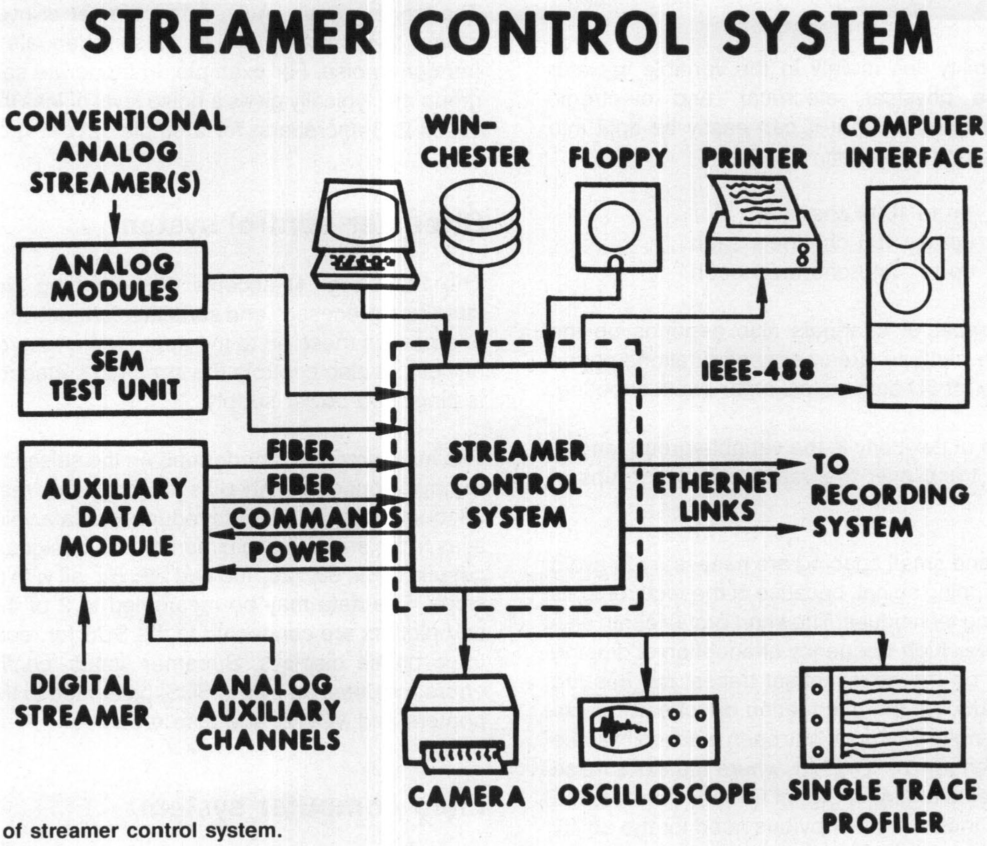

FIGURE 4
Block diagram of streamer control system.

Mapping and Monitoring of Toxic Wastes with Subsurface Electrical Resistivity Arrays

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Summary

Ground water contamination is a major problem facing industrial nations. Electrical methods seem particularly promising in mapping and monitoring ground water regimes since the electrical conductivity of rocks depends almost entirely on the fluid saturation, salinity, and distribution. The most important recent developments in resistivity include the use of numerical modelling and resistivity mapping using subsurface electrodes. The latter yields far greater accuracy and resolution than can be obtained with surface arrays. To illustrate the power of subsurface-surface arrays we have studied an idealised two dimensional model of a contaminated zone. Since we are interested in emphasising the anomaly caused by the repository, or subsequent changes over time in its vicinity, we have discovered that it is very useful to express the apparent resistivity results as percentage differences from either the background (for surface arrays) or from the apparent resistivities observed at a particular depth of the current source (for subsurface arrays). Percent differencing with respect to data at the repository depth dramatically reduce near-surface and topographic effects that usually confound quantitative interpretation of surface surveys. Thus, dc resistivity appears to have great potential for mapping and monitoring zones of impaired ground water.

Introduction

Ground water contamination is a major problem facing industrial nations. Leaching of landfill waste sites, industrial or agricultural liquid wastes, and invasion of saline waters into heavily used aquifers all result in contamination that threatens the water supply. In addition, drilling for oil and natural gas, often with associated reinjection and improperly abandoned wells, can open pathways between clean and uncontaminated aquifers.

