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FINITE-DIFFERENCE SIMULATION OF THE APPLICATION OF ELECTRICAL FLOW THROUGH CONDUCTIVE CONTAMINANT PLUMES

by

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ABSTRACT

The mathematical analogy between ground water flow and electrical flow has been recognized for decades. This analogy is used to illustrate how input data for the ground water flow model MODFLOW can be scaled and used to simulate the two-dimensional flow of electricity through conductive contaminant plumes in porous media. MODFLOW is used to simulate electrical potential fields generated at the land surface by mise-a-la-masse surveys for several simplified contaminant plumes. These simulations illustrate the degree of "visual" distortion in the electrical potential fields that can be expected for various plume conditions. In addition, the simulations show that a conductive contaminant plume will depress the electrical potential field below pre-plume baseline conditions near the plume. Depression of the electrical potential field near conductive, ground water contaminants is significant from the standpoint of early detection of leaks from waste disposal facilities.

INTRODUCTION

The mathematical analogy between electrical flow and ground water flow has long been recognized. According to Hubbert (1940), the analogies between ground water flow and electrical flow were used as a basis for his landmark paper on the theory of ground water motion. Numerous papers and textbooks have subsequently appeared in the ground water literature that describe the relationships between electrical flow and ground water flow. These publications can generally be divided into literature from the 1950's and 60's and more recent literature from the 1970's through to the present. The earlier literature deals primarily with the use of electric analog models to simulate complex ground water flow conditions prior to wide availability of digital computers. The more recent literature deals primarily with the potential relationships between electrical conductance and hydraulic conductance of porous media. Both groups of literature are related in that an electrical flow analogy is used as an efficient, economical tool to provide information that otherwise would be difficult to obtain.

The work of Karplus (1958) generally is considered to be the basis for most subsequent electric analog simulations of ground water flow. Walton (1970) and Prickett (1975) provide excellent discussions of electric analog models in ground water applications. Karplus (1958) and Karplus and Soroka (1959) describe solutions to the Laplace and diffusion equations by finite difference methods. Prickett (1975) describes the evolution from electric analog simulations to finite difference digital computer simulations of ground water flow.

Recent work from the mid-70's to present has concentrated on methods to estimate hydraulic coefficients from analogous electrical coefficients. These investigations range from surface, electrical geophysical methods to estimate aquifer properties (Kelly, 1977; Heigold and others, 1979; Kosinski and Kelly, 1981; Urish, 1981; Biella and others, 1983; Mazac and others, 1985, etc.) to theoretical relationships between moisture content and electrical conductivity of soils (Mualem and Friedman, 1991).

This paper proposes a reversal of the evolutionary path from electric analog models of ground water flow to finite difference, computer models. We suggest herein that the three-dimensional, finite difference, ground water flow model MODFLOW (McDonald and Harbaugh, 1988) can be scaled and "tricked" to simulate steady state electrical flow through contaminated ground water plumes.

MISE-A-LA-MASSE METHOD

The mise-a-la-masse method can be interpreted as "excitation of the mass" (Parasnis, 1967). The method is a variation of galvanic resistivity methods; it involves the injection of a steady-state electrical current directly into a conductive body such as the source of a contaminant plume. The procedure of the mise-a-la-masse method is to ground a single current electrode (i.e., point source) directly into a conductive body of earth materials. A second current electrode that serves as a point current sink is driven into the ground at an infinite distance (i.e., far enough from the first current electrode to have a negligible influence on it). The appropriate hydraulic analogy is the steady-state flow of ground water in the vicinity of a pair of recharging and discharging wells in a confined aquifer. In a typical mise-a-la-masse survey, electrical potentials (i.e., voltages) are measured at the land surface or in boreholes at a movable potential electrode. The potentials are measured on some type of predetermined grid; they represent the voltage differences between a fixed, reference, potential electrode (i.e., constant potential) and the movable potential electrode.

The basic analogy between electrical flow and ground water flow is illustrated in the forms of Ohm's Law (Eq.1) and Darcy's Law (Eq.2), respectively, as follows (Freeze and Cherry, 1979):

$$J_x = -\sigma \frac{\partial V}{\partial x} \qquad \text{Eq.1}$$

where: J_x is the current density(electrical current per unit area) in the x- direction,

σ is the electrical conductivity $\sigma = \sigma\ (x,y,z)$, and

V is the electrical potential.

$$v_x = -K \frac{\partial h}{\partial x} \qquad \text{Eq.2}$$

where: v_x is the specific discharge(discharge per unit area) in the x-direction,

K is the hydraulic conductivity $K = K(x,y,z)$, and

h is the hydraulic head.

