Borehole and Surface Geophysical Monitoring, and Simple Modelling of Groundwater Polluted by Waste Leachates

By G. B. DAVIS,[1] C. BARBER[1] and G. BUSELLI[2]

G.B. Davis*, C. Barber* and G. Buselli**
* CSIRO Division of Water Resources,
Private Bag PO Wembley WA 6014
**CSIRO Division of Exploration Geosciences,
PO Box 136 North Ryde NSW 2113

ABSTRACT

Detailed monitoring of point sources of groundwater pollution is expensive due to the high cost of drilling monitoring boreholes. Whether groundwater pollution is due to mining, industrial or domestic waste disposal, a universal difficulty when monitoring groundwater contamination is the placement of boreholes to adequately define the extent of the pollution plume.

This paper reports groundwater resistivity variations determined from transient electromagnetic soundings at a domestic waste disposal site north of Perth in Western Australia. Together with available hydrogeological and water quality data, the geophysics provides a broad "plume scale" picture of groundwater contamination. A simple three dimensional model of plume development, which takes account of the dimensions of the wastes, has also been developed and shows good agreement with the spread of contamination indicated by the geophysics for relatively small values of the dispersivities. Better estimates of these parameters are still required.

The work indicates that a combination of geophysics and modelling with ground-truth data from groundwater quality monitoring of boreholes is required to avoid difficulties in interpretation of data and to better define the extent and migration of pollution in groundwater.

1. INTRODUCTION

Run-off and seepage from mine wastes and tailings dams have the potential to contaminate shallow groundwaters. Early detection and adequate definition of the extent, and prediction of the rate of spread, of contamination at such point sources of pollution is often difficult due to the limited number of boreholes available for sampling groundwater for determining water quality. Recent work [1] has shown that surface geophysical soundings of resistivity variations in shallow aquifers (to 100m depth) can spatially map more conductive contaminated groundwater against a background of more resistive fresh groundwater. Highly conductive groundwater can develop around mining operations from oxidation and weathering of wastes or exposed rock surfaces in contact with oxygenated water giving low pH leachates. Prediction of the movement of contaminants over time for long term assessment of impact on groundwater quality is also possible through modelling pollution plume migration. The combination of surface geophysical surveys, site specific modelling and groundwater quality monitoring promises to provide a potentially cost-effective alternative to drilling of large numbers of bores to define the extent of contamination of groundwater.

The surface geophysical techniques of interest are DC resistivity and inductive transient electromagnetic (TEM) methods originally developed for mineral exploration purposes [2]. DC resistivity soundings are carried out by driving a direct current into the ground via electrodes and an electrical sounding is made by progressively increasing the distance between the transmitter electrodes. This technique is particularly useful for identifying highly resistive layers. TEM soundings are obtained using square transmitter loops with a side length of 25 to 100 m, driving a current of 10 A into the loop, rapidly switching off the current and monitoring at a separate receiver coil the changing magnetic field generated by induced eddy currents. This study has used the early-time SIROTEM instrument developed by CSIRO which was designed to resolve vertical resistivity contrasts to within 5 to 10 m [3]. This instrument has thirty two early-time channels between delay times of 0.049 and 20.2 ms enabling measurement of near surface conductivity variations at depths of less than 50 m. This is essential for detection of groundwater pollution. This technique when coupled with DC resistivity soundings gives better vertical definition of conductivity contrasts than other EM methods (frequency domain techniques), which are more commonly used [4,5].

Inevitably, any conductivity contrasts identified by geophysical soundings require investigation by drilling to determine whether the contrast is the result of contamination, and if so, to identify chemical variability and vertical stratification of contamination in the aquifer under investigation. This would normally be achieved by pumping of short-screened boreholes [6], or by using multiport or multiscreen single boreholes. Generally, detailed chemical data is also required for calibration of models of contaminant plume development, although it may be possible to use geophysics, groundwater sampling and modelling interactively in the future.

Here the distribution of contamination in groundwater determined by surface geophysical surveys, and predictions of contaminant plume development from a simple model of a field site are compared with available groundwater quality data. An assessment is made of the integration of these techniques in identifying the spatial distribution of contaminated groundwater polluted by leachates from a domestic solid waste disposal site at Morley, a northern suburb of Perth in Western Australia.

