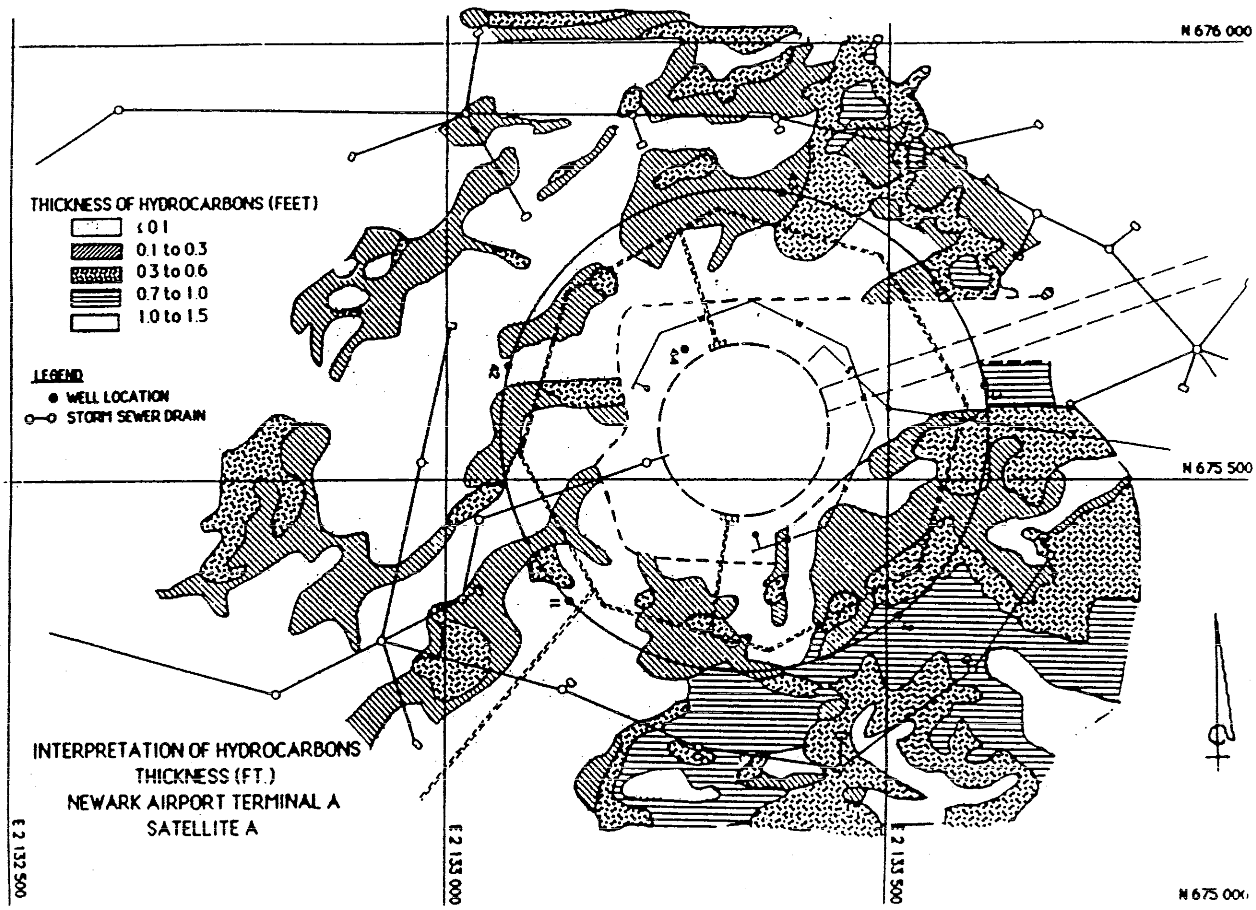
This project area was at Newark, New Jersey. The project area is a terminal of the airport in Newark, where hydrocarbon contamination as seepage was found at various locations. The contamination seepage occurrence was complicated, as well it was logistically impossible to have a drill operating at most locations of the site. Thus a inductive electromagnetic resistivity survey was initiated. The instrument used had a depth of detection zone of about 6 m.