Similar equations would be written for the y and z directions.

Spherical (i.e., converging or diverging) flow of electricity to a point sink or from a point source is described mathematically by Laplace equation in spherical coordinates in three dimensions (r, θ, and ϕ) as follows (Griffiths, 1989):

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial V}{\partial r}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial V}{\partial \theta}\right) + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 V}{\partial \phi^2} = 0 \qquad \text{Eq.3}$$

where: θ is the polar angle,

ϕ is the azimuthal angle, and

r is the radial distance from the point source.

The equivalent equation for ground water flow is written by direct substitution of h (head) for V in Eq.3 (de Marsily, 1986). The relationship between spherical and Cartesian coordinates (x,y,z) is $x = r \sin\theta \cos\phi$, $y = r \sin\theta \sin\phi$, $z = r \cos\theta$. Figure 1 illustrates the equipotentials predicted by the spherical form of the Laplace equation for a single current electrode at the land surface.

Steady-state flow of electricity or ground water through a homogeneous and isotropic, conductive medium bounded by planes is described by the three-dimensional form of the Laplace equation in Cartesian coordinates (Freeze and Cherry, 1979).
For electrical flow:

$$\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 V}{\partial z^2}=0 \qquad \text{Eq.4}$$

where: V is electrical potential.

The equivalent equation for ground water flow is written by direct substitution of h (head) for V.

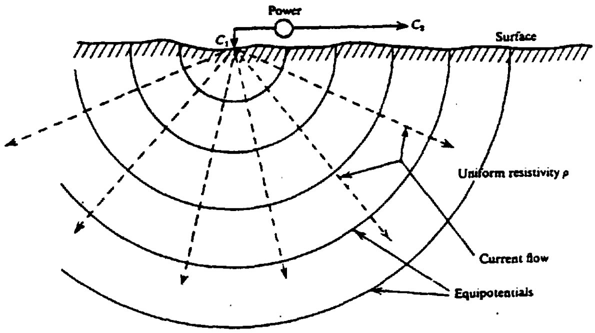


Figure 1. Hemispherical electrical equipotentials about a single current electrode at the land surface (from Telford et al, . 1990)

Dey and Morrison (1979) illustrate the complexity of modelling full three-dimensional electrical flow. Many layers are required to eliminate the effects of the basal nonconductive boundary and to accurately simulate electrical potentials in the vertical dimension. Ease of data input and model operation are the primary advantages of using MODFLOW, as suggested herein, to simulate electrical flow in two dimensions.

APPLICATION OF MODFLOW TO MISE-A-LA-MASSE SIMULATIONS

Combining Eq.1 or Eq.2 (x,y,z) with the continuity equation yields similar partial differential equations that describe the flow of electricity or ground water through a heterogeneous and anisotropic medium. According to McDonald and Harbaugh (1988), MODFLOW provides a numerical solution for three-dimensional movement of ground water of constant density through an aquifer based on the following equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad \text{Eq.5}$$

where:

K_{xx}, K_{yy}, and K_{zz}, are values of hydraulic conductivity along the x, y, and z coordinate axes which are assumed to be parallel to the major axes of hydraulic conductivity;

h	is the potentiometric head;
W	is the volumetric flux per unit volume and represents sources and/or sinks of water;
S_s	is the specific storage of the porous material;
t	is time.

The reader is referred to McDonald and Harbaugh (1988) for information on the finite difference form of Eq.5 used by MODFLOW. It is not necessary to rewrite Eq.5 or the finite difference equations to use MODFLOW to simulate the two-dimensional steady state electrical potential field that would be measured at the land surface by the mise-a-la-masse method. However, it is necessary to scale the input data and to "trick" MODFLOW to simulate the physics of electrical flow. Scaling relationships for resistance networks for ground water simulations suggested by Karplus (1958), Bermes (1960), Davis and DeWeist (1966), Bear (1972), Prickett (1975), and Freeze and Cherry (1979), can be used to scale input data for MODFLOW. The analogous quantities that must be scaled for steady-state electrical flow are as follows (Freeze and Cherry, 1979):

Hydraulic head (h) in meters (m) = Electrical potential (V) in volts;

Transmissivity (T) in (m^2/d) = Conductance (C) in Siemens (S);

Pumping/Injection rate (Q) in (m^3/d) = Current Strength (I) in coulombs/second (Amperes).