2. FIELD SITE AND HYDROGEOLOGICAL DATA

The Morley landfill is situated in a working sandpit on the Swan Coastal Plain of Western Australia. The landfill lies in a north-south trending sand dune ridge consisting of unconsolidated yellowish and whitish sands, mainly of very fine to medium sands (80%), medium to coarse sands (10%), and silts and finer materials (10%). Disposal of wastes commenced in late 1980. The wastes consist primarily of solid domestic refuse (some baled) and limited quantities of liquid wastes. The landfill area is almost rectangular and has approximate dimensions 175 by 270 m.

Depth below ground surface to the water table varies considerably around the site from exposed groundwater in the deepest excavations to 40 m on the western edges of the site. Water tables fluctuate seasonally about 1.5 m and the groundwater gradient is approximately 2-3 m per kilometre in a south-westerly direction. The distance to the water table below the base of the wastes is approximately 4 m.

3. GEOPHYSICAL RESULTS AND WATER QUALITY DATA

Extensive TEM surveys at the Morley site were carried out in May 1986, March 1987 and September 1987 with DC soundings being taken in March also. The TEM loop layout consisted principally of 25 x 25 m square loops with positions as given in Figure 1. Prior to March 1987 traverses B, C, D, E and F, and portions of A, G, H and I were

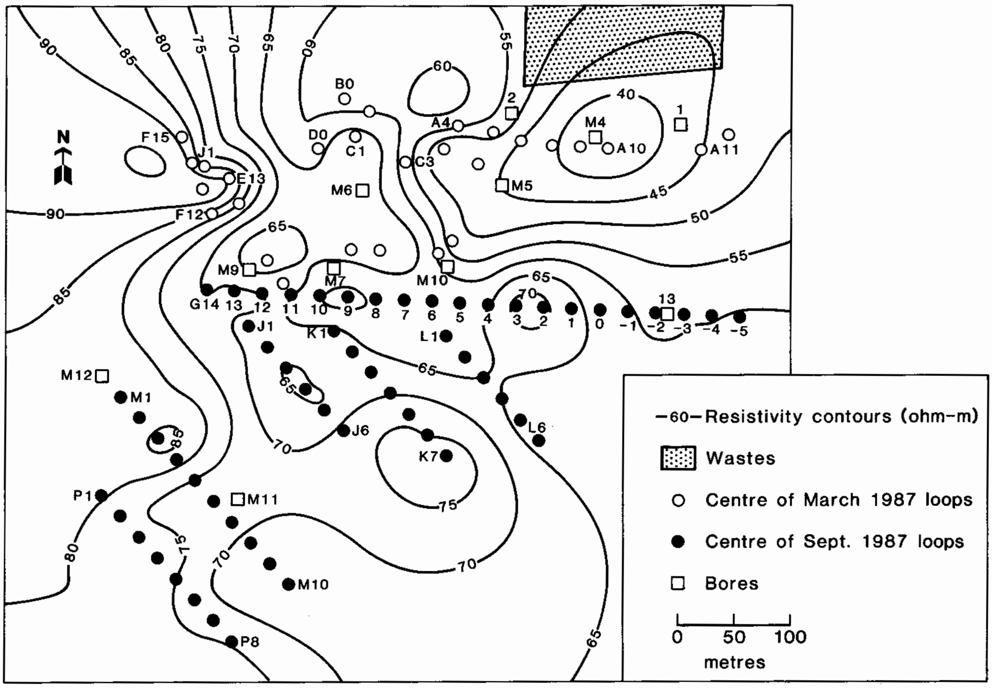

Figure 1. Resistivity contours obtained from computer inversion of TEM soundings at 5 ohm metre intervals, with borehole placements and centres of TEM loops marked.

made. In March 1987 24 TEM soundings were made completing traverses A and G with some repeat measurements being taken on the earlier traverses. In September 1987 repeat soundings were made along traverse G with 43 further soundings along 5 other traverses (J-P) (see Fig.1). These latter traverses were perpendicular to the direction of groundwater flow downgradient of the wastes. Readings were also taken in traverses G, L, K, J and M using 10 m loop sizes to assess whether better definition of groundwater/aquifer conductivity was possible.

Measured voltages from the early-time SIROTEM were transformed into apparent resistivity, and the resulting sounding curve was interpreted in terms of a sequence of horizontal layers using computer inversion. Data obtained from the 25 m loops gave similar apparent resistivities for the sand formation for both March and September 1987 and for May 1986, so survey results were amalgamated.

