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NON-INVASIVE METHODS FOR ASSESSING GROUND-WATER POLLUTION FROM LANDFILLS: A COMPARATIVE STUDY FROM FIELD EXPERIMENTS

The United States Environment Protection Agency (USEPA) provides strict guidelines for investigating landfills for possible surface-water and ground-water pollution. Non-invasive methods often must be employed if landfill contents are unknown.

Field comparisons of several non-invasive methods in both deep and shallow landfills showed that although magnetics and surface and subsurface geological and chemical testing worked equally well for both, ground-water tracing, gravimetrics, resistivity, electromagnetic induction (EM), and very-low-frequency electromagnetic induction (VLF-EM) worked best in the deep fill. Ground-penetrating radar (GPR) was more useful in shallow fill.

This study showed how non-invasive methods must be especially tailored to each landfill investigation.

1. INTRODUCTION

1.1. THE PROBLEM

How can one investigate the interior of a landfill, or in EPA terminology, a Solid Waste Management Unit (SWMU), and determine where ground-water pollution is coming from if one is not allowed to drill or dig into the SWMU for exploratory purposes because of the possibility of disturbing containers of potentially toxic materials? What are the best methods for remote investigations, considering the depth and contents of the SWMU, and the geological nature of the soil surrounding it? Can existing methods be modified to be more useful in such investigations? Such questions motivated this study at two SWMUs owned and operated by Purdue University in northwestern Indiana (USA), which came under scrutiny by the EPA pursuant to requirements of the Resources Conservation and Recovery Act (RCRA).

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This particular study was part of a larger, EPA-mandated RCRA Facilities Investigation (RFI) of the SWMUs, and was a pilot study for the state of Indiana. The complete Final Report of the RFI (ten volumes) was submitted by LEAP et al. [8] and was accepted by the EPA in February, 1991.

1.2. RESEARCH OBJECTIVES

Research objectives included determining the contents of the SWMUs, their potential for causing ground-water and surface-water pollution, the effectiveness of various non-invasive exploration and testing methods, and finally, the effects of the SWMUs on the environment and human health.

1.3. RESEARCH APPROACH

The approach to meeting the above objectives included the following steps:

1. All historical data such as aerial photos, old maps, etc., were gathered and examined closely to determine the characteristics of the sites before filling began. This proved to be a most useful approach and gave valuable data on original topography and conditions by which later investigative results were compared.
In addition, interviews with former workers, who had information about the history and filling of the SWMUs, proved very valuable. Checking of past hauling records and waste disposal records provided some information.

2. General geology and soil typology were determined from existing geological maps, soils maps, and surficial and subsurface investigations. The latter included hand augering for samples, drilling for deep samples, laboratory testing to determine engineering properties, permeabilities, etc.

3. General flow directions of ground water were estimated from previously-drilled wells near the SWMUs, and later refined by drilling monitoring wells next to the SWMUs, positioned so that they would be most likely to intercept contaminated ground water if any should be leaving the vicinity of the SWMUs.

4. Chemical quality was determined by periodic sampling and analysis of stream sediments, soil samples, stream waters and ground waters. Analyses were performed by a commercial laboratory where water was analyzed for over 260 chemical species in accordance with the rules set forth in the U.S. Code of Federal Regulations, Chapter 40, Part 261, Appendix IX. Soil and sediment samples were analyzed in accordance with the parameter list for the Contract Laboratory Program (CLP) for sites falling under the auspices of the Comprehensive Environmental Compensation and Liability Act (CERCLA) passed by the U.S. Congress.
Chemical analyses were performed on samples from upgradient as well as downgradient locations in order to determine if there were any differences that might indicate true contamination of downgradient samples. Radiological analyses were also performed on soil and water samples.

5. Various surface geophysical methods were employed to determine the interior structure and contents by remote means. These included surveys by magnetometer, gravimeter, ground-penetrating radar (GPR), electrical resistivity, electromagnetic induction (EM), and very-low-frequency electromagnetic induction (VLF-EM).

6. Subsurface characteristics of soil downgradient were determined by test drilling by hollow-stem auger, with extraction of samples which were later laboratory tested for various soil properties; and with hydraulic rotary drilling for deep holes. Wells were emplaced in the drill holes. Gamma-ray logging was conducted in the holes to aid in determining the lithology and stratigraphy of the subsurface.

7. Both gravity and magnetic-surveying methods were combined to produce a hybrid method, utilizing Poissons's Theorem, to aid in subsurface interpretation.

8. Analysis for tritium yielded information about water residence time in the deep SWMU.

9. Finally, the results of geophysical, chemical, geological investigations were compared with each other to determine how well the remote methods performed in elucidating the subsurface characteristics.

2. DESCRIPTION OF FIELD EXPERIMENTAL SITES

2.1. LOCATIONS

Figure 1 shows a map of the Unitet States of America, the state of Indiana and Tippecanoe County in which the sites are located. Figure 2 shows a close-up view of the region near West Lafayette, Indiana, and the exact location of both the

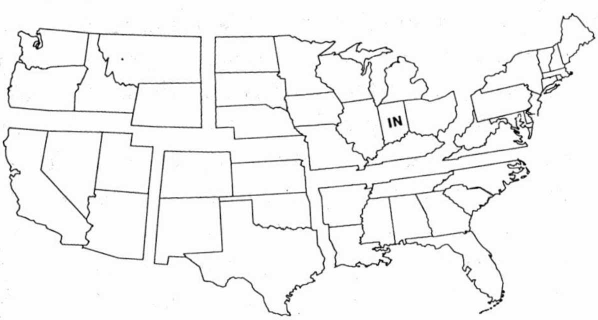

Fig. 1. Map of the United States of America showing various regions and the state of Indiana

Horticultural Research Farm SWMU (hereafter called the Hort Farm SWMU), and the Thomas Farm SWMU. Both arms are used for research purposes by the School

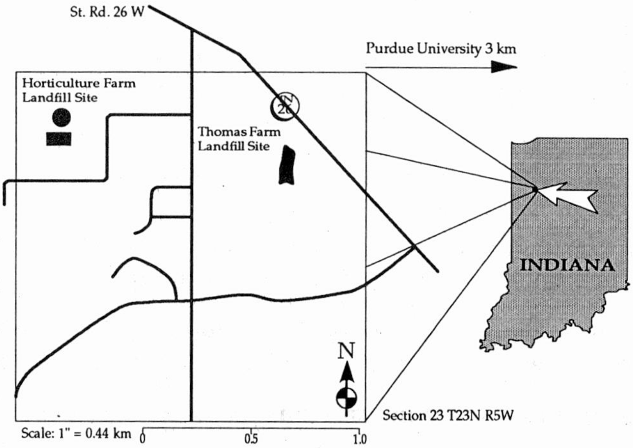

Fig. 2. Locations of the Thomas Farm and Hort Farm SWMUs [13]

of Agriculture at Purdue University. Both sites are located in Section 23, Township 23 North, Range 5 West; and are approximately one kilometer apart.

2.2. REGIONAL HYDROGEOLOG

The bottom of the ground-water flow system is composed of the Mississipian-Devonian New Albany shale, a marine black shale which serves as an aquitard to vertical flow downward from the unconsolidated Pleistocene glacially-deposited materials above it (figure 3). Above the shale, and beneath both of the SWMUs, there is one major deep aquifer system which rests immediately upon the shale.

The system is known as the Wabash Valley aquifer, and it is part of a vast outwash valley-train deposit deposited by glacial meltwater. It is confined in places, and semi-confined in others by overlying till. Near the Wabash River, it is unconfined and it is composed of late Pleistocene, late Wisconsinian outwash, but it extends northwestward for several kilometers beneath the till highlands upon which the SWMUs are found. Thickness of this system ranges from approximately 50 meters beneath the SWMUs to a maximum thickness of nearly 90 meters near the Wabash River.

Flow in this aquifer is generally from the northwest to the southeast and into the Wabash River as can be determined from the potentiometric map shown in figure 4. Near the SWMUs, the flow is to the southwest, toward a thicker part of the aquifer.

The hydraulic conductivity of this aquifer is approximately 125 meters/day, effective porosity is around 0.30, and the storativity has been estimated to range from 0.03 to 0.15 (POHLMANN [11]). Velocity of ground water through this aquifer beneath the SWMUs is estimated at 0.79 meters/day, along a gradient of 0.0019, as determined by Darcy's Law

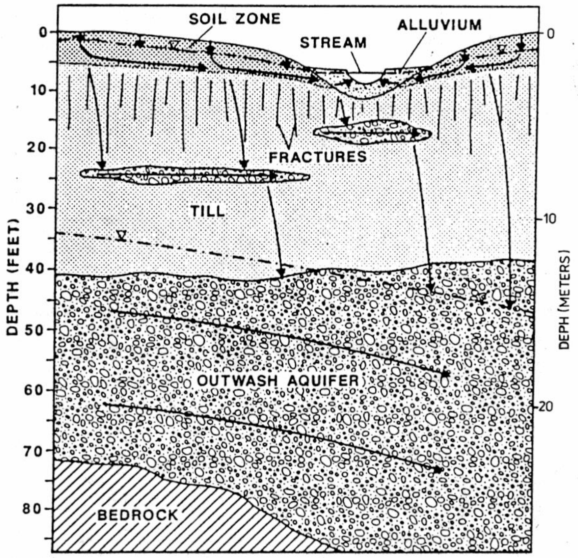

Fig. 3. Cross section of the geology underlying the SWMUs [11]

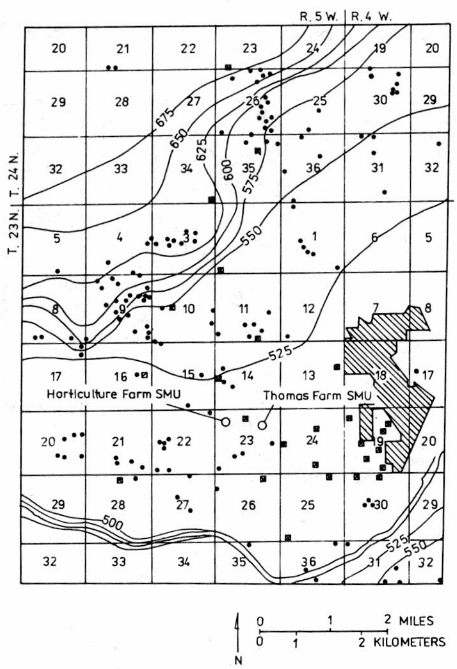

Fig. 4. Potentiometric map of the unconsolidated deep Wabash Valley aquifer system [11]
–575 – potentiometric surface, contour interval 25 feet, 1 – measured water levels, February–April, 1986, 2 – water level from well log