A scale factor equal to the model grid dimensions ($Dx = Dy$) is needed for distance. However, because steady-state electrical flow is being simulated, no time scale factor is needed. The scaling relationships for electrical potential (V), conductance (C), and current strength (I) are as follows (Freeze and Cherry, 1979):

$$F_1 = \frac{h}{V} \qquad \text{Eq. 6}$$

$$F_2 = \frac{Q}{I} \qquad \text{Eq. 7}$$

$$C = \frac{F1\,T}{F2} \quad \text{(for injection node)} \qquad \text{Eq. 8}$$

We used the relationships in Eqs. 6-8 to scale the original input data for MODFLOW as follows:

1) One metre of head equals 1 volt of electrical potential;

2) A well injection rate of 100, 000 m^3/d equals a current injection rate of 1 ampere; an

3) An aquifer transmissivity of 69, 314.7 m^2/d equals an electrical conductance of 0.01 Siemens / m (i.e., typical of a sand and gravel aquifer containing fresh water with a resistivity equal to 100 Ohm-m).

These relationships are used to simulate the utility of the mise-a-la-masse method to detect the presence of conductive contaminant plumes. Osiensky and Donaldson (1994) demonstrate the utility of the method in controlled field experiments.

It should be noted that the conductive contaminant plumes simulated herein, while representative of many plumes throughout the world, are relatively poor conductors. The electrical conductivity of good conductors such as copper and aluminum are several orders of magnitude greater than the simulated contaminant plumes. For example, the electrical conductivity of copper and aluminum is 5.80 X 10^7 (S/m) and 3.54 X 10^7 S/m, respectively; the electrical conductivity of seawater is approximately 5 S/m (Lorrain and others, 1988). By contrast, the electrical conductivity of pure water is 4 X 10^{-6} S/m (Griffiths, 1989). Because the simulated plumes are poor conductors, the theoretical conditions of 1) constant electrical potential (*V*) throughout the conductor and 2) the surface of the conductor forms a surface of equipotential are not applicable.

According to Keller (1987), the electrical conductance for a porous medium (σ_m)is given by the Archie (1942) formula as:

$$\sigma_m = a\sigma_w S^n \phi^m \qquad \text{Eq. 9}$$

where: ϕ is the porosity,

S is the fraction of pores containing water (i.e., S =1 for complete saturation),

σ_w is the electrical conductance of the pore water,

n is an empirical exponent based on the texture of the rock. Values range between 1.3 in loosly packed granular media to about 2.2 in well-cemented granular rocks (Parkhomenko, 1967)

a and m are empirical constants used to force the formula to fit the behavior of the rock type interest (Keller, 1987) (Table 1).

Pore structure has a potentially significant effect on the electrical conductance of porous media. Keller divides pore geometry into the following types: 1) intergranular porosity in sedimentary rocks, 2) fracture, joint and microcrack pores in crystalline rocks, and 3) vugs, vesicles, or other large, poorly interconnected pores as in extrusive volcanic rocks. According to Keller (1987), for a given porosity and water saturation, fracture porosity will typically exhibit the highest rock conductivity due to the simpler shape of the pores while vuggy porosity will result in the lowest conductivity because of the complex pores. Changes in the electrical potential field that occur over time are due to changes in the electrical conductance of the porous medium through which the controlled electrical current is passed. If the effects of "noise" can be identified and separated from the measured electrical potentials, the differences between baseline and subsequent data sets will reflect changes in the electrical conductance of the ground water in accordance with the Archie (1942) formula.

Table 1. Suggested values for constants *a* and *m* for use in Archie's formula when the lithology of a rock is known (from Keller, 1987).