As the source and volume of subsurface contamination is determined and then, as remediation progresses, the changes in the contamination must be monitored. Drilling is the most accurate means of characterizing the contamination but has associated with it some serious drawbacks. The number of holes required to map a plume with confidence is large and frequently expensive. In many cases such drilling may be especially difficult and expensive due to commercial or other development in the surroundings. Further, the invasive nature of the drilling process may worsen the problem (for instance in areas with confining beds) especially in probing the source area.

Geophysical methods of mapping the electrical resistivity of the ground have proven very successful in delineating areas contaminated with certain chemicals. The electrical conductivity of the ground can be measured by injecting current into the ground through pairs of electrodes and then measuring the resulting voltage drops in the vicinity with other pairs of electrodes. Any or all of the electrodes can be placed in the subsurface, although traditionally surface arrays have been employed. Measurements of voltage and current for different electrode geometries are then used to infer the subsurface distribution of conductivity.

Surface current and potential electrode arrays have been used for many years to determine the subsurface resistivity. The most important recent developments are the use of two and three-dimensional numerical models for interpretation, and resistivity mapping using subsurface electrodes. The latter yields far greater accuracy and resolution than can be obtained with surface arrays. This new development opens the way to more quantitative analysis of ground conductivity and offers exciting opportunities to map and monitor fluid content, temperature and fracture distribution at contaminated sites. To illustrate the power of subsurface-surface arrays we have picked an idealized model of a contamination plume to show the responses from conventional and from borehole-to-surface arrays.

Modelling

The model is shown in Fig. 1. We have assumed that the effective resistivity of a 10 m thick zone has decreased by a factor of two under the normal or background value (in this case 100 ohm-m). The results of a standard dipole-dipole surface survey are presented for the model of Fig. 1 in Fig. 2. The apparent resistivity data are shown as a contoured pseudo section (a standard format) and also projected into a three-dimensional perspective plot (Fig. 2). Since we are interested in emphasising the anomaly caused by the plume, or subsequent changes over time in its vicinity, we have discovered that it is very useful to express the apparent resistivity results as percentage differences from the background. The data in Fig. 3 are the percent differences observed in the apparent resistivity relative to the 100 ohm-m half-space. The anomaly is diffuse and broad but quite large enough to be detected. Our experience in high accuracy field surveys has shown that it is possible to make apparent resistivity measurements with an accuracy of 0.1%. For time monitoring with fixed surface electrodes the sensitivity to small changes in the plume resistivity (e.g. as water re-entered the zone) would therefore be quite high.

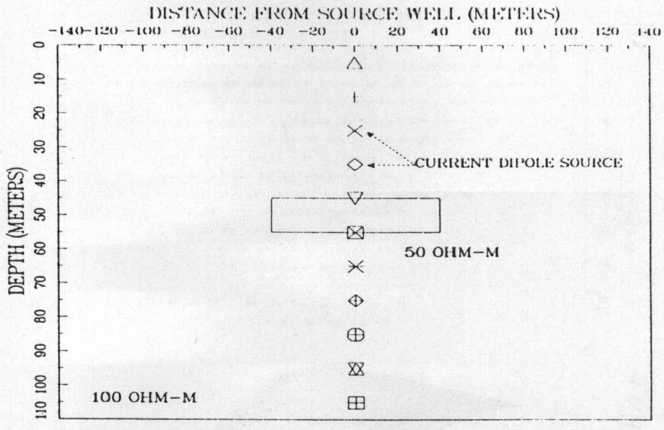

FIGURE 1

Idealised model of a contaminated ground water zone. The symbols represent current electrodes in the subsurface dipole configuration.