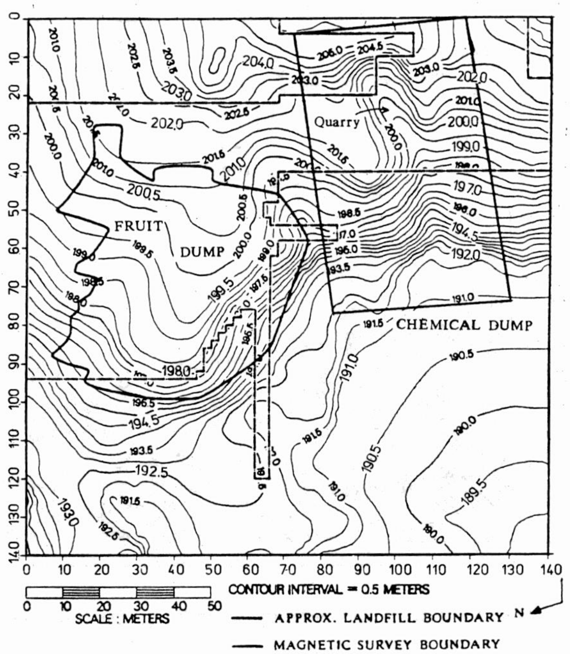

Fig. 5. Pre-fill topography of the Hort Farm SWMU [8]

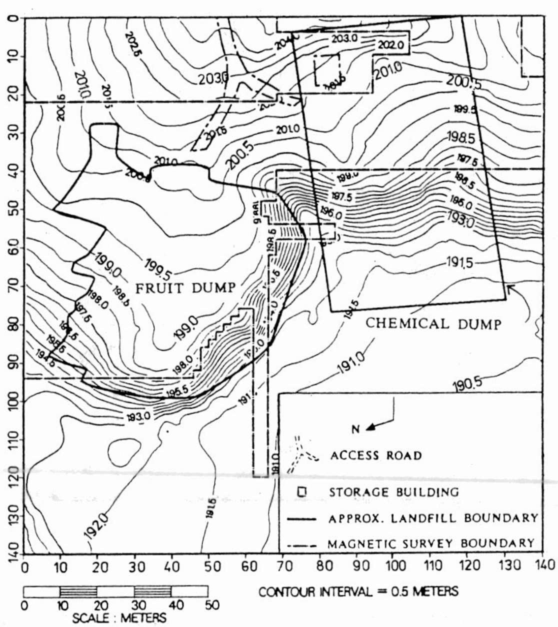

Fig. 6. Post-fill topography of the Hort Farm SWMU [8]

$$v = \frac{K}{n_e} \frac{\partial h}{\partial l} \tag{1}$$

where K – hydraulic conductivity; n_e – effective porosity; h – hydraulic head; and l – flow path length.

In the till above this aquifer system, several small aquifers can be found in many places, generally separated from the lower one by till. A significant unsaturated zone separates any upper aquifer from the lower one.

2.3. THE HORTICULTURAL RESEARCH FARM SWMU

Figure 5 shows the topography of the Horticultural Research Farm (hereafter called the Hort Farm) SWMU, as determined from aerial photos taken in 1958 before dumping had begun. Figure 6 shows the topography in 1989. The 1958 data shows the outline of a gravel quarry that is now abandoned and filled up, and no longer visible as illustrated in figure 5. The gravel was deposited as glacial outwash in a valley-side deposit when the valley served as a minor sluiceway for melting ice about 10,000 years ago, during waning of the late Wisconsinian glacial stage, roughly equivalent to the European glacial time periods, Würm, Weichsel or Valdai (FLINT [4]).

The quarry was used as a dump for agricultural chemicals for a time according to eyewitness reports. Into this dump were reportedly emplaced boxes and drums of various, but unidentified chemicals. The practice was discontinued in the late 1950s; the containers were removed and the quarry depression filled up with locally-derived earthen fill.

Laboratory chemicals were disposed of on the steep, south-facing slope just north of the quarry. Chemicals from teaching laboratories, including salts, acids, bases, peroxides, spent solvents, and reactive metals were simply thrown over the hill and the bottles were broken on the rocks below. Often, these chemicals proceeded to burn by reacting with each other.

The flat area on top of the Fruit Dump was used to dispose of old and abandoned farm machinery and assorted metal junk. Over the edges of the Fruit Dump were thrown rotten apples, pulp from cider-making operations, and other bio-degradable products of a vegetable nature. Along the edge of the Fruit Dump, metal junk, old drums, cans and other containers were disposed of and later covered with a thin layer of earthen fill.

Dumping of chemicals at this site ceased in the early 1970s, and all dumping of all kinds ceased in 1987.

2.4. THE THOMAS FARM SWMU

The pre-fill topography of the Thomas Farm SWMU is shown in figure 7. This SWMU was developed in a valley containing an intermittent stream. The valley was completely filled with refuse and soil to produce the present topography as shown in figure 8.

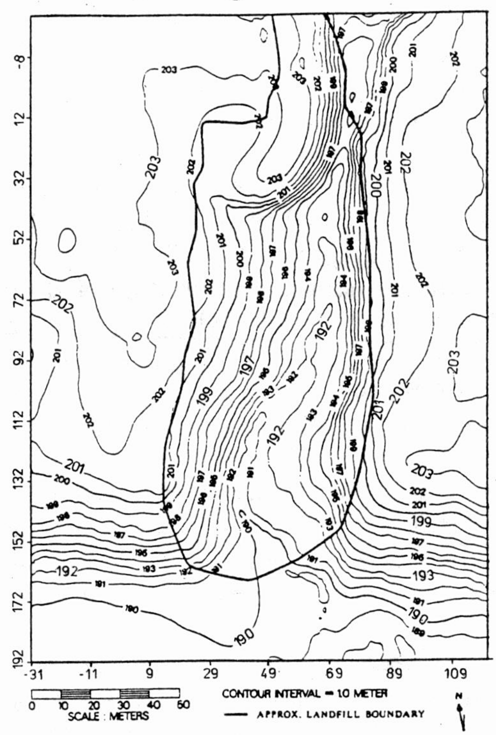

Fig. 7. Pre-fill topography of the Thomas Farm SWMU [8]

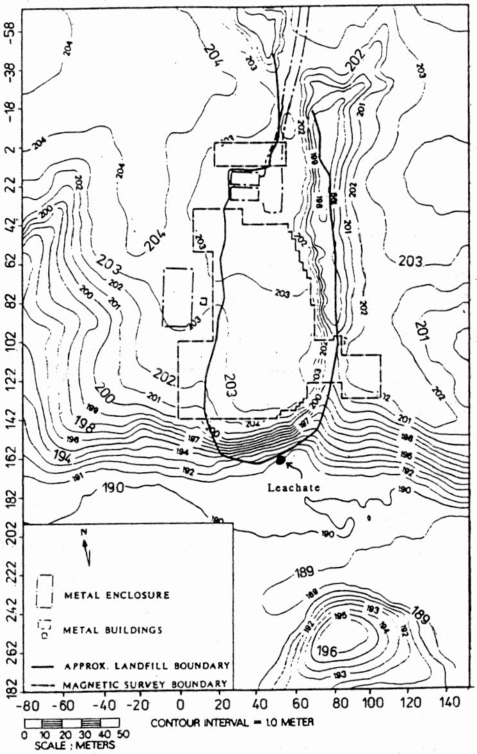

Fig. 8. Post-fill topography of the Hort Farm SWMU [8]

The former stream is clearly visible in figure 7; the present SWMU is drained by a leachate seep at its south end which is in the exact location of the old stream before filling. Thus, the fill in the SWMU has essentially dammed the buried stream and raised the water level to above the surrounding land surface at the south end. As a result, the SWMU is now essentially a unique aquifer with its own water table.

The present thickness of fill in the Thomas Farm SWMU ranges between 10 and 13 meters (3 to 4 times the thickness of the Hort Farm SWMU). Composition of the fill is tree limbs, grass clippings, construction debris, farm machinery, metal junk and minor amounts of laboratory chemicals from the Purdue University teaching laboratories.

3. RESEARCH METHODOLOGY AND RESULTS

3.1. PRE-FILL TOPOGRAPHY VS PRESENT-DAY TOPOGRAPHY

The description of the former and present topographies of both SWMUs, as discussed above, was made possible by aerial photographs that were taken before filling began and in April of 1988. These photos were then digitally scanned and converted to topographic maps with an accuracy of ± 0.30 m as required by the EPA.

The establishment of the pre-fill topography is most important as a first step in any kind of site investigation where a source of ground-water pollution is suspected, because it gives the investigator a real, physical basis of information with which to build a more sophisticated investigation program, and also, it serves as a calibration surface for checking the results of other investigations.

3.2. GEOLOGICAL SURVEYING

3.2.1. SOILS MAPPING

Soils maps are a very necessary resource for such investigations in lieu of a detailed geologic map, especially if there is a question of relative permeabilities of soil and the nature of the parent material. From soils maps, one can often determine the underlying geology, and the geological history of the area as well. In the United States, soils maps can be obtained from major agricultural universities, county agricultural agents, and the U.S. Soil Conservation Service.

3.2.2. TEST DRILLING AND TESTING OF CORE SAMPLES

Several test holes were drilled with hollow-stem auger rigs, and continuous cores were obtained. These holes were drilled to 30 meters below the surface. Cores were analyzed for porosity, storativity, cation-exchange capacity, moisture content and vertical infiltration rates. In both SWMUs, this information proved extremely useful in determining the likelihood of vertical penetration of pollutants.

The low moisture content at depth ($<3\%$) and low vertical permeability (1.5×10^{-7} cm/sec) was found to be characteristic of a thick unsaturated clay-till layer with a high ion-exchange capacity which was determined to serve as a protective barrier to downward migration of contaminants at both sites.

This kind of subsurface information, determined at sites around the SWMUs, was used to infer similar conditions beneath the SWMUs because drilling into the SWMUs was prohibited. No other direct method would have allowed such inferences with such accuracy. Without such boring and testing, this kind of information would have been impossible to ascertain. It is highly recommended for all such investigations.