Description of Rocks	Constants	
	a	m
Weakly cemented detrital rocks, such as sand, sandstone, and some limestones, with a porosity range from 25 to 45%, usually Tertiary in age	0.88	1.37
Moderately well cemented sedimentary rocks, including sandstones and limestones, with a porosity range from 18 to 35%, usually Mezozoic in age	0.62	1.72
Well cemented sedimentary rocks with a porosity range from 5 to 25%, usually Paleozoic in age	0.62	1.95
Highly porous volcanic rocks, such as tuff, with porosity in the range from 20 to 80%	3.5	1.44
Rocks with less than 4% porosity, including dense igneous rocks and metamorphosed sedimentary rocks	1.4	1.58

MODFLOW ELECTRICAL SIMULATIONS

Baseline conditions for the simulations consist of a homogeneous and isotropic aquifer with an electrical conductivity($\sigma_x = \sigma_y$) of 0.01 S/m. The aquifer is simulated as a single layer. Initial head (voltage) in the aquifer is zero. The steady state electrical potential distribution for a land surface point source is predicted by the following equation (Telford, et.al, 1990):

$$V = \left(\frac{I}{2\pi\sigma}\right)\frac{1}{r} \qquad \text{Eq. 10a}$$

where: V is electrical potential(volts),

I is electrical current(amperes),

s is electrical conductivity(S/m), and

r is distance from the electrical source.

Rewriting Eq 10a as a voltage difference between two radial distances from the injection point gives

$$V_1 - V_2 = \left(\frac{I}{2\pi\sigma}\right) \times \left(\frac{1}{r1} - \frac{1}{r2}\right) \qquad \text{Eq. 10b}$$

Equations 10a and 10b predict that voltage decreases by 1/2 for doubling of distance from the current source in a homogeneous, isotropic medium.

For steady state conditions, the difference in hydraulic head between two observation wells near an injection well is predicted by the following equation (Thiem,1906):

$$h_1 - h_2 = \frac{-Q}{2\pi T} \ell n \frac{r_1}{r_2} \qquad \text{Eq.11}$$

where: h_1 and h_2 are heads at two observation wells, respectively,

Q is the well injection rate,

T is the transmissivity of the aquifer, and

r_1 and r_2 are the radial distances of the two observation wells, repectively, from the injection well.

MODFLOW accurately simulates the hydraulic head difference predicted by Eq.11 for steady state conditions (i.e., head varies linearly with the log of distance). However, to make MODFLOW simulate the conditions of Eq.10b, it was necessary to "trick" MODFLOW by doubling the transmissivity(T) with doubling of radial distance from the injection well. Nodal transmissivity values are increased by a factor of two each time nodal distance from the injection point doubles. Internodal transmissivity values for nodes between those of double distance are based on the harmonic mean of two end point transmissivity values. For example, if $DX=DY=100\ m$, and $T_1=1000\ m^2/d$, $r_1=400\ m$, $T_2=2000\ m^2/d$ and $r_2=800\ m$, $T_{mean}=1333.3\ m^2/d$ for all nodes at a distance $r=600\ m$ from the injection node.

The transmissivity distribution for each of the simulations is based on Eq.9 and the relationship between Eq.10b and Eq.11 (figure 2). Baseline conditions represent a typical sand and gravel aquifer containing fresh water. Plumes containing pore water with a uniform electrical conductivity of 0.50 S/m, 1.0 S/m and 2.0 S/m, respectively,

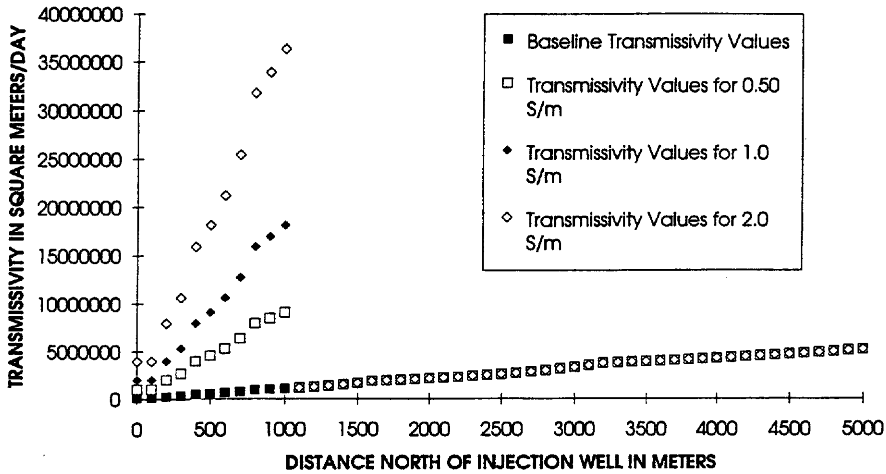


Figure 2 Transmissivity values used to simulate baseline conditions and plumes containing pore water with electrical conductivity values of 0.5 S/m, 1.0 S/m and 2 S/m. Figure 4 shows the location of the plot are modelled.