Estimated values for the resistivity and thickness of the sand formation are contoured in Figures 1 and 2. Contours in regions with little survey data or near the plot boundaries should be viewed as uncertain. From Figure 1 it is apparent that a low resistivity feature occurs extending out from the wastes with longitudinal extent of at least 450 to 550 m from the south-western corner of the wastes, and a width that varies from a few hundred metres close to the wastes to a narrowed tongue towards borehole M11. A low resistivity feature is also seen in the region of surveys G0 to G-5.

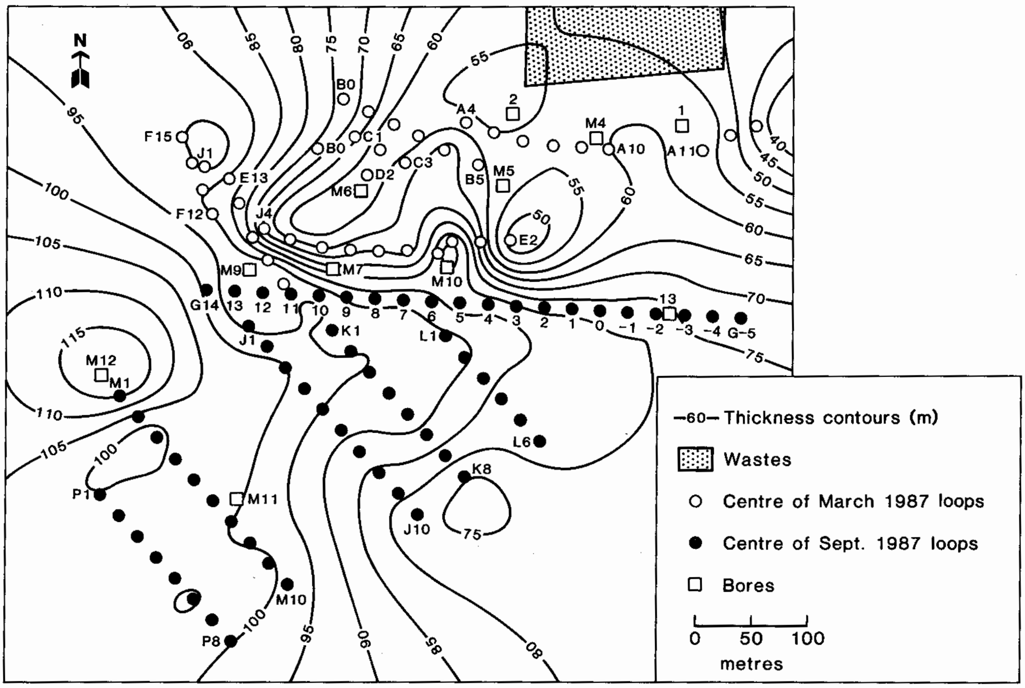

Figure 2. Thickness contours for the sand formation obtained from computer inversion of TEM soundings.

BOREHOLE	Sample depth(m)	pH	EC mS/m	Cl mg/l	SO4 mg/l	TOC mg/l	NH4-N mg/l
			86/87	86/87	86/87	86/87	86/87
1A	18-20	5.37	41/62	50/79	16/13	5/13	0.8/3
1B	34-36	5.59	27/28	63/53	7/8	8/6	0.3/0.2
1C	53-55	6.22	44/44	93/101	0.2/0.1	11/10	0.4/0.3
2A	13-15	6.6	217/288	277/392	0.4/0.5	61/83	112/142
2B	30-32	5.68	33/36	89/88	0.1/0.2	12/13	0.5/0.3
2C	48-50	6.56	206/294	254/418	0.5/0.2	52/84	101/153
3A	13-15	5.08	26/23	21/27	14/9	3/3	0.2/0.1
3B	32-34	5.62	35/34	90/87	0.1/0.1	7/5	0.2/0.2
3C	43-45	6.04	40/41	93/93	0.1/0.1	11/14	0.3/0.3
4	10-12	6.61	245/236	306/325	0.2/0.6	89/88	128/115
5.A	10		98/185	122/267	5/2.4	125/176	47/86
5.B	20		283/286	386/431	0.4/0.2	222/296	147/151
5.C	30		453/428	562/569	0.3/0.3	291/309	298/284
5.D	40		181/238	245/338	0.3/0.5	196/224	54/113
5.E	50		47/45	02/109	0.3/0.1	115/138	1/0.3

Table 1. Summary results of groundwater quality monitoring at the Morley landfill. Mean values for 1986/1987 given, based on monthly data. Bores 1-4 are short-screened, bore 5 is a multiport with 5 sample ports A-E.