Over a two month period a very detailed survey was completed. The contractor was then given drill hole data from seven holes, giving hydrocarbon contamination thickness values. The contractor then correlated the electromagnetic data to the hydrocarbon thickness data. This was accomplished by taking a resistivity value proximal to a drill hole, and plotting thickness versus resistivity on a graph. This was done for a number of locations, until a value for resistivity corresponding to a contaminant thickness range was ascertained. This correlation was then used to convert resistivity values into contaminant thickness values, including error ranges for the thicknesses. It should be noted that this method does not extract the geologic variation from the data, although this variation at each of the seven drill holes would be accounted for in the error calculation. This data was contoured, Figure #8, page 12. (Saunders, 1985)

To test the validity of the electromagnetic data and the correlation method, the hydrocarbon contaminant thickness values were compared to 28 other test holes at the project site. This comparison showed a 90% agreement of the data to the drill hole data.

The contaminant thickness map was then used to delineate the hydrocarbon leakage areas. It was inferred that leakage from fuel hydrants was largely responsible for the contamination.

Figure #8: Contamination Thickness Map Derived from Electromagnetics and Drilling



(Saunders, 1985)

CONCLUSION

The electromagnetic methods outlined are useful on many remediation projects, given that proper planning is undertaken. The techniques are site specific, hence it is important that the semi-quantitative calculations described in this text are carried out to confirm if the technique is applicable to a project. Precise field technique is also a necessity. Remediation experienced geophysicists should interpret the data.

Electromagnetic remote sensing of contaminants is shown to be applicable for soluble resistivity altering contaminants, and for hydrocarbon contaminants which are less dense than water. The separation of the electromagnetic influence due to geologic or site conditions, from anomalous electromagnetic contamination values is important since it greatly increases the resolution of the method. Negating near surface effects by varying the range of detection and data processing is a partial solution. Correlation to drilling data is a technique which links direct sampling to electromagnetic data, greatly reducing costs yet providing accurate hydrocarbon contamination thicknesses.

The techniques and methods outlined in this paper are not perfected, yet they are functional and cost effective, as illustrated by the field examples. These electromagnetic remote sensing surveys are not a replacement of drilling, but can augment drill data, and save the majority of "dry" (non-contamination intersecting) drill holes.

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BIBLIOGRAPHY

Carmichael,R.S., ed. 1982. "CRC Handbook of Physical Properties of Rocks", Vol. 1, p. 273. CRC Press, Boca Raton, Florida

Culley, R.W., Jagodits, F.L. and Middleton, R.S. 1975. "E-Phase System for the Detection of Buried Granular Deposits", Symposium on Modern Innovations in Subsurface Exploration, 5th Annual Meeting of Transportation Research Board.

Fink, M., 1990. Personal conversation.

Greenhouse, J.P. and Harris, R.D., 1983. "Migration of Contaminants in Groundwater at a Landfill: A Case Study", Journal of Hydrology, Vol. 63, p. 177-197.

Greenhouse, J.P. and Slaine, D.D., 1986. "Geophysical Modelling and Mapping of Contaminated Groundwater Around Three Waste Disposal Sites in Southern Ontario", Canadian Geotechnical Journal, Vol. 23, p. 372-384

Keller, G.V. and Frischknecht, F.C., 1966. "Electrical Methods in Geophysical Prospecting", Pergamon Press, New York, N.Y.

Kledstad, G., Sendlein, L.V. and Palmquist, R.C., 1975. "Limitations of the Electrical Resistivity Measurements in Landfill Investigations", Ground Water, Vol. 13(5), p. 418-427.

McNeill, J.D., 1980. "Electromagnetic Terrain Conductivity Measurements at Low Induction Numbers", Geonics Ltd., Technical Note TN-6, Mississauga, Ontario., 15p.

Parasnis, D.S., 1979. "Principles of Applied Geophysics", Halstead Press, New York, N.Y., 275p.

Saunders, W.R. and Germeroth, R.M., 1985. "Electromagnetic Measurements for Subsurface Hydrocarbon Investigations", Proceedings of the NWWA/API Conference on Petroleum Hydrocarbon and Organic Chemicals in Ground Water-Prevention, Detection and Restoration, Proceedings 1985.

Slaine, D.D., Lee, P.K. and Phimister, J.P., 1984. "A Comparision of a Geophysically and Geochemically Mapped Contaminant Plume", In Proceedings of Surface and Borehole Geophysical Methods in Ground Water Investigations, National Well Water Association and United States Environmental Protection Agency, Texas.

Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A., 1976."Applied Geophysics", Cambridge University Press, London, 860p.

Valentine, R.M. and Kwader, T., 1985. "Terrain Conductivity as a Tool for Delineating Hydrocarbon Plumes in a Shallow Aquifer", Second National Conference on Surface and Borehole Geophysical Methods and Groundwater, Proceedings 1985.

Weast, R.C. ed. 1973. "CRC Handbook of Chemistry and Physics", CRC Press, Boca Raton, Florida