3.2.3. DRILLING AND INSTALLATIONS OF MONITORING WELLS

Monitoring wells for observing water levels and extracting samples for chemical analysis had to be drilled and finished according to EPA specifications in the Technical Enforcement Guidance Document (TEGD). If the outline of the SWMU is well defined, at least four monitoring wells must be emplaced. Three must be downgradient and one upgradient.

At least one of the downgradient wells must be drilled to the uppermost aquitard beneath the aquifer system of interest. In this case, the aquitard is the aforementioned New Albany shale.

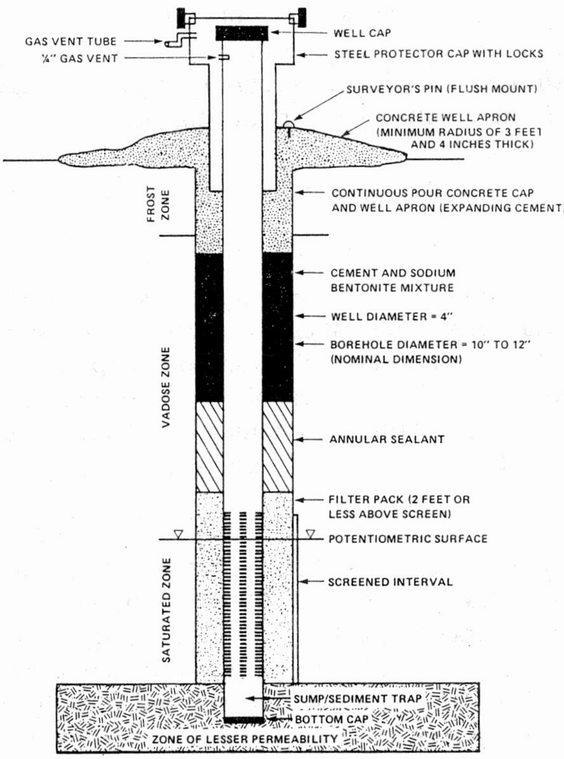

Fig. 9. Schematic diagram of monitoring well emplaced according to EPA directions [17]

Figure 9 shows the general requirements for installing monitoring wells to prevent cross contamination from one aquifer to another. All tools, pipe, and instruments lowered into the holes had to be decontaminated with hot water. All drilling fluids, igneous filter-pack gravel, and bentonite for sealing purposes had to be analyzed for possible contamination.

Monitoring wells had to be positioned around the SWMUs in a non-invasive manner such that they would be in an optimum position to intercept any subsurface contaminants moving downgradient from the SWMUs. Proper positioning could only be made from studying a map of water-level data taken from surrounding private wells.

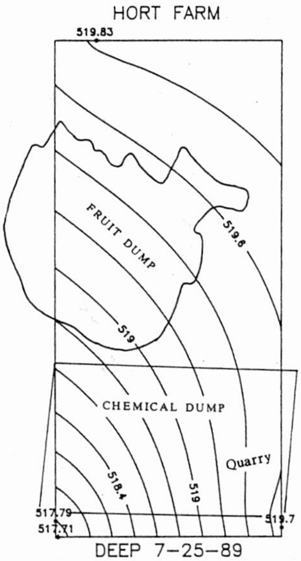

Fig. 10. Water-table map and monitoring well locations at the Hort Farm SWMU [8]

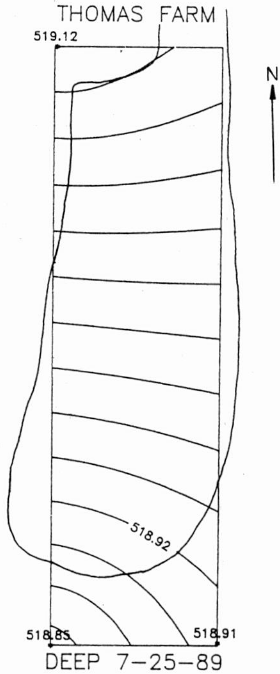

Fig. 11. Water-table map and monitoring well locations at the Thomas Farm SWMU [8]

Once the general gradient of the regional water table was established, the wells were positioned to be most effective in intercepting any potential contamination. Figures 10 and 11 show the positions of deep monitoring wells emplaced at the Hort Farm and the Thomas Farm SWMUs, respectively, and the water-table contours at each site.

Because of the locations of the monitoring the wells in this non-invasive manner, analyses of samples from the wells were used to show that contaminants were not getting into the deep aquifer from which potable water was being taken.

3.3. CHEMICAL ANALYSIS

3.3.1. GROUND-WATER AND SURFACE-WATER CHEMISTRY

If there has been no verifiable, detailed record kept of the chemical materials emplaced in a landfill, the EPA may require for RFIs, as it did in this case, the analysis of both ground water and surface water under the directives set forth in the

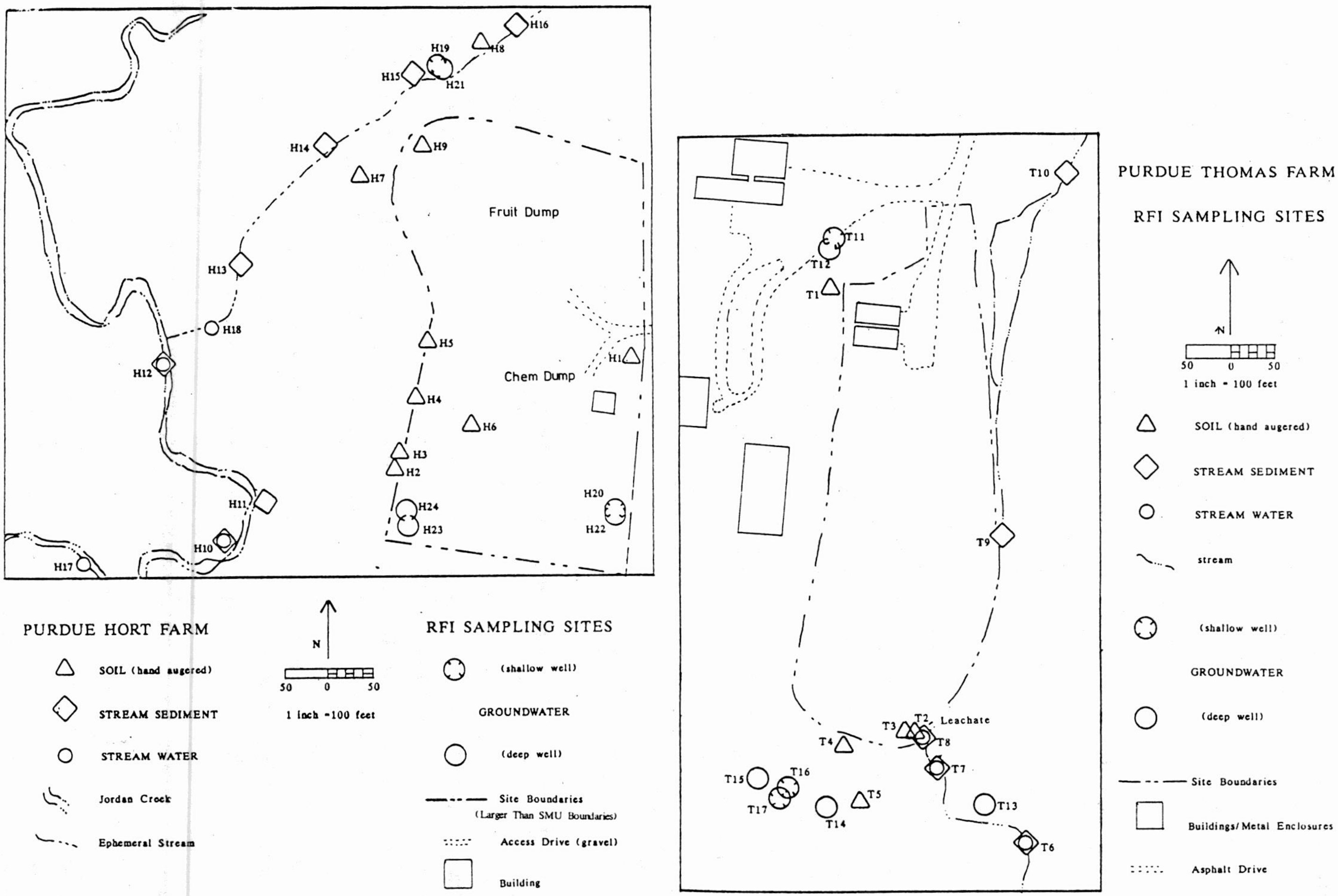

Fig. 12. Surface-water sampling sites at the Hort Farm (a) and Thomas Farm SWMUs (b) [8]

United States Code of Federal Regulations, Chapter 40, Part 261, Appendix IX. This directive requires analysis for metals, cyanide, semi-volatile analytes, volatile analytes and PCBs/Pesticides; this Appendix includes well over 260 different elements and compounds.

Sampling in three separate rounds at different times was also required at all monitoring wells and stream-sampling locations; upgradient as well as downgradient samples were taken. This resulted in analysis from both sites of 43 ground-water samples and stream-water samples. Figure 12 shows surface-water and ground-water sampling sites at the Thomas Farm and Hort Farm SWMUs.

Many elements and compounds, toxic in large enough quantities, exist naturally in soils and water. These result from weathering of minerals and from biological processes. Therefore, it in necessary to carefully analyze samples from upgradient locations for background chemistry. Ultimately, the criteria by which the presence of contamination can be judged are dependent upon background concentration of the chemical species in question. Generally, if a concentration exceeds background, contamination is suspected. After comparing analyses of downgradient with upgradient samples, it was concluded that no contamination was escaping to the hydrological system, except chloride, which was due to pile of road salt (NaCl) which had previously been stored on the surface of the Thomas Farm SWMU.

Such non-invasive sampling was still valid even though sampling was not done in the SWMU itself, because the monitoring wells and surface-water sampling sites were placed in positions most likely to intercept pollution.

3.3.2. SOIL AND STREAM SEDIMENT CHEMISTRY

The EPA requirement for sampling of soil and stream sediment was that the samples be analyzed for all parameters in the Contract Laboratory Program (CLP) list of analytes for Superfund investigations under the U.S. Comprehensive Environmental Compensation and Liability Act (CERCLA). This list contains over 160 parameters in the same five categories as required for water samples.

This non-invasive study was aimed at detecting any solid pollutants downgradient from the SWMUs. After sampling and analyzing a total of 41 soil samples and 16 stream-sediment samples from both locations, no soil contamination was found. Only very small concentrations of PCBs and PICs were detected in stream sediments downgradient from the Thomas Farm SWMU.

