70-820
PDR

United States Department of the Interior

GEOLOGICAL SURVEY

RETURN TO 396-SS

Water Resources Divison
237 J.O. Pastore Federal Bldg
Providence, Rhode Island 02903

September 17, 1985

'85 SEP 19 P1:05

Mr. William T. Crow
U.S. Nuclear Regulatory Commission
Mail Stop SS396
Washington, D.C. 20555

Dear Bill:

Enclosed is a copy of the report "Geohydrologic data for a low-level radioactive contamination site, Wood River Junction, Rhode Island" by Barb Ryan and others. Let me know if you would like additional copies. Also enclosed are copies of two articles from USGS Water Supply Paper 2270 that address the ground-water contamination problem at the Wood River Junction plant.

I requested funding for follow-up sampling of ground-water at Wood Junction in FY 86, but chances of getting it seem slim. Ken Kipp, who is doing the solute-transport modeling, said he plans to do some follow-up sampling, possibly in FY 87 or 88, but not in FY 86. He said he didn't think he needed 1986 data to determine whether his model could accurately predict the fate of the contaminant plume.

If the NRC would be interested in funding collection of water quality data in FY 86 from selected wells in the monitoring network, give me a call. Perhaps we can work something out between your office and mine.

Sincerely yours,

Herb

Herbert E. Johnston
Chief, Rhode Island Office

Enclosures

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DESCRIPTION:

enclosed is a Copy of the report "Geohydrologic data for a low-level radioactive Contamination site

10/08/85 INITIAL CEC

An Electromagnetic Method for Delineating Ground-Water Contamination, Wood River Junction, Rhode Island

By Paul M. Barlow *and* Barbara J. Ryan

Abstract

Surface electromagnetic (EM) surveys were conducted in August 1981 to delineate the areal and vertical extent of ground-water contamination at a site in Wood River Junction, Rhode Island. The surveys were conducted in conjunction with a 3-year study of low-level radioactive ground-water contamination from a cold-scrap recovery operation (Ryan and Kipp, 1983).

Surface electromagnetic induction techniques that measure terrane conductivity were used in August 1981 at a low-level radionuclide waste site in Wood River Junction, Rhode Island, to delineate areal and vertical extent of contamination in a sand and gravel aquifer of glacial origin. Data from the terrane-conductivity survey were consistent with values of specific conductance of ground water measured as part of a 3-year study of ground-water contamination at the site. Data from the terrane- and specific-conductance surveys indicate that a plume of contaminated ground water extends from wastewater lagoons and trenches at the plant site to the Pawcatuck River. Above background terrane conductivities are present over an area that is 370 meters in length, ranges in width from 100 to 200 meters, and ranges in depth from land surface to 25 meters below land surface.

Electromagnetic data were contoured in linear and in dimensionless logarithmic units. Electromagnetic data contoured in linear units indicated high-conductivity zones that suggested potential ground-water contamination. Linear contouring also depicted changes in conductivity with depth more clearly than did the logarithmic contouring.

Logarithmic contouring of electromagnetic data was successful in masking background noise, thereby delineating boundaries of the contamination plume more clearly. Selection of background apparent-conductivity values at the site for the logarithmic contouring schemes proved to be the greatest objection to the logarithmic method. Background values which were too high caused an unrealistic reduction in the boundaries of the contamination plume, whereas background apparent-conductivity values that were too low allowed interference from background noise to bias the hydrogeologic interpretation.

INTRODUCTION

Surface electromagnetic (EM) surveys were conducted in August 1981 to delineate the areal and vertical extent of ground-water contamination at a site in Wood River Junction, Rhode Island. The surveys were conducted in conjunction with a 3-year study of low-level radioactive ground-water contamination from a cold-scrap recovery operation (Ryan and Kipp, 1983).