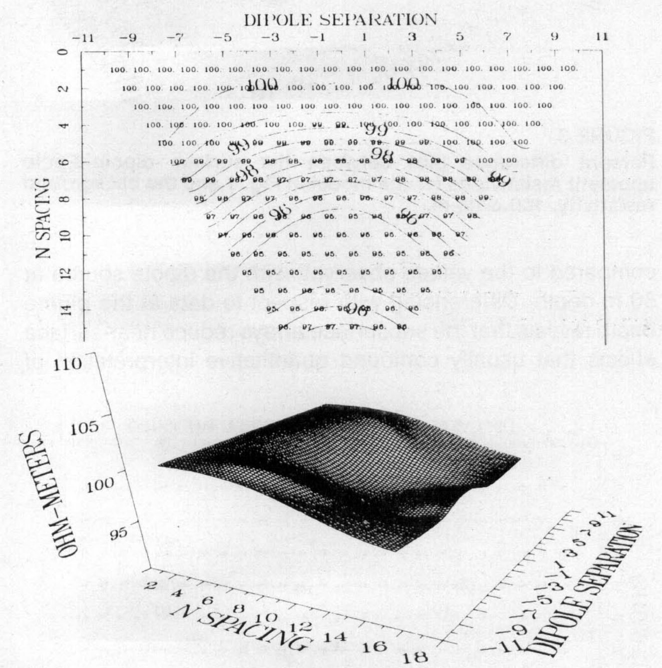

FIGURE 2

Dipole-dipole apparent resistivities for the model in Fig. 1. 'Dipole Separation' refers to the location of the dipoles relative to the centre of the model.

Resolution can be improved using subsurface dipole sources and surface receiver dipoles. As shown in the model (Fig. 1), the current electrodes are placed every 10 m vertically and are treated as a series of dipole sources. The apparent resistivities measured for a given depth of the current dipole and location of surface potential electrodes are plotted vertically midway between the current electrodes and horizontally midway beneath the potential electrodes.

A dramatic definition of the contamination plume boundaries is produced by using percent differences calculated, not in reference to the background halfspace resistivity, but compared to the apparent resistivities observed at a particular depth of the current dipole source. An example is shown in Fig. 4 in which all the apparent resistivities in the section are

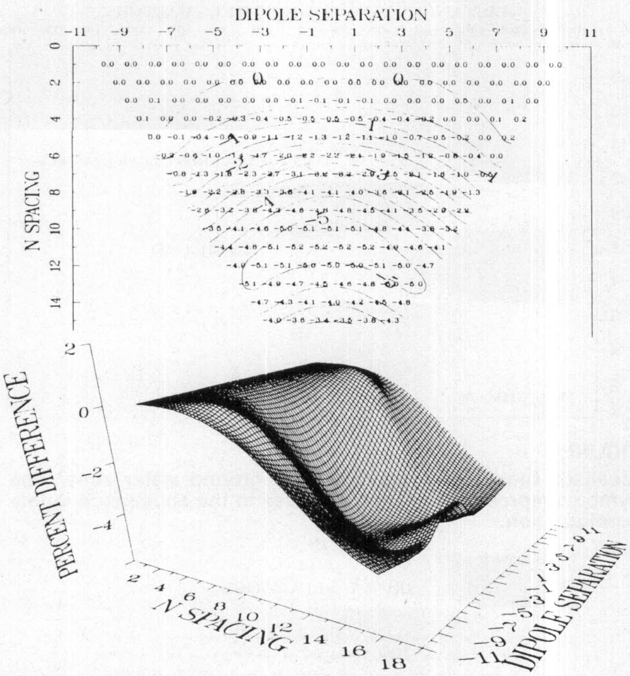

FIGURE 3
Percent difference plot between the surface dipole-dipole apparent resistivities for the model in Fig. 1 and the background resistivity, 100 ohm-m.

compared to the values observed with the dipole source at 50 m depth. Differencing with respect to data at the plume depth reveals that the subsurface arrays reduce near-surface effects that usually confound quantitative interpretation of surface surveys. This technique also eliminates 'anomalies' caused by topographic features.