Each plume is simulated by increasing the transmissivity values (i.e., the electrical conductance of the aquifer) in accordance with Eq.9 for the appropriate nodal volumes that contain the plume. The model consists of a 101 X 101 grid with a 100 meter uniform grid spacing (Δx, Δy). A fully penetrating injection well is located at the center of the grid (i.e., node (51,51). It was necessary to calibrate MODFLOW by adjusting the original scaled transmissivity values and the well injection rate. Calibration was needed because of round off error within PREMOD (i.e., a MODFLOW preprocessor by Andersen, 1988) and within MODFLOW itself using an injection rate of 48, 450 m^3/d (i.e., 0.50 amperes) in all cases. The base transmissivity was decreased to 58, 650 m^2/d from the original scaled value of 69, 314.7 m^2/d.

Figure 3 is a contour map of baseline, electrical potentials (voltages) that would be measured at the top of the aquifer. These electrical potentials effectively represent voltages that would be measured at the land surface for the conditions simulated (e.g., no variable, unsaturated zone). The baseline conditions depicted in Figure 3 are intended to illustrate the electrical potential field that might exist at the site of a proposed waste containment facility (i.e. no ground water contamination).

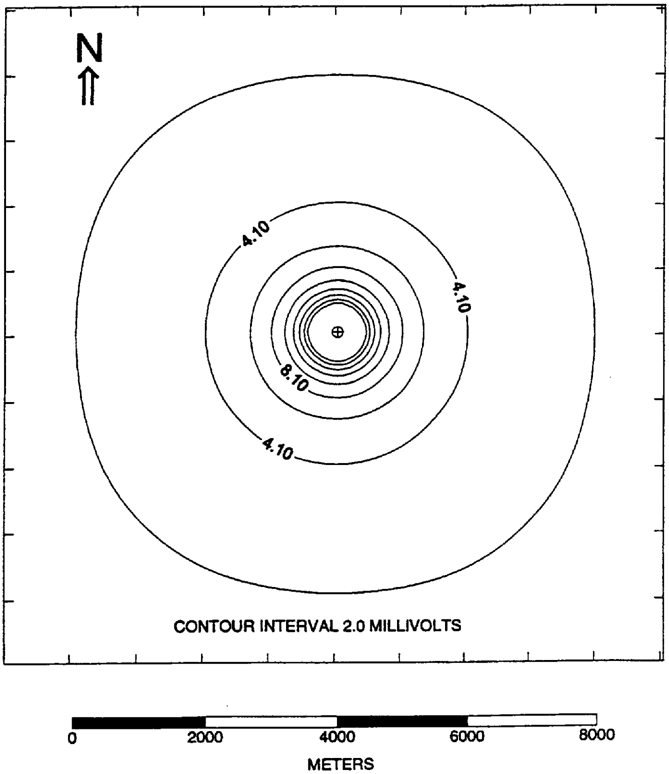


Figure 3. Contour map of the simulated, baseline electrical potential field for an aquifer with an electrical conductance of 0.01 S/m (resistivity 100 Ohm-m).