Surface electromagnetic induction techniques that measure terrane conductivity have been found to be an effective tool in the preliminary assessment of ground-water pollution at many industrial and municipal contamination sites (Kelly, 1976, p. 7; Greenhouse and Slaine, 1983, p. 49; McNeill, 1980b, p. 11). Electromagnetic induction techniques are a relatively inexpensive and reliable method of mapping contamination plumes and may, in the early stages of a study of ground-water contamination, aid in the placement of water-quality observation wells (Greenhouse and Slaine, 1983, p. 49).

The ability of earth materials to transmit an electrical current is related directly to the electrical conductivity of the interstitial pore fluid and, to a lesser extent, the rock type. Electrical conductivity of the interstitial pore fluid (water) is determined primarily by ion concentrations in the solution. As the ion content of the pore fluid increases, the ability of the fluid to conduct an electrical charge and the conductivity of the earth material also increase.

The instrument used in the EM surveys consists of an alternating-current transmitter coil that produces a time varying magnetic field (primary field), which, in turn, induces small eddy currents in the earth (fig. 1). These currents produce a secondary magnetic field, which, together with the primary magnetic field, are intercepted by a receiver coil (McNeill, 1980b, p. 5; Evans, 1982, p. 105–108; Zohdy and others, 1974, p. 55). Because the magnitude of

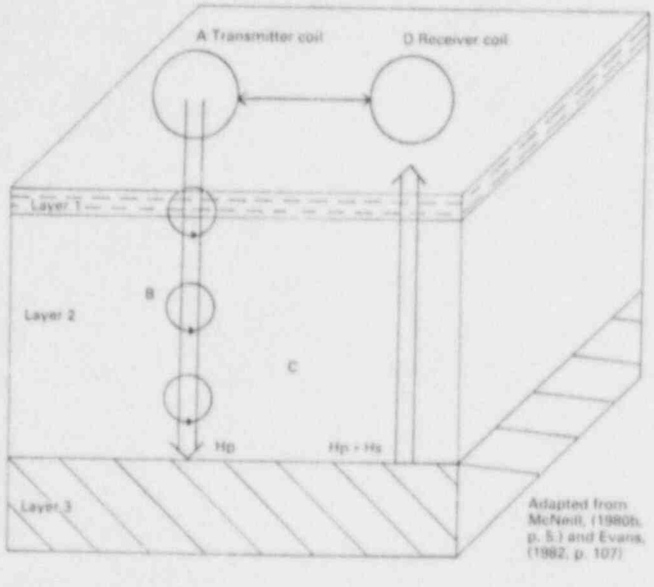

Figure 1. Schematic model showing theory of electromagnetic instrumentation and terrane-conductivity measurement. (*A*) Transmitter coil produces primary magnetic field (Hp); (*B*) Induced current loops produce a secondary magnetic field (Hs). Relationship to eddy currents not shown; (*C*) Current flow is achieved by the availability of charged particles in the sediments and pore fluids; and (*D*) Receiver coil senses primary and secondary magnetic fields. Conductivities are recorded.

the currents induced by the transmitter is a function of hydrogeologic conditions, the magnitude of the secondary EM field is linearly proportional to the terrane conductivity (relative ease with which an electrical current will flow through the rock type).

The apparent terrane conductivity measured by the receiver coil is a function of the thickness of the rock type layer, the electrical conductivity of the pore fluid, depth of the rock type layer from the surface, intercoil spacings, and operating frequencies of the instrument (Evans, 1982, p. 108; McNeill, 1980b, p. 5). The relative contributions to the apparent conductivity of each of these factors need not be determined to interpret electromagnetic data. Results of data collected from many traverses at a study site are adequate to indicate relative lateral changes in the terrane conductivity (Evans, 1982, p. 108).

Greenhouse and Slaine (1983, p. 47–59) suggested that the presentation of electromagnetic data should be standardized by converting measured apparent conductivity values to logarithmic ratios of measured values to background apparent-conductivity values. The dimensionless ratios then are contoured to outline the zone of contamination. Greenhouse and Slaine cited three advantages to logarithmic contouring of converted data over linear contouring of raw data: First, logarithmic contours of converted data do not cluster near the contaminant source to the extent that linear contours of raw data might; second, a common format of instrument and survey results may be realized by the use of nondimensional contour units with a zero background value; and, finally, the method of contouring logarithmic values is objective except for the choice of a background apparent-conductivity value.