3.4. GEOPHYSICAL EXPLORATION

3.4.1. MAGNETOMETER SURVEYING

Magnetometer surveys were some of the most successful non-invasive exploration methods undertaken, in both shallow and deep SWMUs. These surveys were conducted with the objectives of determining the locations of ferrous metals that might also indicate the positions of buried steel drums. If drilling into the SWMUs

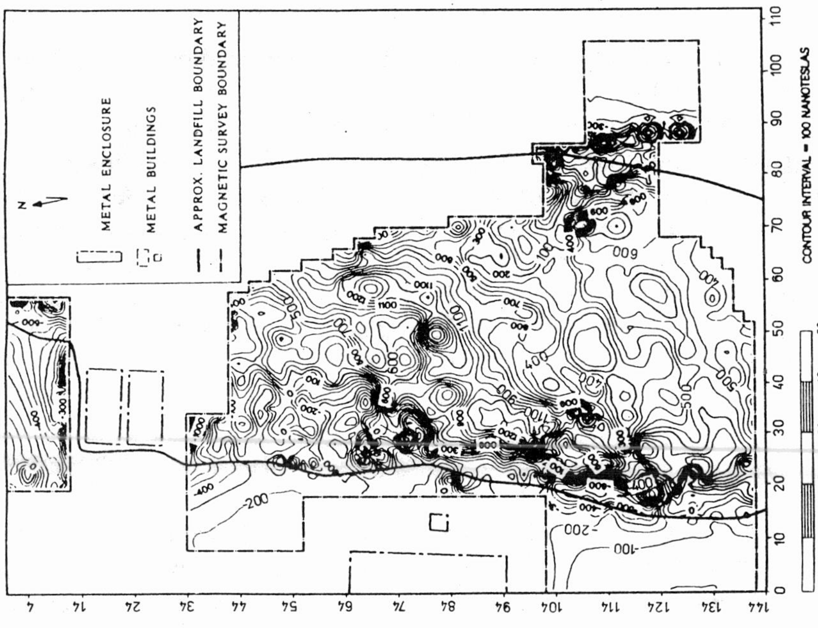

Fig. 13. Total-field magnetic intensity data from the Thomas Farm SWMU [13]

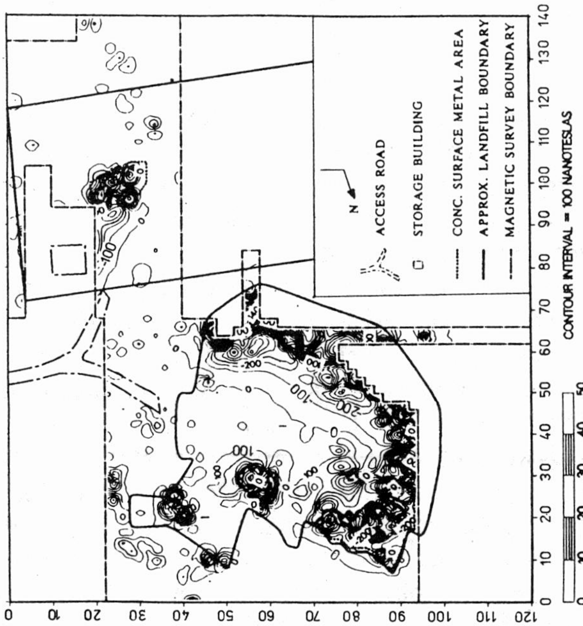

Fig. 14. Total-field magnetic intensity data from the Hort Farm SWMU [13]

were to be permitted in the future, this information would be of great value in locating drilling sites in such a way as to minimize the risk of drilling into buried metal, especially drums.

Magnetic data were collected digitally at both SWMUs using an EG&G Geometrics G-856 proton-precession magnetometer. Temporal variations in total field data were monitored with an EG&G Geometrics G-826A base magnetometer approximately 150 meters from the SWMU.

Observations were made at a height of one meter above the ground surface at stations located on 2 m × 2 m grid. Figure 13 shows observed total field intensity from magnetometer surveying of the Thomas Farm SWMU; figure 14 shows the same for the Hort Farm SWMU.

It easy to see the numerous anomalies on both sites. All of these anomalies result from buried metal that is not visible from the surface. In figure 13, the greatest number and strength of anomalies are along the west side of the Thomas Farm SWMU.

As is shown on the map of the original topography (figure 7), the original land surface is highest along the west edge. A small area of strong anomalies is also found along the eastern edge – this results from the presence of a metal fence. The more broad and weaker anomalies are due to ferrous metal occurrences at depth.

The Hort Farm SWMU (figure 14) shows strong anomalies around the edge of the Fruit Dump. Here metal junk, cans, and other containers are covered by perhaps one to two meters of earth. Scattered anomalies over the area are due to surface junk.

Further refinement of the magnetic data by methods including reduction-to-pole, upward and downward continuation, wave-number filtering, and vertical-gradient calculations gave a slightly better interpretation of especially the deep anomalies (ROBERTS [13], ROBERTS et al. [15], HINZE et al. [5]), but the general magnetic surveying at one meter from the ground surface worked equally well in spotting anomaly locations in both shallow and deep fills. The magnetic method proved to be by far the most successful method for locating buried metal.

One especially useful piece of information from magnetic surveying of the Hort Farm SWMU was the absence of anomalies at the location of the aforementioned old quarry which had later been utilized as a chemical dump. The absence of an anomaly at this point, indicated the absence of buried chemical drums which the investigators previously had feared might be present.

3.4.2. GRAVITY SURVEYING

Gravity exploration was performed only at the Thomas Farm SWMU where the thickness of fill was significant enough to produce a density difference between the fill and surrounding ground. This study may have been the first recorded case of using gravity for determining landfill characteristics (ROBERTS [13], ROBERTS et al. [14]), although it has been used in the past for determining depth to bedrock beneath landfills by RODRIQUES [16] and KICK [7].

The theoretical gravity equation for a point source is

$$g = \frac{Gm}{r^2} \tag{2}$$

where g – cm/s^2; G – the universal gravitational constant (6.67×10^{-8} dyne-cm^2/g^2); m – mass of the object (gms); r – distance from object to measurement point (cm).

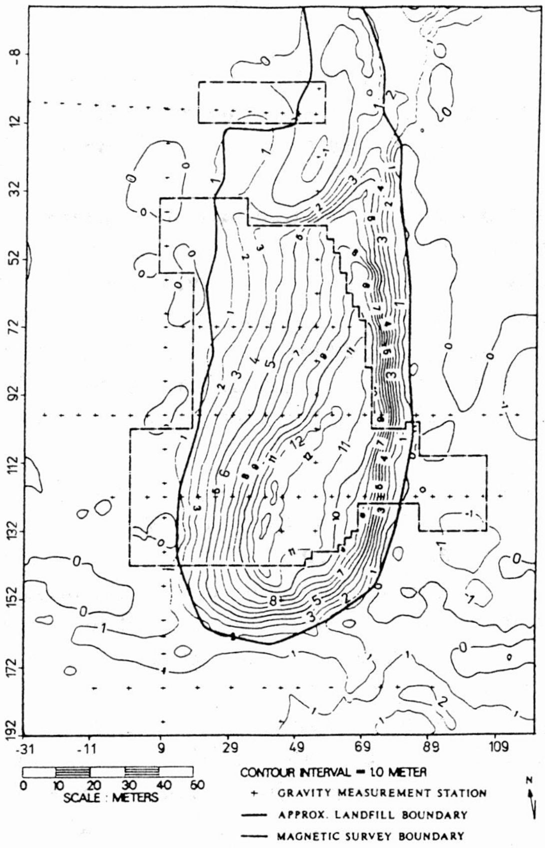

Fig. 15. Isopach map of the Thomas Farm SWMU [13]

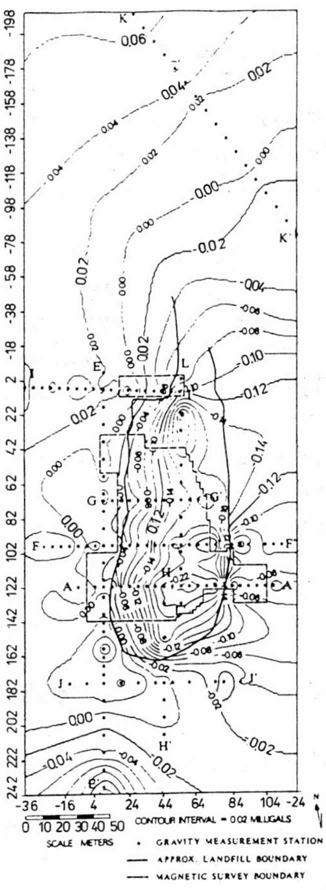

Fig. 16. Complete Bouger gravity anomaly contour map of the Thomas Farm SWMU [13]

The isopach map of the Thomas Farm SWMU is shown in figure 15 for reference and comparison of gravity-survey results. The SWMU and near environs were covered with approximately 200 gravity stations at intervals of 5 to 10 meters. Gravity measurements were made with a La Coste–Romberg Model G gravimeter.

Gravity stations and the Bouger gravity anomaly contour map are shown in figure 16. Gravity measurements were made with a precision of ± 0.01 mGals.

One will note a regional variation over the area. This variation is due to changes in thickness of glacial till and bedrock topography underlying it. A regional trend in gravity was derived by fitting a third-degree polynomial surface to the values obtained at approximately 90 stations surrounding the actual landfill. This surface was then subtracted from the Bouger anomaly to yield a residual gravity anomaly map shown in figure 17. It is assumed that the residual anomaly is derived solely from the density contrast between the landfill material and the surrounding glacial sediments.