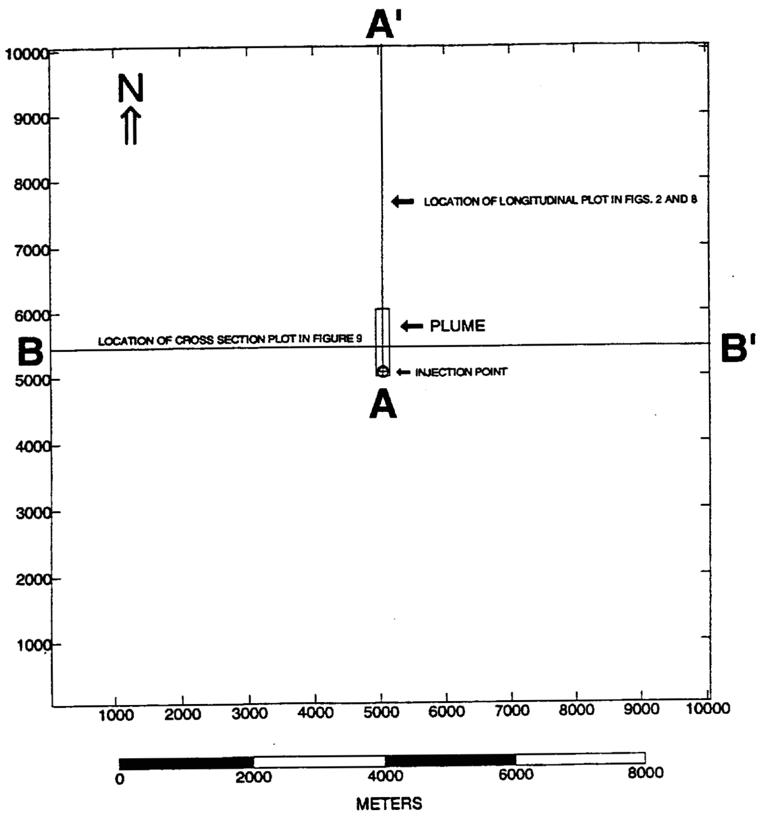


Figure 4 Shows the location of the longitudinal and cross sectional plot.

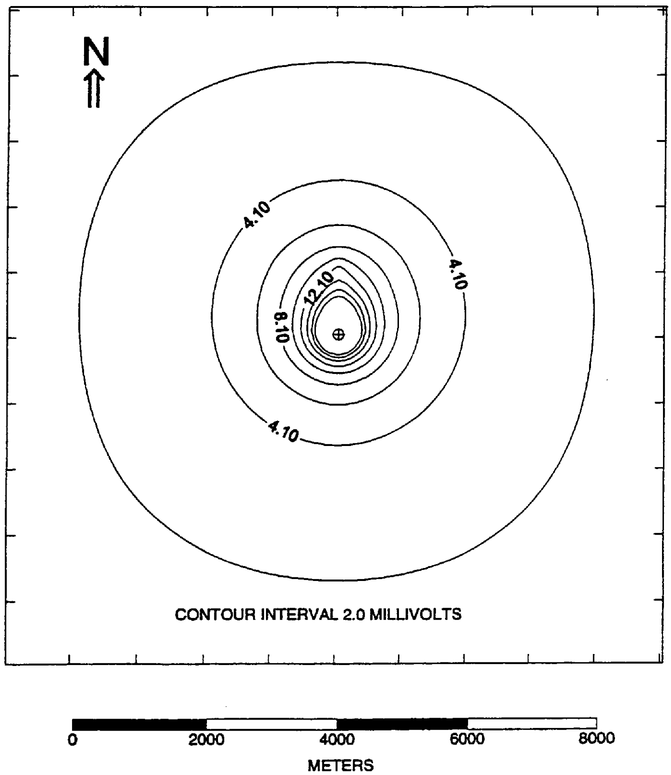


Figure 5 Contour map of the simulated, electrical potential field for a plume containing pore water with an electrical conductivity 0.50 S/m