Beyond the G line in a southerly direction there are no extra soundings to enable better definition of this anomaly although drilling of observation hole 13 adjacent to loop G-2 indicates low conductivity groundwater to 10 m below water table. This low resistivity anomaly may therefore be due to the variability of formation resistivity across the site. Thickness contours for the sand layer are given in Figure 2 showing a general correlation with the topography of the site. The resistivity of the basement layer showed little variation between 4 and 10 ohm metres and is not shown graphically.

A network of nine short-screened monitoring boreholes (1,2,3 each with three levels A, B, C) drilled prior to waste disposal at the site were augmented by a further short-screened bore(4), a multiport bore(5), eight multiscreened boreholes (M5 to M12) and another investigative hole (13) (Fig.1). Sampling for groundwater quality has been carried out monthly for two years in boreholes 1 to 5 whilst some preliminary sampling has commenced in boreholes M5 to M12. Background groundwater quality exhibits an EC range of 20-40 mS/m (20-90 mg/l as Cl) as in 3, whilst boreholes in contaminated regions have a range of 100-500 mS/m (100-800 mg/l as Cl) as in 2, 4 and 5. Table 1 shows summary results for boreholes 1 to 5 and indicates an increasing trend in groundwater contamination for boreholes 2A, 2C, 5.A, 5.B and 5.D for the monthly samplings in 1987 compared to 1986. A single sampling of the multiscreened boreholes and one other borehole (Table 2) indicates persistent pollution at depth in the region of M5 and M10 and some contamination in M6, M7 and M11.

BOREHOLE	No. of screens	Penetration depth below water table(m)	EC (mS/m)	Cl (mg/l)	TOC (mg/l)
M5	4	22	255	327	86
M6	4	21	197	112	17
M7	6	31	78	116	15
M9	6	31	39	92	5
M10	4	20	195	238	60
M11	3	13	64	108	9
M12	6	28	28	65	2
13	1	10	19	14	-

Table 2. Groundwater quality parameters for Morley averaged over the number of screens sampled for each borehole. August 1987 sampling for M5 to M12, March 1988 sampling for 13.

4. MODELLING

A semi-analytic model of plume development in groundwater as it moves out from the landfill has been formulated. Chloride is used as the conservative tracer of groundwater contamination. The model accounts for advective transport in one direction under a constant groundwater flow velocity and assumes dispersion in three dimensions. The model also accounts for the finite dimensions of the wastes. Aligning the x axis (direction of constant groundwater velocity) of the advection dispersion equation with the principal flow direction in the field (south-westerly) results in the solution for the concentration of a conservative solute $C_c(x,y,z,t)$ for continuous injection of the solute at a point as [7]

$$C_c = \frac{M\exp(xv/2D_x)}{8\pi nR(D_yD_z)^{1/2}}\left\{\exp(-Rv/2D_x)\operatorname{erfc}\left[\frac{R-vt}{2(D_xt)^{1/2}}\right] + \exp(Rv/2D_x)\operatorname{erfc}\left[\frac{R+vt}{2(D_xt)^{1/2}}\right]\right\} \quad (1)$$

where

$$R=(x^2+D_xy^2/D_y + D_xz^2/D_z)^{1/2} \quad (2)$$

and where M is the rate of "injection" of solute (as Cl) at the point source (g/yr), v is groundwater velocity (m/yr), n is porosity of the sand aquifer, D_x, D_y, D_z are the dispersion coefficients in each of the three directions (m^2/yr), y is the direction perpendicular to groundwater flow (m), z is the depth coordinate (m) and t is time after the initial deposition of wastes (yr). The complementary error function erfc(x) is defined as

$$\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-u^2}\, du \qquad (3)$$

and is given in standard mathematical tables. In comparison to the spatial scale at which we wish to observe pollution movement in the groundwater, the wastes are large so we integrate the point source solution (1) over the finite dimensions of the wastes to give

$$c(x,y,z,t) = \frac{2}{A} \int_{x'} \int_{y'} c_c(x-x',\ y-y',\ z,\ t)\, dy'dx' \qquad (4)$$

where c is Cl concentration above background (mg/l), A is the planar surface area of the wastes (m^2), and x' and y' are the planar dimensions of the wastes (m). Equation (4) was evaluated using a nested integration routine.