This report summarizes the use of EM surveys to delineate a ground-water contamination plume at a low-level radioactive waste site in Wood River Junction, Rhode Island (fig. 2). The objectives of this paper are to compare the results of EM surveys to specific conductance measurements of ground water to evaluate the ability of such a survey to delineate ground-water contamination and the advantages and disadvantages of linear and logarithmic contouring of electromagnetic data.

In this report, the results of horizontal- and vertical-dipole measurements are included. It has been noted (McNeill, 1980b, p. 6; Greenhouse and Slaine, 1983, p. 48) that data acquired from the vertical-dipole configuration are more commonly subject to cultural interferences than data acquired from horizontal-dipole configurations. Misalinement of coils in the vertical-dipole configuration and a pronounced departure from linearity of response at high

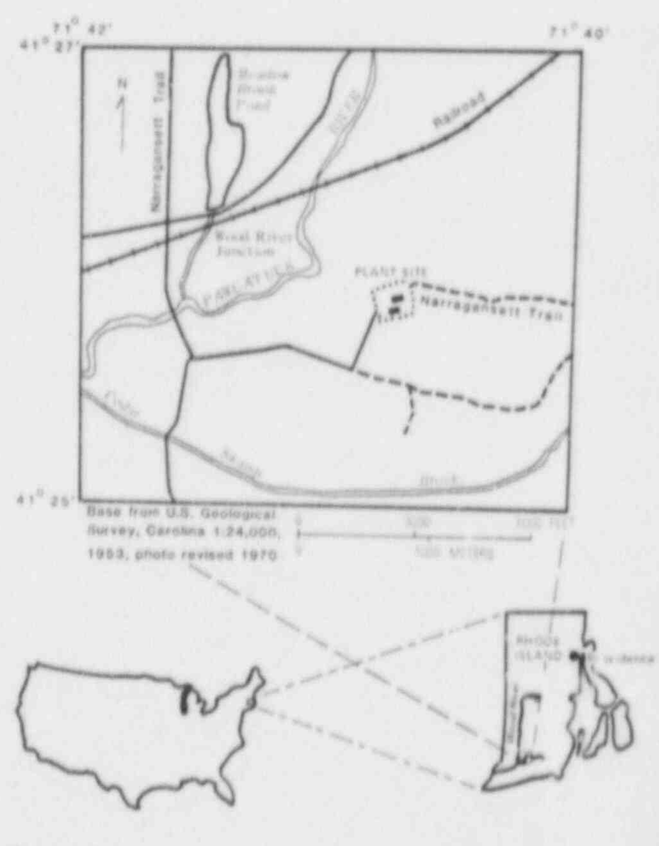

Figure 2. Location of study area.

values of terrane conductivity also may be causes for spurious readings in the vertical-dipole configuration.

SITE DESCRIPTION

From 1966 to 1980, liquid wastes containing radionuclides and other chemical solutes were discharged to lined lagoons at a cold-scrap uranium-recovery plant in Wood River Junction, Rhode Island (fig. 3). Leakage from the lagoons resulted in contamination of a highly permeable sand and gravel aquifer of glacial origin. Chemical constituents in the contaminated ground water included nitrate, potassium, strontium-90, and technetium-99. Concentrations of nitrate and calcium, both of which were present in plant effluents, ranged from 3 to 600 mg/L and from 10 to 700 mg/L, respectively. Nitrate and calcium ions were the predominant constituents of the high dissolved-solids concentrations (as much as 1,960 mg/L) in the contaminated ground water.