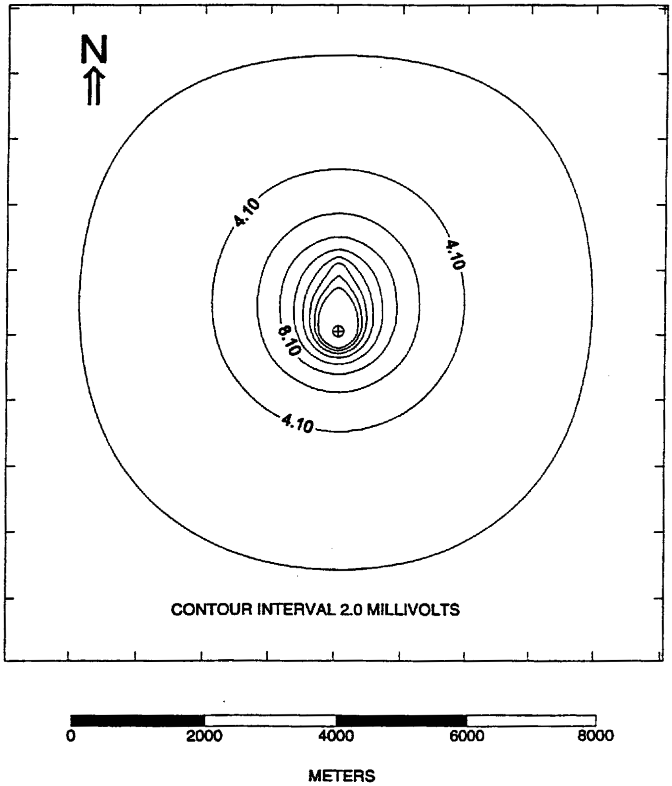


Figure 6 Contour map of the simulated, electrical potential field for a plume containing pore water with an electrical conductivity 1.0 S/m

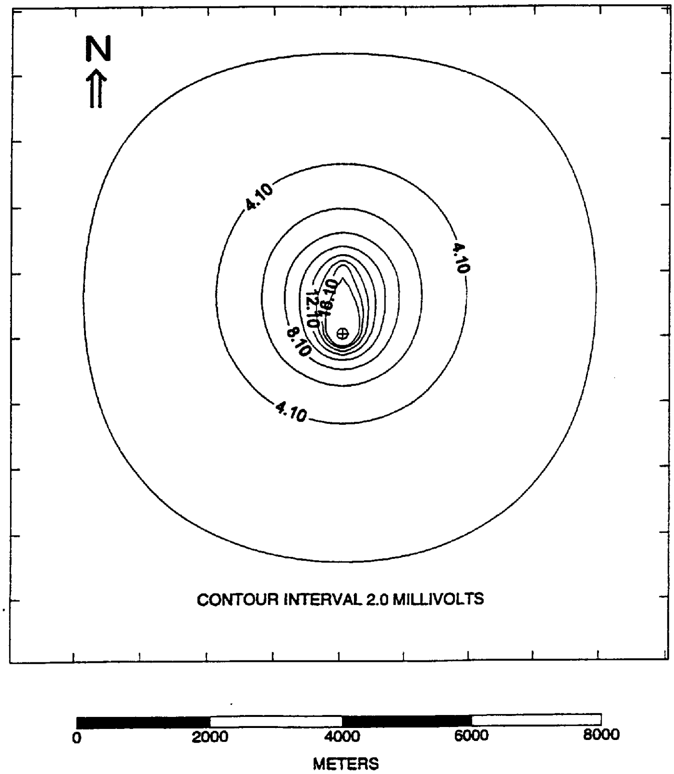
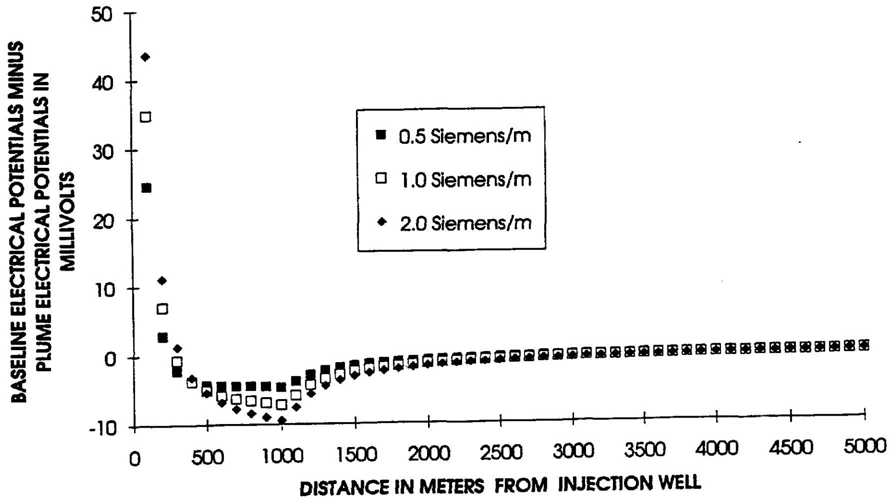


Figure 7 Contour map of the simulated, electrical potential field for a plume containing pore water with an electrical conductivity 2.0 S/m



Figurte 8. Longitudinal plot of the change in electrical potentials along the central line of the plume (Location in Figure 4)

Figure 4 is a plan view that shows the location of the plume for each simulation. Figures 5 through 7 are contour maps of electrical potentials for the identical conditions as shown in Figure 3 except for the presence of a simplified, rectangular shaped plume that extends north from the current electrode. The plume in each case is 1000 m long by 100 m wide and penetrates the entire aquifer thickness. Figure 5 illustrates the predicted electrical potential field for a plume containing pore water with an electrical conductivity of 0.50 S/m. Figure 6 shows the predicted electrical potential field for a plume containing pore water with an electrical conductivity of 1.0 S/m. Figure 7 shows the electrical potential field for a plume containing pore water with an electrical conductivity of 2.0 S/m. These figures illustrate that "visual" definition of the plume (i.e., distortion of the equipotentials) is greatest for an electrical conductivity of 2.0 S/m as is expected.