α_x(m)	α_y(m)	α_z(m)	Longitudinal extent of contours(m)		
			50	100	200 (mg/l)
100	10	1	370	150	10
100	10	0.1	670	500	300
100	1	0.1	780	625	430
50	5	0.5	500	340	125
30	3	0.3	550	430	250
20	2	0.2	570	480	340
10	1	0.1	580	520	430
10	0.4	0.4	530	450	300

Table 3. Estimated longitudinal extent after 6 yrs of 50, 100 and 200 mg/l contours at the water table for varying α_x, α_y, and α_z.

The model requires the following parameters as input variables. The porosity of the sand aquifer is estimated to be 30% and the accession of Cl to groundwater has been calculated from the product of recharge and Cl concentration in the wastes as ~2.4×10^7 g/yr.
Grain size analysis on drill cuttings from the site suggest hydraulic conductivities in the range 20 - 30 m/day and with a gradient of approximately 3 m/km, this gives a mean groundwater velocity of 70 to 110 m/yr. Dispersion coefficients were taken to be linearly dependent on the velocity such that $D_x = \alpha_x.v$, $D_y =$

$\alpha_y.v$ and $D_z = \alpha_z.v$ where α_x, α_y and α_z are the directional dispersivities.

An indication of the variability of the longitudinal extent of the 50, 100 and 200 mg/l contours (above background) for various values of the dispersivities is given in Table 3. The extent of the plume appears to be highly sensitive to the magnitude of the dispersivity in the z direction. In Figure 3 concentration contours are shown at the water table, after 6 years for v= 100 m/yr, α_x= 30 m, α_y= 3 m and α_z= 0.3 m. The 50 mg/l contour extends longitudinally 550 m away from the nearest edge of the landfill and laterally the plume width is not much different from the diagonal width of the waste pile. The 200 mg/l contour extends some 250 m away from the wastes and envelopes boreholes 2, M4, M5 and M10. Boreholes M6 and M7 lie on the contour. Comparing contours calculated from a two dimensional point source model with contours produced from the three dimensional model shows correspondence of the contours in the far field. However, close to the wastes the predictions differed markedly indicating the need to account for the finite dimensions of the "point source" on model predictions of plume spread.