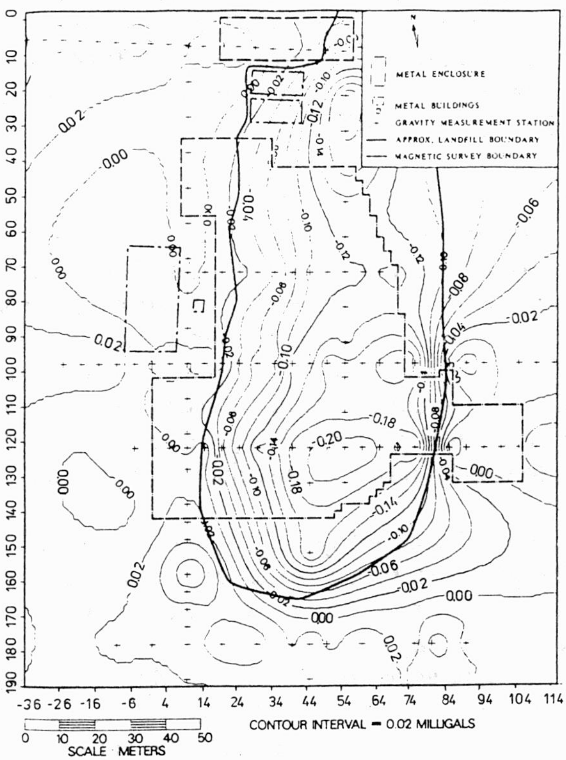

Fig. 17. Residual gravity anomaly contour map of the Thomas Farm SWMU [13]

One major discovery was the utility of the gravity method in determining the approximate bottom location and topography of the landfill. This was accomplished without *a priori* knowledge of the bottom.

A modeling method by CADY [1] was used to model the residual gravity data of profile lines extending over the landfill. From these modeling efforts, computed profiles of SWMU cross-sections were obtained which are strikingly similar to those derived from topographic maps of pre-fill and post-fill times.

Additional, but less trustworthy, estimates of fill porosity and percent saturation were also obtained, and are described in ROBERTS [13] and ROBERTS et al. [14].

The gravity method for estimating the depth and bottom profile of a landfill is therefore highly recommended as a most useful non-invasive method, providing the density contrast between fill and surrounding soil is great enough.

3.4.3. COMBINED ANALYSIS OF GRAVITY AND MAGNETIC DATA

Gravity and magnetic data were combined to yield more useful information about the Thomas Farm SWMU utilizing Poisson's theorem [5]. This approach was tried in an attempt to specify the ratio of the source magnetization to density contrasts, and thus, more accurately determine the characteristics of the landfill contrasts, especially, the relative amounts of iron in various parts of the landfills.

Poisson's theorem (POISSON [12], HINZE [5], HINZE et al. [6]) relates the vertical magnetic anomaly field (ΔH_z) to the anomalous vertical-gradient of the gravity field ($d\Delta g/dz$) of a source by the equation

$$\Delta H_z = (\Delta J/G\Delta\sigma)(d\Delta g/dz) \tag{3}$$

where ΔJ – magnetic polarization contrast of the source; $\Delta\sigma$ – density contrast of the source; G – the universal gravitational constant. No assumptions are required *a priori* about depth, shape or volume of the source of the anomalies.

In order to use this method, the magnetic survey data shown in figure 13 had to be reduced to pole, i.e., the magnetic observation data were processed so that the data would be equivalent to that observed if the earth's magnetic field were dipping vertically at the observation site. This technique is especially useful when the earth's magnetic field has a low inclination, because the dip of the field determines the shape of an anomaly.

If the component of the anomaly due to the vertical dip component of the magnetic field can be observed, then a better idea of the true nature of the magnetic anomaly source can be ascertained because the anomaly is then less affected by lateral components of the magnetic field.

In addition, gravity data were upward continued to 12 meters above the ground in order to obtain a vertical gradient of the gravity data. This process tends to homogenize the physical-property contrasts of the source.

A contour map of reduced-to-pole magnetic data is shown in figure 18. In figure 19 is shown the contoured data of the vertical gradient of the upward-continued gravity anomaly at 12 meters above the ground.

It was assumed that the surrounding glacial till possessed negligible magnetic susceptibility, and that iron objects possess 8 emc/cm^3 for magnetic susceptibility (HINZE et al. [6]). It was further assumed that iron objects possess a density of 7800 kg/m^3, and that an empty 55-gallon steel drum (a U.S. standard volume equal to 208 liters) possesses a weight of 25 kg.

With these assumptions, it was calculated that the mass of iron objects per unit length perpendicular to profiles AA′, BB′, and CC′ (figure 19) were 365, 265 and

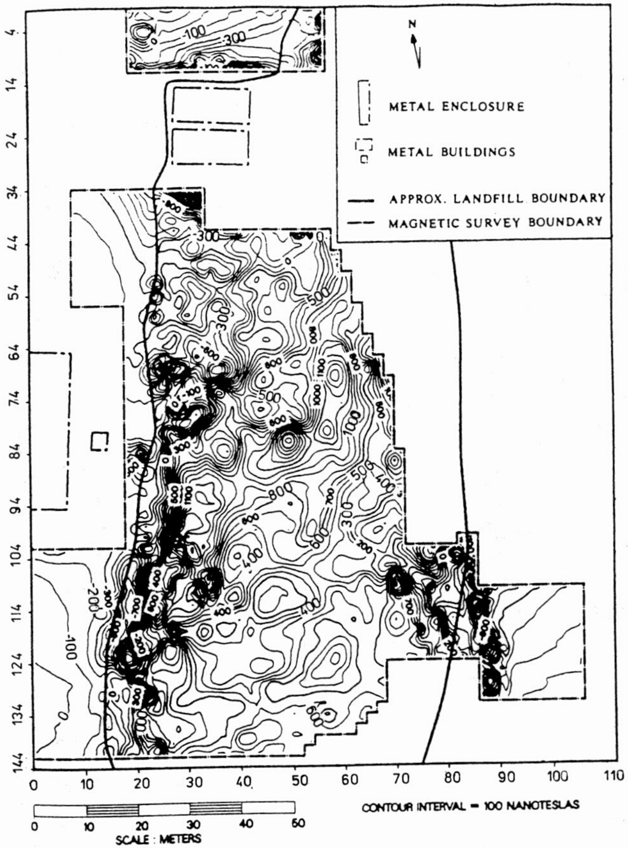

Fig. 18. Contour map of the reduced to pole magnetic data from the Thomas Farm SWMU [13]

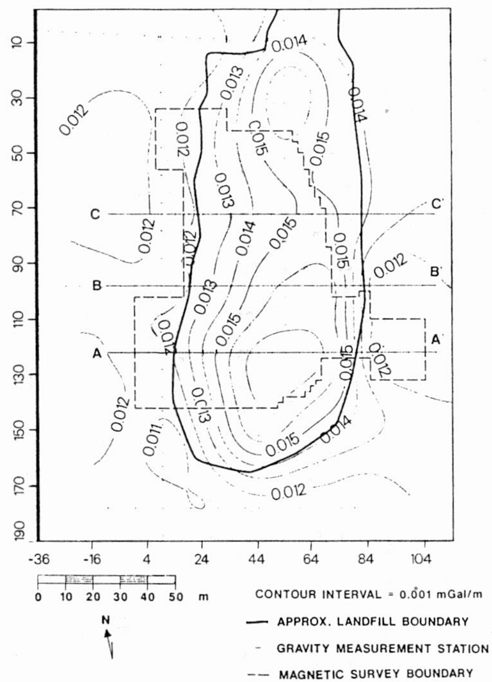

Fig. 19. Contour map of the vertical-gradient of the upward-continued 12-m residual gravity anomaly data at the Thomas Farm SWMU [6]

220 kg/m, respectively. Profile AA′ has the highest iron mass per unit length of the landfill followed by profiles BB′ and CC′, respectively. This derived information matches historical information obtained from eye-witnesses who claimed that more iron junk was emplaced in the north end, and fill containing less iron was placed gradually sothward over time.

It is especially noteworthy that if 55-gallon (208-liter) drums had been emplaced as the only iron objects, then using this approach, it would have been theoretically possible to determine the approximate number of drums per unit length of the landfill. If the approximate number of drums were known previously from historical records, and if the computed number were significantly less, then one would have to assume the possibility of oxidation of the drums with consequent release of any contained pollutants (ROBERTS [13]).

This method needs more work in order to more highly refine it, but already, there is reason enough to seriously consider the method as a standard operating in exploring landfills with enough fill depth and density contrast between fill and surrounding soil.

3.4.4. GROUND-PENETRATING RADAR, GPR

Ground-penetrating radar (GPR) exploration employs the transmission and detection of reflected very-high-frequency (VHF) electromagnetic waves. A diagram of a GPR unit is shown in figure 20. The antenna serves as both transmitter and receiver, and the signal (in order of nanoseconds) is recorded digitally and also on a chart.

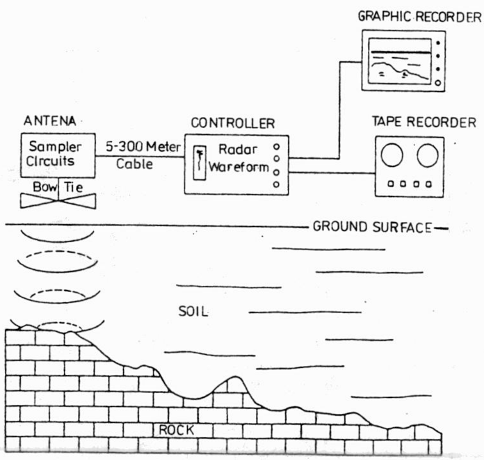

Fig. 20. Schematic diagram of a .typical GPR unit in operation [13]

GPR is a fairly new geophysical method and has been in use less than two decades. Its success in detecting buried objects depends largely on the conductivity of the medium – it can penetrate hundreds of feet of granite, but may not penetrate two meters in a clay-rich soil due to signal attenuation by clay. However, the method has proven successful in locating drums and other objects buried in sand to depths of 10 to 15 meters.

The reflection coefficient from an interface is given as (URLICKSEN [18])

$$r = (z_2 - z_1)/(z_2 + z_1) \tag{4}$$

where z_1 – electrical impedance of media above the interface (in ohms); z_2 – electrical impedance of media below the interface (in ohms).

The electrical impedance in turn is given by

$$z = \frac{\sqrt{j\omega\mu}}{\sqrt{(\sigma + j\omega\varepsilon}} \tag{5}$$

where μ – magnetic susceptibility (henr/m); σ – conductivity (mho/m); j – $\sqrt{(-1)}$; ε – dielectric permittivity; ω – $2\pi f$, where f – frequency (in Hz).

In this study, GPR permitted quick assessment of the shallow subsurface, including determination of the west edge of the Thomas Farm SWMU. However, data from depth was difficult to decipher due to ringing of the reflected signal due to reflections from non-magnetic material.