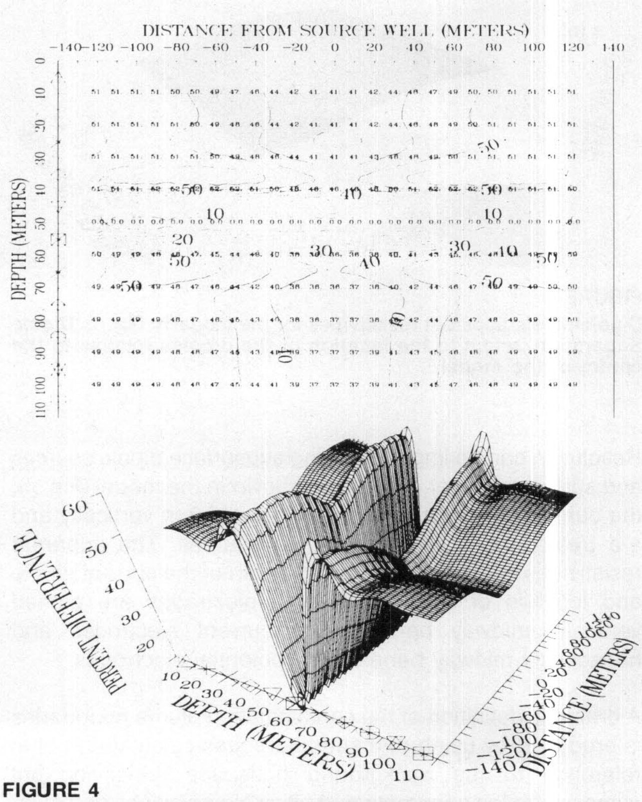

FIGURE 4
Percent differences using borehole dipole sources referenced to the apparent resistivities obtained with the current dipole at 50 m depth.

Finally we have examined the power of these subsurface methods to see changes that might occur after the plume has migrated down-gradient an additional 20 m (Fig. 5). In Fig. 6 we have plotted the percent changes that this brings about referenced against the data from Model 1. The pseudo section is diagnostic of the zone that has changed and the changes are well above the accuracy that can be expected for the measurements.

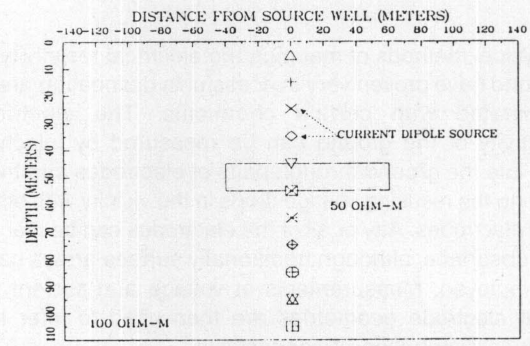

FIGURE 5
The contaminated zone in Fig. 1 has progressed an additional 20 m after some given time.

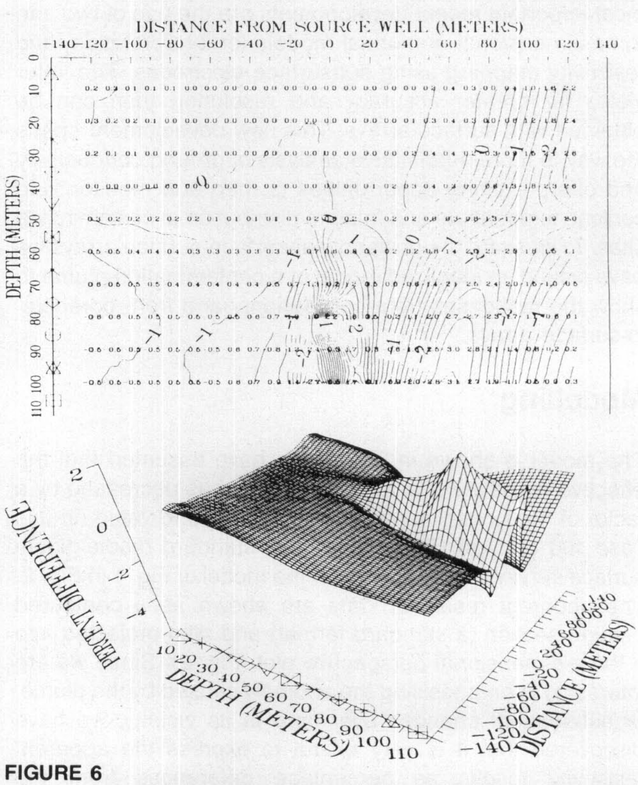

FIGURE 6
Percent difference plot between the apparent resistivities observed for the models in Figs. 1 and 5. The model in Fig. 1 is the reference.

In summary, dc resistivity mapping with combinations of surface and subsurface electrodes appears to have great potential for contamination plume mapping and monitoring. Much work remains to be done in selecting the best array geometries for sensitivity in mapping features of interest in site studies.