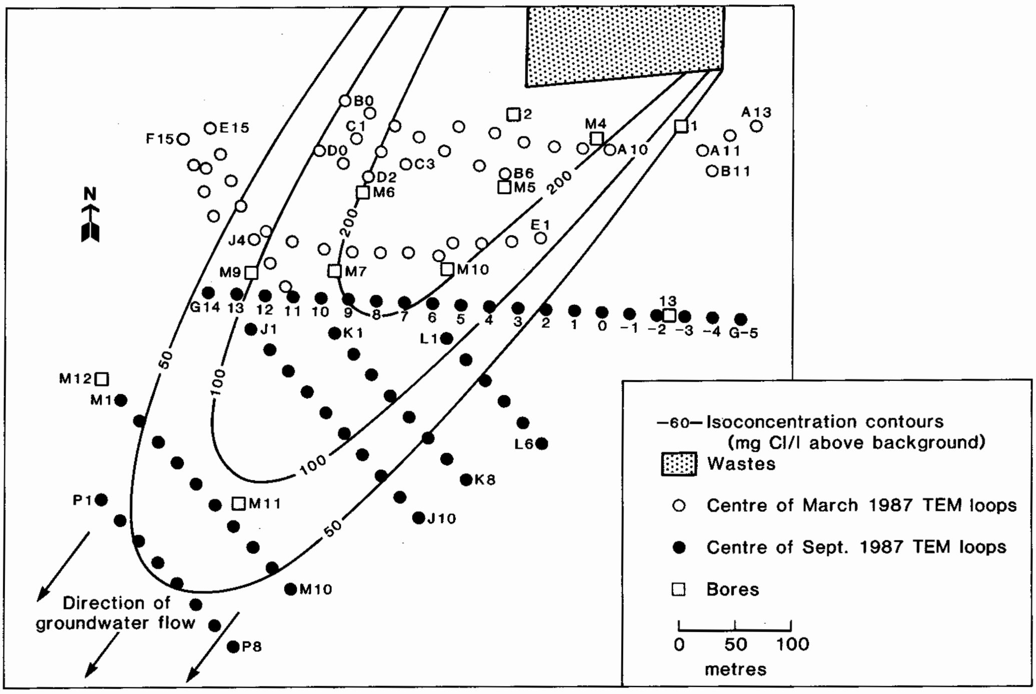

Figure 3. Model prediction of 50, 100 and 200 mg/l (above background) Cl contours at the water table after 6 years for α_x= 30 m, α_y= 3 m, α_z= 0.3 m and v= 100 m/y.

5. DISCUSSION AND CONCLUSIONS

The surface geophysics and available data on the local groundwater gradient (R.B. Salama - personal communication) both indicate that contaminant transport in groundwater is in a south-westerly direction. A low resistive, plume-like structure of extent 450 to 550 m is detected by the geophysics which is in broad agreement with groundwater quality data obtained from monitoring boreholes (Tables 1 and 2 and Fig.1). The geophysical results also suggest that borehole M12, although not currently polluted, may be useful into the future as a borehole in which contamination may develop giving a better indication of the movement and dispersal of the contaminant.

Results given in Figure 3 for the simple model indicate general agreement with geophysical results (Fig.1) and water quality data (Tables 1 and 2). Sound estimates of the dispersivities are required, however before such a model could be used predictively with confidence. Currently a tracer study is being undertaken at the Morley site to obtain plot scale estimates of the dispersivities and it is hoped that the geophysics will provide a framework for obtaining broader scale estimates. The variation of contamination with depth in the groundwater is also being monitored in the multiscreened boreholes to aid in better estimation of vertical dispersivities especially.

It is difficult at the Morley site to closely relate the model and geophysical results because of the lack of information on background formation resistivity around the landfill. This shows significant variability (Fig.1), which is assumed to be related to the variability in clay content within the aquifer and underlying formation. As part of a larger study at a yet to be commissioned site further north of Perth, water levels and water quality are being monitored at regular intervals and six-monthly background geophysical surveys are being undertaken to account for seasonal trends in data. It is hoped that such monitoring will provide the necessary pre-disposal data for adequate model prediction and for ground-truthing of the surface geophysics.

Whilst the results obtained and presented here are preliminary, the concept of integrating models, surface geophysics and borehole water quality data shows promise in aiding the monitoring of pollution plume migration in groundwater, whether the pollutant is from domestic, industrial or mining waste origins.

6. ACKNOWLEDGEMENTS

The efforts of Mr M. Height (CSIRO) in producing the contour plots in Figures 1 and 2 are appreciated. Comments on the manuscript by Dr L.R. Townley (CSIRO) and Dr B.C. Bates (CSIRO) are also appreciated.

7. REFERENCES

1. Buselli, G., Barber, C. and Williamson, D.R. The mapping of groundwater contamination and soil salinity by electromagnetic methods. Hydrol. and Water Resources Symp. (Brisbane) pp. 317 - 322, (1986).

2. Buselli, G. and O'Neill, B. SIROTEM: A new portable instrument for multichannel transient electromagnetic measurements. Bull. Aust. Soc. Explor. Geophys., Vol 8(3), pp 82-87, (1977).

3. Buselli, G. Stratigraphic mapping applications of TEM. Explor. Geophys., Vol 16(2/3), pp 177 - 179, (1985).

4. Benson, R.C., Glaccum, R.A. and Noel, M.R. Geophysical techniques for sensing buried wastes and waste migration. Environmental Monitoring Systems Laboratory, US-EPA, (1982).

5. Slaine, D.D. and Greenhouse, J.P. Case studies of geophysical contaminant mapping at several waste disposal sites. Proc. 2nd Nat. Symp. on Aquifer Restoration and Groundwater Monitoring. Columbus Ohio, pp. 299-315, (1982).

6. Barber, C. and Davis, G.B. Representative sampling of groundwater from short-screened boreholes. Ground Water, Vol 25(5), pp 581 - 587, (1987).

7. Hunt, B. Dispersive sources in uniform ground-water flow. ASCE J. Hydraul. Div., Vol 104(1), pp 75 - 85, (1978).