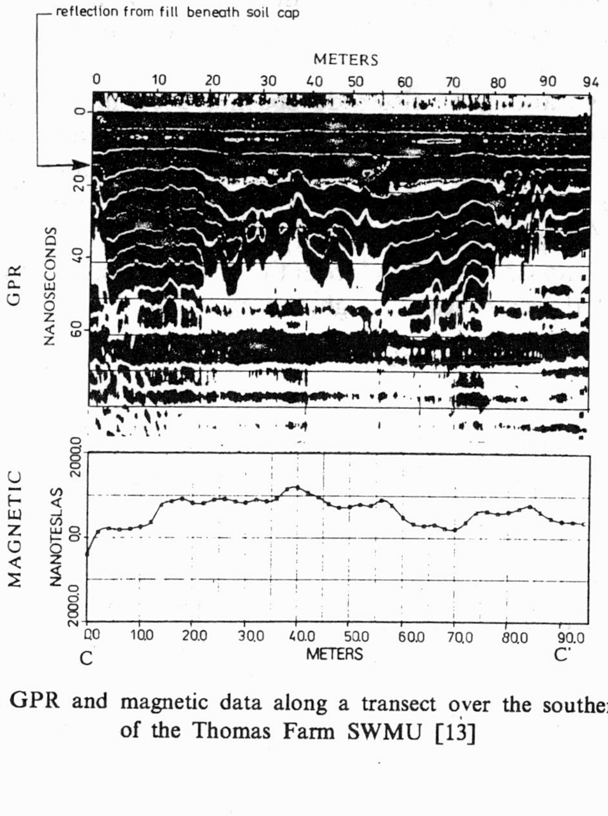

Fig. 21. GPR and magnetic data along a transect over the southern end of the Thomas Farm SWMU [13]

The GPR record did show a distinct reflection along a line over the Thomas Farm SWMU where at the same position, the magnetometer revealed a zone of significant magnetic intensity (figure 21). More detailed interpretation was hampered by ringing which reduced the visibility beneath the conductive zone.

At the Hort Farm SWMU (the shallow landfill), GPR data were of less utility than at the other site due to many reflections that were correlated with shallow water tables and shallow zones of water saturation, or with the interfaces between topsoil and unweathered till beneath.

One additional bit of important information, also found by GPR at this site, was the fact that no metal drums or non-metallic containers were detected in the old quarry, thus corroborating the same inference determined by magnetic surveying.

It is therefore apparent that the success of GPR in landfill investigations in till is heavily dependent upon the lithology of the till, the depth and layering of the fill, and the difference in conductivity between fill and surrounding soils. GPR was not as successful at these sites as at others because of the high amounts of clay and the frequent layers of fill material that had been emplaced. However, GPR should be considered as a potent exploratory or reconnaissance method in landfill studies.

3.4.5. ELECTRICAL RESISTIVITY SURVEYS

The resistivity method utilizes two electrodes driven vertically into the ground a known distance apart. Current is forced into the earth and the drop in potential is measured at two nearby electrodes. The apparent resistivity is calculated in units of ohm-meters (Ω-m).

Different configurations of electrode spacing used in this study include (a) Wenner; (b) Mise-a-la-Masse; (c) Schlumberger, and (d) Lee arrays (figure 22). Each array has both its strong and weak points. The Wenner array was used more than any other because of its good signal/noise ratio, depth sensitivity and resolution of horizontal layers (ROBERTS [13]).

Apparent resistivity (Ω-m) is found from the drop in electrical potential measured across two potential electrodes through the equation

$$\rho_a = 2\pi a(\Delta V/I) \tag{6}$$

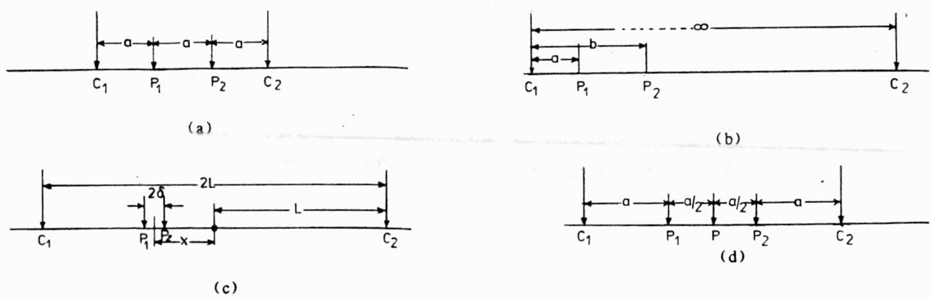

Fig. 22. Resistivity arrays used in this study [13]

where a – a-spacing of the array (m); ΔV – the measured drop in electrical potential between the potential electrodes (volts); I – the current forced into the earth by current electrodes (amperes).

As the a-spacing is increased, the depth of penetration of current is also increased. A set of measurements with increasing a-spacing about a points is called a depth sounding, and the resulting data can yield a vertical resistivity model Resistivity surveys are especially useful in searching for subsurface liquid pollutants because the pollutant plumes are often conductive.

The major negative attribute of resistivity surveying is the length of time it takes to perform a survey as contrasted with the time required for less accurate electromagnetic methods described later.

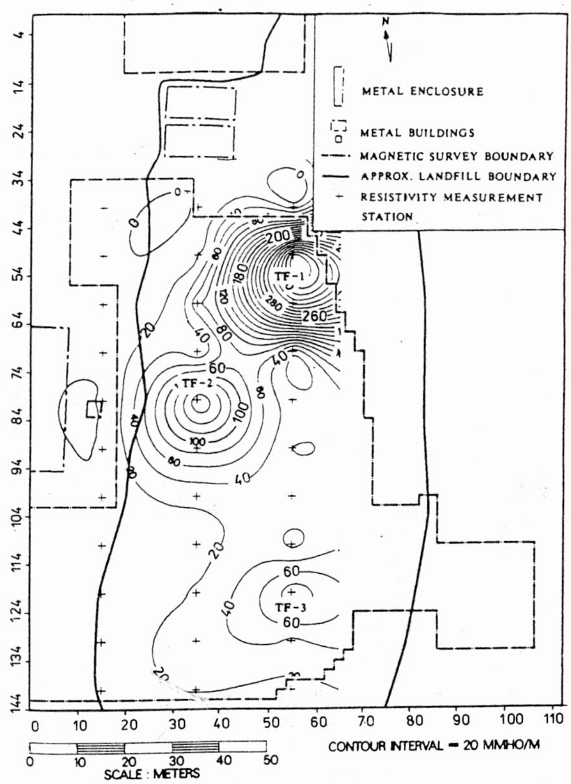

Fig. 23. Contour map of Wenner array (0.3 m a-spacing) conductivity data over the Thomas Farm SWMU surface [13]

Resistivity data were taken over a grid. The data were then contoured over the grid in units of conductivity (the inverse of resistivity) to make it easier to correlate with other electromagnetic data discussed later. Units of conductivity are generally

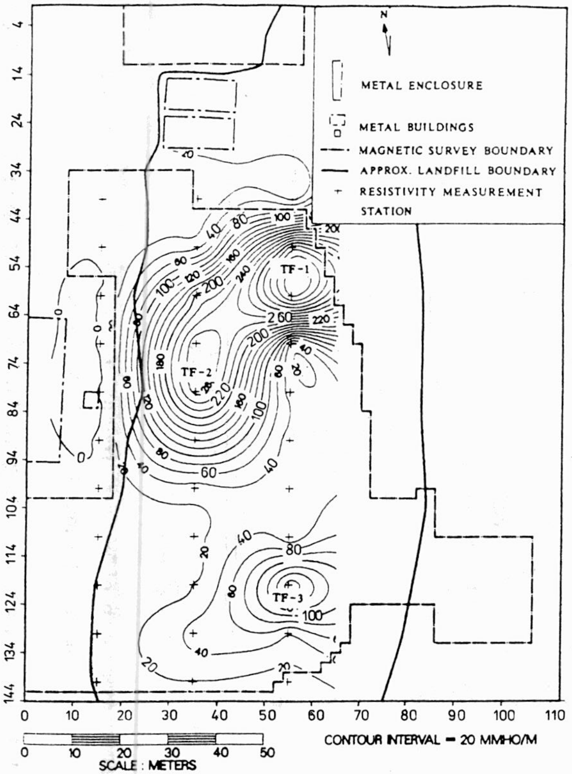

Fig. 24. Contour map of the Wenner array (0.5 m *a*-spacing) conductivity data over the Thomas Farm SWMU surface [13]

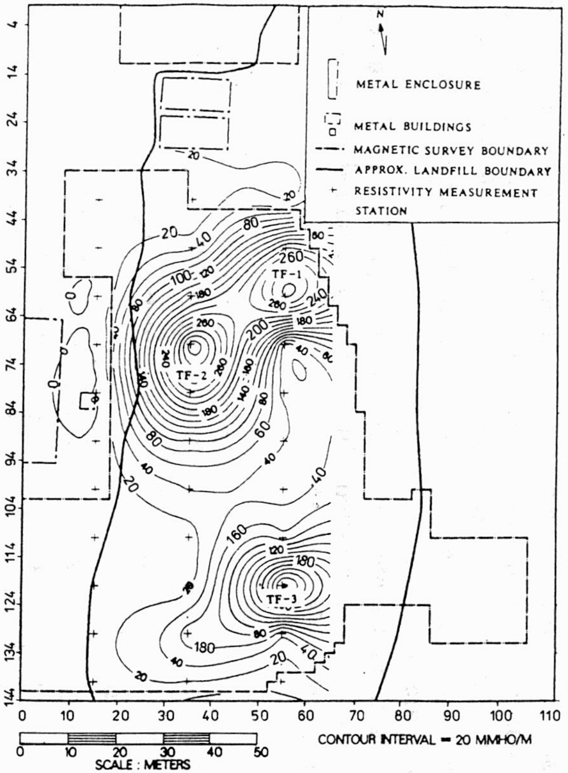

Fig. 25. Contour map of the Wenner array (1.0 m *a*-spacing) conductivity data over the Thomas Farm SWMU surface [13]

expressed as millimhos per meter (mmho/m), which are inversely proportional to units of resistivity as shown by the formula

$$\sigma = 1.000/\rho. \tag{7}$$

Figures 23, 24, and 25 show three high-conductivity areas detected on the Thomas Farm SWMU. The first of these figures shows results from the use of a 0.3-m *a*-spacing; the second, 0.5 m; and the third from a 1.0-m *a*-spacing.