Specific conductance of contaminated ground water sampled from approximately 100 observation wells ranged from 150 to 5,000 µS/cm at 25°C; uncontaminated ground water at the site generally had a specific conductance of less than 100 µS/cm at 25°C. Specific conductance data indicate that a plume of contaminated ground water extends from the plant area to the Pawcatuck River and adjacent swamp. The plume is 520 m long and 100 m wide (fig. 4) and is confined to the upper 25 m of saturated thickness, where sediments consist of medium to coarse sand and gravel (fig. 5). The top of the contamination plume is about 10 m below the water table between the plant and river, whereas contamination is encountered at the water table within the swamp area.

ELECTROMAGNETIC SURVEY

Method

The EM surveys were conducted in August 1981 (Duran, 1982) with a Geonics EM 34-3 inductive terrane-conductivity meter. Measurements were obtained in both horizontal- and vertical-dipole modes at 20-m intercoil separations, providing effec-

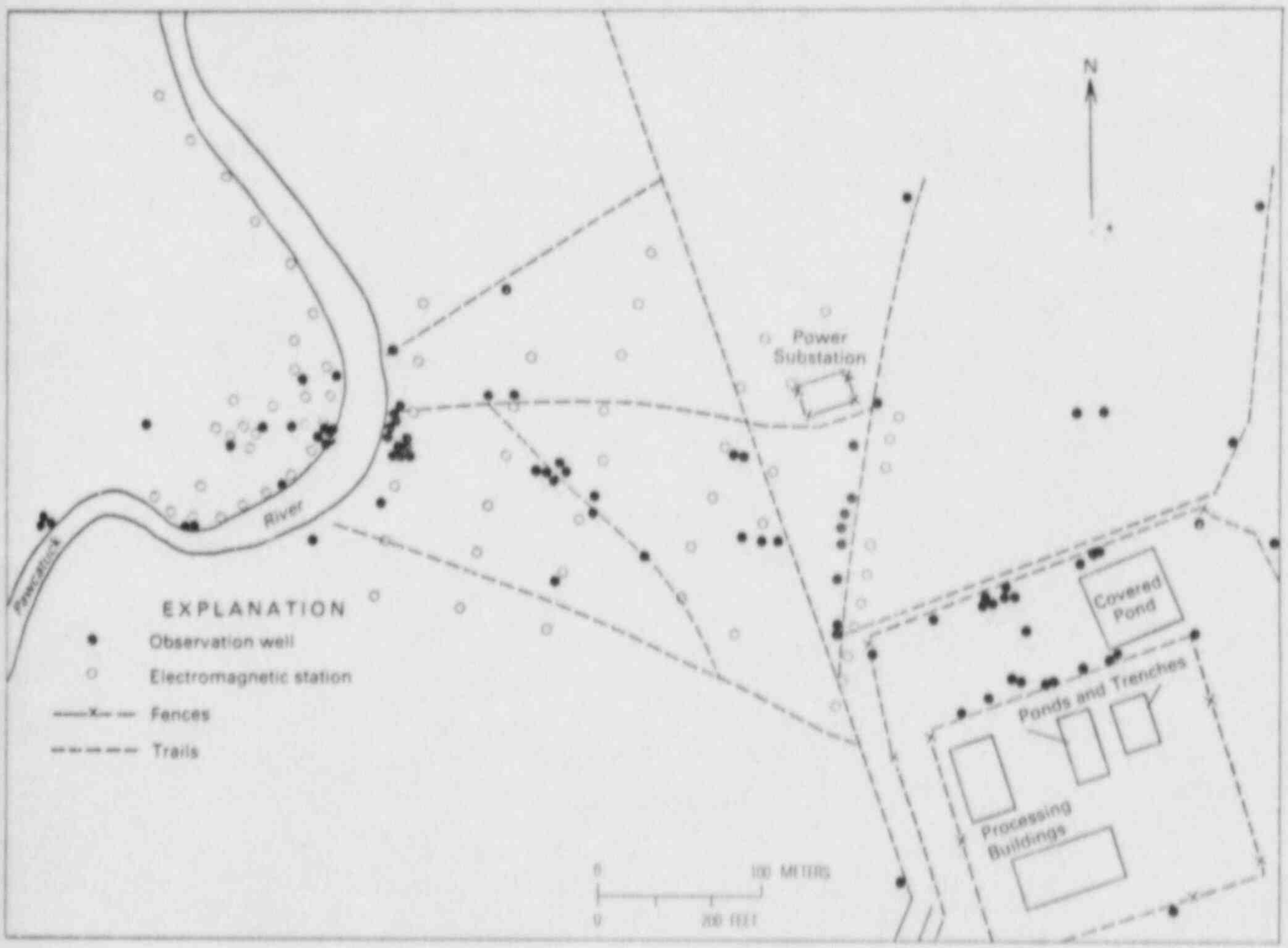

Figure 3. Location of observation wells and electromagnetic stations.