Figure 8 is a longitudinal plot of electrical potentials down the centerline of the plumes (i.e., north of the injection point). This figure shows that the presence of the plumes results in lower electrical potentials (i.e., below baseline conditions). Figure 9

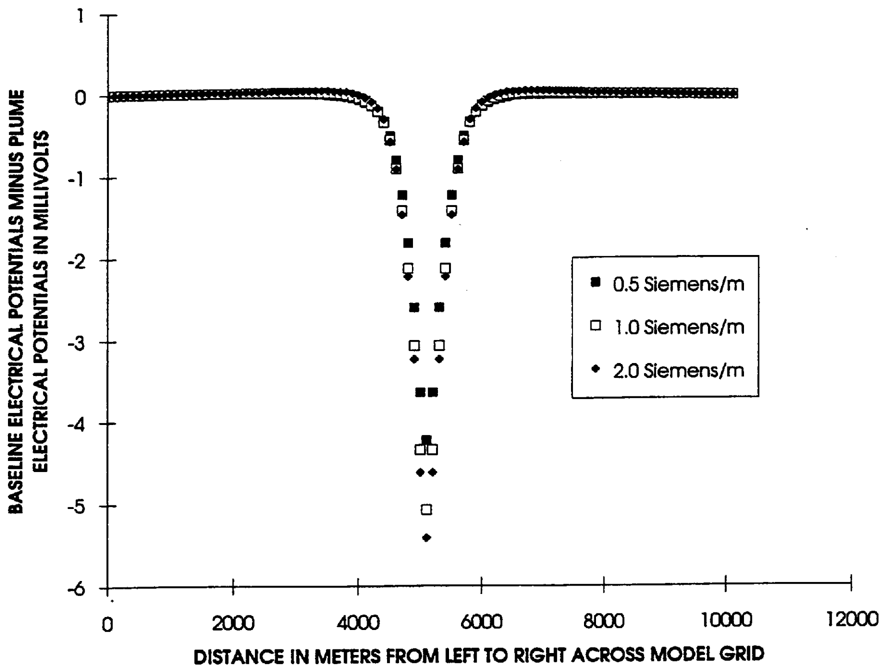


Figure 9 Cross sectional plot of the changes in electrical potentials across the finite difference grid 500m north of tthe injection point (Location in Figure 4)

is a plot of electrical potentials across the grid 500 meters north of the injection point. This figure clearly shows the location of the plumes. Osiensky and Donaldson (1994) show that depression of the electrical potential field below baseline conditions occurs near the plume when a sufficient quantity (dependent upon the sensitivity of voltage measurements) of electrolye reaches a shallow water table. Depression of the electrical potential field below baseline is significant from the standpoint of an early warning system for detection of ground water contamination.

Comparison of Figures 5 through 9 shows that the greatest change in the electrical potentials occurs at the location of the plume. These figures illustrate that if subsequent data sets (i.e., with plume present) are subtracted from the baseline data, the location of the plume can be delineated.

SUMMARY

Two or three-dimensional, saturated, ground water flow models such as MODFLOW can be used to simulate electrical flow through conductive contaminant plumes. By scaling the input data in accordance with published scaling factors for

Two or three-dimensional, saturated, ground water flow models such as MODFLOW can be used to simulate electrical flow through conductive contaminant plumes. By scaling the input data in accordance with published scaling factors for resistance network, electric analog models, electrical flow through porous media can be simulated. The electrical potential field generated by a mise-a-la-masse survey can be simulated in two-dimensions. These simulations can illustrate the degree of distortion in the electrical potential fields that should be expected for the conditions modeled. In addition, the simulations may be used to help design more effective mise-a-la-masse surveys for specific hydrogeological and plume conditions.

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