One will note that at site TF-1, the conductivity is highest with use of the 0.3-m spacing, and decreases with increaing *a*-spacing, indicating that most of the conductive material is near the surface. This is due to the residual sodium chloride from a pile of road salt that had previously been stored there.

At the other two sites (TF-2 and TF-3), the greater conductivities were found with *a*-spacings of one meter. This probably suggests that the conductive material at these two sites is deeper than at TF-1. These same sites were also the locations of ringing in the GPR data taken over them.

At the Hort Farm, the resistivity variations with depth appeared to correlate fairly well with changes in stratigraphy with depth.

Less confidence was placed in results from the other kind of arrays mentioned earlier, but the Wenner array survey proved to be of significant value in locating areas of high conductivity at various depths.

3.4.6. ELECTROMAGNETIC INDUCTION, EM

Electromagnetic induction employs two circular loops of wire – one for transmission, and one for receiving. The transmitting loop transmits an alternating current in the KHz range. This current produces an alternating magnetic field in the subsurface which, in turn, induces alternating currents in conductive materials in the subsurface, 90 degrees out of phase with the primary magnetic field.

The receiver coil measures both primary and secondary magnetic fields. Taking the ratio of the secondary magnetic field to the primary field, the apparent conductivity of the subsurface can be found by the equation (McNeill [10])

$$\sigma_a = 4/(\omega\mu_0 s^2)(H_s/H_p) \tag{8}$$

where $\omega = 2\pi f$, where f – the frequency of the transmitted current (in Hz); μ_0 – permeability of the free space; s – coil-separation distance (m); H_s – the secondary magnetic field at the receiver coil; H_p – primary magnetic field at the receiver coil.

Increasing the spacing between transmitting and receiving coils allows greater depth of penetration. Coils can be oriented vertically or horizontally. Expected depth of penetration is approximately 1.5 times the coil spacing for the vertical-dipole mode, and 0.75 times the coil spacing for the horizontal spacing. In this study, surveys were made at 10, 20 and 40-meter spacings, giving a maximum depth of penetration of about 60 m. The vertical dipole mode is not as sensitive to surface conductivity as is the horizontal mode, but the vertical mode is better at detecting conductive anomalies at depth.

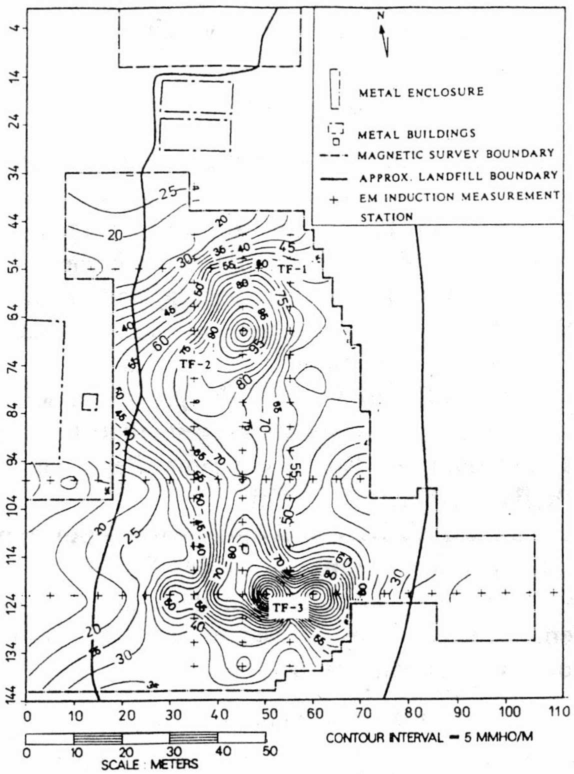

Fig. 26. Contour map of EM induction data taken over the Thomas Farm SWMU [13]

Figure 26 shows a contour map of EM induction data taken over the surface of the Thomas Farm SWMU with 1-m coil spacing in horizontal-dipole mode. Comparison of this figure with figures 21, and 23–25 showing results of GPR, magnetic and Wenner array resistivity surveys, illustrates the close comparison of results by both methods. At the Hort Farm SWMU Fruit Dump, the presence of large masses of metal at or near the surface reduced the precision and effectiveness of the EM approach.

In general, the EM method proved to be a valuable reconnaissance tool in the deeper fill at the Thomas Farm SWMU, but less effective in shallow fill where metal was at or near the surface. It was not as accurate as resistivity, but it is recommended as a means of obtaining general information over a wide area in a relatively short time span.

3.4.7. VERY-LOW-FREQUENCY ELECTROMAGNETIC METHOD; VLF-EM

Very-low-frequency electromagnetic waves are generated by very powerful transmitting stations around the world in the range of 3–30 KHz. These transmitters are used mainly by defense establishments of various nations for communication with submarines.

Near the VLF transmitter, the wave patterns are toroidal (doughnut or bagel-shaped). At large distances the wave curvature is negligible so that it can be considered plane-polarized. The magnetic component of the VLF wave is horizontal and perpendicular to the vector from the VLF wave to the transmitter.

Wave propagation takes the forms of subsurface direct-path, ground-reflected path, shear-wave (reflected off the ionosphere) and guided-path propagation between the ground and the ionosphere. Of these, the best measurements of the subsurface is provided by the guided-path movement.

Depth of penetration is given in meters by WRIGHT [20] as

$$d = 1.7\sqrt{\rho} \tag{9}$$

where ρ – resistivity in ohm-meters.

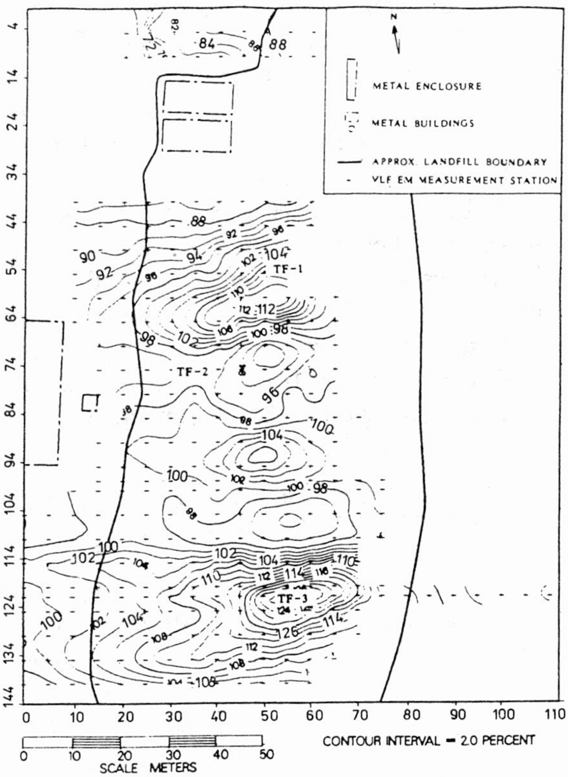

Fig. 27. Contour map of VLF-EM total-field intensity data taken over the surface of the Thomas Farm SWMU [13]

VLF waves in the subsurface cause large current sheets known as galvanic currents. If an anomalous conductor is present, the galvanic currents are attracted to it. The resulting disturbance in the magnetic and electric components of the VLF wave causes the wave to become elliptically polarized with the plane of the ellipse tilted from the horizontal.

The VLF/Magnetometer Omni Plus equipment measures the tilt of the polarization ellipse, the total magnetic component of the field, the vertical in-phase component and the vertical out-of-phase component.

VLF data were collected over a gridded area of the Thomas Farm SWMU at 5-m spacings. The depth of penetration was calculated to be 5 to 8 m using an average conductivity found from resistivity and EM data of 50 to 100 mmho/m.

The VLF method is very sensitive to surface conductivity, but the results of VLF surveying over the Thomas Farm SWMU provided information about conductivity anomalies in the subsurface which compare well with that of resistivity. Figure 27 shows a map of the total-field intensity of VLF data over the Thomas Farm SWMU taken while tuned to the transmitter at Annapolis, Maryland, USA.

Anomalies TF-1 and TF-3 in the deeper areas of the SWMU appear similar to those shown in results from electrical resistivity (figures 23–25). However, anomaly TF-2 does not appear in the VLF-EM map – the reason for this is unclear. Perhaps the sensitivity of the VLF method to near-surface conductivity may have caused a masking of the shallow conductive anomaly at TF-2.

Use of the VLF-EM method at the Hort Farm SWMU was hampered by the presence of metal at or just below the surface. Although there was a strong correlation of VLF anomalies with the magnetic anomalies, the details from VLF were not as well-defined as those from magnetometer surveys.

Thus the VLF-EM method is much better for locating deep conductive anomalies than for shallow exploration. It has the advantage that like EM, it can be used for a reconnaissance study over a large area in a fairly short time.

3.5. GENERAL CONCLUSIONS ABOUT RELATIVE EFFECTIVENESS OF GEOPHYSICAL TECHNIQUES

Table 1 shows general conclusions by ROBERTS [13] regarding the relative effectiveness of the various geophysical methods attempted in this study in shallow and deep landfills. In general, the classical magnetic, gravity, and resistivity methods, used for many years, still are the best overall methods for accuracy in pinpointing buried metal, and for determining depth to landfill bottoms.

3.6. GROUND-WATER TRACING

Groun-water tracing with atmospheric environmental isotopes has been used for many years to track water movement through the subsurface in order to determine the age of water and its recharge rate. This study showed how atmospheric tritium (radioactive hydrogen) can be used as a tracer to great advantage in determining the thoroughput time and residence time of water within a SWMU. This information, in turn, can contribute much to understanding the water balance of a landfill.