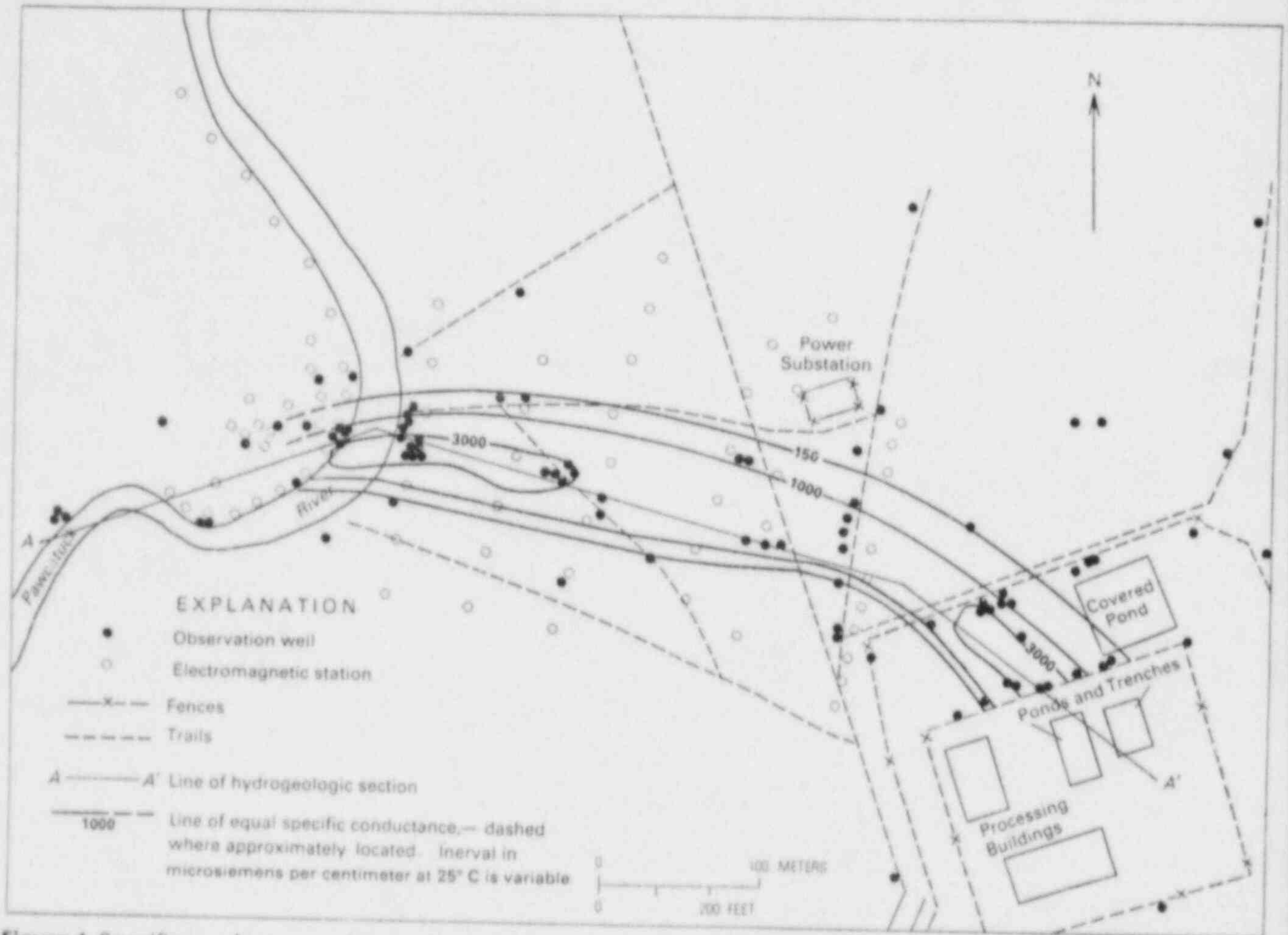

Figure 4. Specific conductance of ground water, Wood River Junction, Rhode Island, April 1982.

tive depths of exploration on the order of 15 and 30 m, respectively (fig. 6). A thorough explanation of the electrical conductivity of soils and rocks and of the theory and operation of the EM 34–3 instrument has been given by McNeill (1980a, b).

EM stations were located by pace and compass with the aid of aerial photographs. Data stations were located midway between the transmitter and receiver coils (Duran, 1982, p. 106). Six traverses (lines 3–8) were made approximately perpendicular to the direction of ground-water flow between the plant and the eastern bank of the Pawcatuck River (fig. 7; table 1). On the western side of the river, one traverse (line 2) was made parallel to the river; this traverse then formed the basis for several traverses perpendicular to the river (line 1). Station spacings were approximately 33 m, with the exception of those located near the plant and in the swamp west of the Pawcatuck River, which were 15 m apart.

Linear and Logarithmic Contouring

Contouring of the electromagnetic data was done by two methods using linear and logarithmic units. The first method (linear contouring) consisted of contouring apparent-conductivity values from field measurements at 1.0 to 2.0 mS/m at 25°C contour intervals. Contouring of EM data in this manner did not necessitate the determination of a background apparent-conductivity level. Therefore, no attempt was made to determine the level of background noise [natural scatter of terrane-conductivity values caused by "topography, spatial or temporal variations in the depth to water table, observation accuracy, lateral changes of lithology, and cultural interference from power lines, metal fences, etc.", Greenhouse and Slaine (1983, p. 48)].

The second method of contouring follows the recommendation of Greenhouse and Slaine (1983, p. 49). They suggested the conversion of data to the following logarithmic format:

$$20 \log_{10} \frac{\sigma(x, y)}{\sigma \text{ (background)}},$$

where $\sigma\,(x,y)$ equals apparent conductivity readings at any location on a grid with x and y coordinates and σ (background) equals the background apparent-conductivity value.