Table 1

Relative effectiveness and applicability of potential-field geophysical methods based on the Thomas Farm and Hort Farm landfill investigations [13]

Applications/Concerns	GPR	Magnetic	Gravity	Resistivity	EM 34-3 H. Dipole	EM 34-3 V. Dipole	VLF-EM
Detection of electrically conductive zones							
Vertical resolution	1	NA	NA	5	2	4	1
> 2 m depth	2	NA	NA	5	4	3	1
> 2 m depth	1	NA	NA	5	3	4	1
Lateral resolution	2	NA	NA	5	3	4	1
Detection of non-magnetic objects							
< 2 m depth	5	NA	1	NA	NA	NA	NA
> 2 m depth	3	NA	1	NA	NA	NA	NA
Detection of magnetic objects							
< 2 m depth	4	5	1	1	2	2	2
> 2 m depth	3	5	1	1	2	2	2
Determination of landfill thickness	1	3	5	2	2	2	1
Determination of lateral landfill surface contacts	5	4	3	2	2	2	2
Quantitative interpretation capabilities	1	4	5	3	2	2	1
Average signal-to-noise ratio	3	4	5	4	3	3	2
Confidence in forward and inverse interpretation	NA	4	4	4	3	3	NA
Surveying efficiency	5	4	1	2	3	3	4
Initial qualitative interpretation capabilities	2	5	1	3	4	4	2

5 = high degree, 1 = low degree, NA = not applicaple

Tritium moves through the hydrological system as tritiated water (HTO) with a half life of 12.43 years (MANN et al. [9]), and is a low-level beta emitter. Tritium is normally measured in tritium units (TU) where 1 TU=(1 atom T)/(10^{18} atoms H). Figure 28 shows the distribution of tritium in tritium units over time at Ottawa, Ontario, Canada; and Chicago, Illinois, USA (DANIELS et al. [3]). The high peak occurring in the early 60s is due to the large load of tritium put into the atmosphere by above-ground nuclear weapons testing in the late 50s and early 60s. Since the cessation of atmospheric nuclear testing, the world's atmospheric tritium has been decreasing.

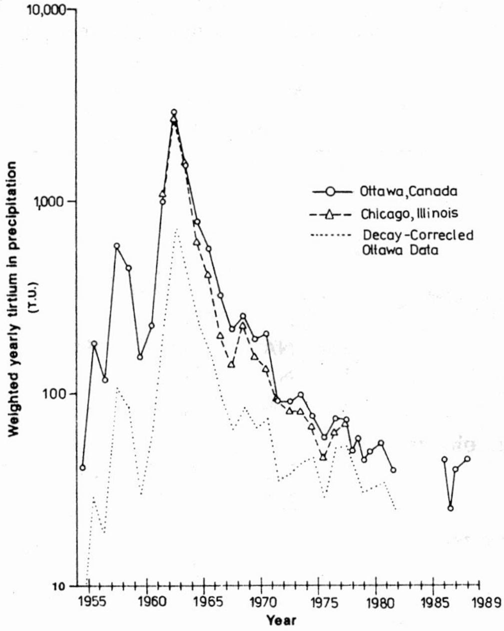

Fig. 28. Tritium in precipitation at Ottawa and Chicago [3]

Tritium concentration can also be reported in curies (Ci). One curie equals 2.22×10^{12} disintegrations per minute of any radioactive substance.

The following equations are used to determine the elapsed time, Δt, between the entrance of tritiated water from the atmosphere into a particular hydrologic system (a landfill for example) and its exit at a sampling point (CHASE and RABINOWITZ [2])

$$\Delta t = -\ln(N/N_0)/\lambda \tag{10}$$

and

$$\lambda = 0.693/t_{1/2} \tag{11}$$

where $N(t)$ – concentration at sampling time; N_0 – concentration that entered the system; $t_{1/2}$ – half life of the isotope.

Six tritium analyses taken of precipitation in the West Lafayette, Indiana area, between August 1988 and March 1990 had values ranging between 8.2 and 14.3 TU. These values are consistent with reported values for tritium in the northern hemisphere (figure 28). Table 2 shows tritium analyses for stream and ground water at the Thomas Farm. All water samples were collected between August 1988 and March 1990. Three tritium analyses of well TA1 and two tritium analyses of the seep at the toe of the SWMU gave results that ranged from 31.6 to 33.7 TU. Using figure 28, we judge that water having 30 TU represents precipitation less than 5 years old. Thus, residence time of water in the SWMU is 5 years or less.

Table 2

Results of tritium analyses of water from the Thomas Farm SWMU and surroundings

Sample number	Well	^3H in TU
TUGW-**0061**-012689	TA-1	32.9
TUGW-**0078**-032389		33.7
TUGW-**0095**-053189		33.3
TDGW-**0105**-062089	TR-6	56.1
TDGW-**0118**-062989		57.7
TDGW-**0106**-062089	TR-5	84.8
TDGW-**0119**-062989		76.6
TDSW-**0060**-012689	Seep	33.0
TDSW-**0077**-032389		31.6

The sample numbers are coded for easy reference. The 'T' stands for 'Thomas Farm'. The next letter is either a 'U' for 'upgradient' sample, or 'D' for 'downgradient sample'. The next two letters denote the type of sample. 'SW' represents 'Stream Water', while 'GW' represents 'Ground Water'. The bold numbers represent the sequential sample number of the entire project. Finally, the last 6 numbers denote the date at which the sample was taken. For example, TDGW-**0105**-062089 is a downgradient groundwater sample taken at the Thomas Farm on June 20, 1989. This was the 105th sample taken in the entire project.

In contrast, the much higher tritium activity of well TR5 (averaging 80 TU) indicates that this well is presently receiving water that fell as precipitation in the 1960's. According to figure 28, rainfall with tritium activities around 80 TU has not fallen since the mid-1970's. Correcting for tritium's 12-year half life would put recharge to TR5 back into the mid-1960's.

Well TR6 is only 4 meters away from TR5; yet the depth-to-water for TR6 (18 m) is 6 meters deeper than that for TR5. In other words, TR6 taps a separate perched water zone, and the deeper perched aquifer of TR6 is receiving more modern recharge than TR5 as judged from the lower tritium activity of TR6. The two tritium analyses of TR6 average 56 TU. Again, using figure 28, we estimate that 56 TU corresponds to rainfall in the early 1980's. Adjusting for the tritium's half life, this would put recharge for TR-6 probably in the mid-1970's.

4. CONCLUSIONS

Results from this comparative study illustrate the relative effectiveness of various methods, used alone or in conjunction with others, for exploring both shallow and deep landfills for possible surface-water and ground-water pollution. In general, we conclude the following about non-invasive methods described in this paper:

1. Basic knowledge of soils and surface and subsurface geology is a must – a necessary first step for making sense of the results of other methods. This approach is too often overlooked in environmental studies in favour of more sophisticated geophysical methods.

2. History of the landfills before, during and after filling is most important. Knowledge of topography before and after filling is also very useful for interpretation of result from nearly all methods of exploration.

3. It is also necessary that previous knowledge of regional ground-water flow directions be ascertained from pre-existing wells before monitoring wells are drilled and emplaced for ground-water sampling in order to better position them for capture of possible pollutants.

4. If at all possible, every attempt should be made to determine the composition of materials placed in the fill in order to better target chemical species for analysis.

5. Geophysical exploration methods must be used judiciously, but they can yield very good information about the surface of landfills.

Exploration of deep landfills is best accomplished by gravity, magnetics and combinations of both. Gravity is generally useless in shallow fills, whereas magnetics can detect anomalies in both shallow and deep fills.

Both EM and VLF-EM are good methods for general reconnaissance of deep fills. Shallow buried metal may limit the effectiveness of these methods. They can, however, be used to locate areas of high conductivity over which more detailed resistivity, gravity, magnetic, or GPR surveys can be made.

Resistivity is a good method in both shallow and deep landfills, but excessive metal at or near the surface may reduce the interpretability of the results by this method.

Ground-penetrating radar (GPR) is not very efficient in deep fills, especially in layered fills containing clay or saturated zones. It is useful for detecting buried containers in sandy fills 10 meters or less in thickness, and under the right conditions, detecting non-metallic containers which could not be detected by other electromagnetic methods.

6. Tracing ground-water movement with environmental isotopes through a landfill, especially a deep fill with a ground-water discharge point on the surface, or

with properly-placed down-gradient monitoring wells, can be most useful in determining the residence time and travel time of water in the landfills, or travel time of water to permeable zones beneath the landfills.

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BEZINWAZYJNE METODY OCENY ZANIECZYSZCZENIA WÓD PODZIEMNYCH Z WYSYPISK. BADANIA PORÓWNAWCZE OPARTE NA DOŚWIADCZENIACH PRZEPROWADZONYCH W TERENIE

Amerykańska Agencja Ochrony Środowiska (USEPA) dostarcza dokładne wytyczne badania wysypisk w celu oceny potencjalnego zanieczyszczenia wód powierzchniowych i podziemnych. Gdy nie wiadomo, co tworzy wysypisko, często należy stosować metody bezinwazyjne.

Terenowe badania porównawcze kilku bezinwazyjnych metod przeprowadzone zarówno dla głębinowych, jak i płytkich wysypisk wykazały, że testy magnetyczne, geologiczne powierzchniowe i podpowierzchniowe oraz chemiczne dają porównywalne wyniki dla obu rodzajów wysypisk. Stwierdzono jednak, że w przypadku wysypisk głębinowych najlepsze rezultaty uzyskuje się stosując następujące metody: badanie wód podziemnych, testy grawimetryczne, pomiary oporności gruntów i elektromagnetycznej indukcji (EM) oraz elektromagnetycznej indukcji o bardzo niskiej częstotliwości (VLF-EM). W przypadku płytkich wysypisk najbardziej użyteczna okazała się metoda gruntowej penetracji radarowej (GPR).

Badania wykazały, że wybór bezinwazyjnej metody zależy od rodzaju wysypiska.

БЕЗВМЕШАТЕЛЬСТВЕННЫЕ МЕТОДЫ ОЦЕНКИ ЗАГРЯЗНЕНИЯ ПОДЗЕМНЫХ ВОД ИЗ МЕСТ ДЛЯ ОТВАЛА. СРАВНИТЕЛЬНЫЕ ИССЛЕДОВАНИЯ, БАЗИРУЮЩИЕ НА МЕСТНЫХ ОПЫТАХ

Американское Агентство Охраны Среды (USEPA) доставляет точные указания, касающиеся исследований мест для отвала с целью оценки потенциального загрязнения поверхностных и подземных вод. Когда не известно, что составляет отвал, надо применять безвмешательственные методы.

Местные сравнительные исследования нескольких безвмешательственных методов, проведенные как для глубинных, так и для мелких отвалов обанаружили, что магнетические, геологические поверхностные и подповерхностные, а также химические тесты дают сходные результаты для обоих видов отвалов. Было однако установлено, что в случае глубинных отвалов наилучшие результаты получают, применяя следующие методы: исследование подземных вод, гравиметрические тесты, измерения сопротивления грунтов и электромагнитной индукции (EM), а также электромагнитной индукции очень малой частоты (VLF-EM). В случае мелких отвалов наиболее полезным является метод грунтовой пенетрации с помощью радиолокационных станций (GPR).

Исследования обнаружили, что выбор безвмешательственного метода зависит от вида отвала.