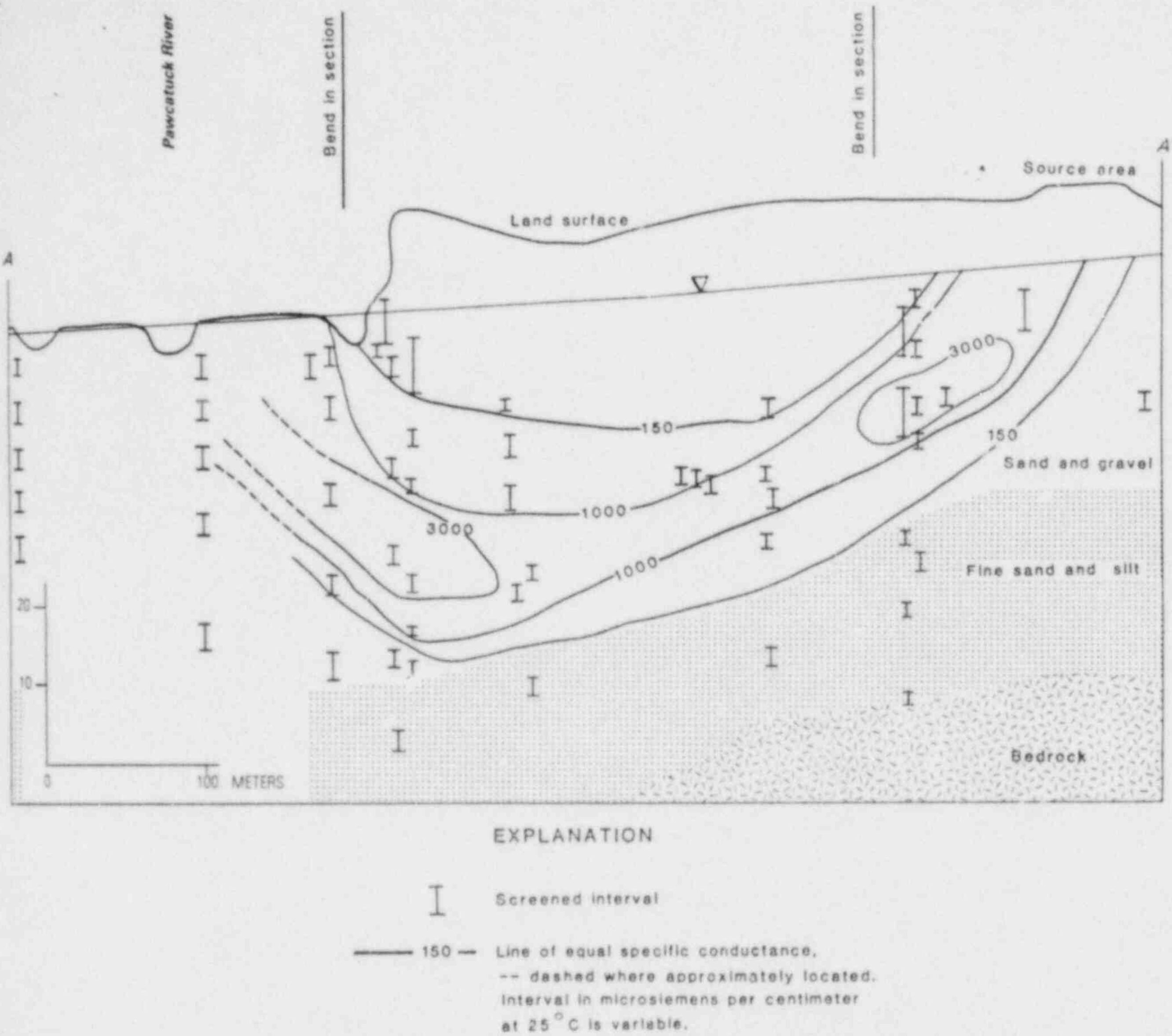

Figure 5. Specific conductance of ground water, Wood River Junction, Rhode Island, April 1982, cross-sectional view.

The dimensionless ratios (decibel units) obtained from the logarithmic format for each station and the linear nondimensionless values then are contoured. The zero logarithmic contour [0 decibel (db)] then separates contaminated from noncontaminated areas. Contour intervals of 4 db, which were used in this study, correspond to incremental changes of a factor of approximately 1.6 above background apparent conductivity.

Results

Data from the EM surveys indicate a high-conductivity zone at the site in an area which extends from the plant to the Pawcatuck River and adjacent swamp (figs. 8–13). Above background conductivities are present over an area 370 m in length by 100 to 200 m in width; this is compatible with specific conductance results (fig. 14).

Although difficult to quantify, the vertical extent of the high-conductivity zone has been qualitatively identified with the aid of effective depths of penetration for the horizontal- and vertical-dipole configurations (fig. 6). Contours of linear vertical-dipole data show local high-conductivity zones near the power substation and near the plant, where fences and transmission lines are concentrated (fig. 11). These elevated conductivity values may be the result of electrical currents produced by the power substation and power lines that interfere with the electromagnetic instrumentation or high ground-water conductivity between 6 and 12 m below land surface [the

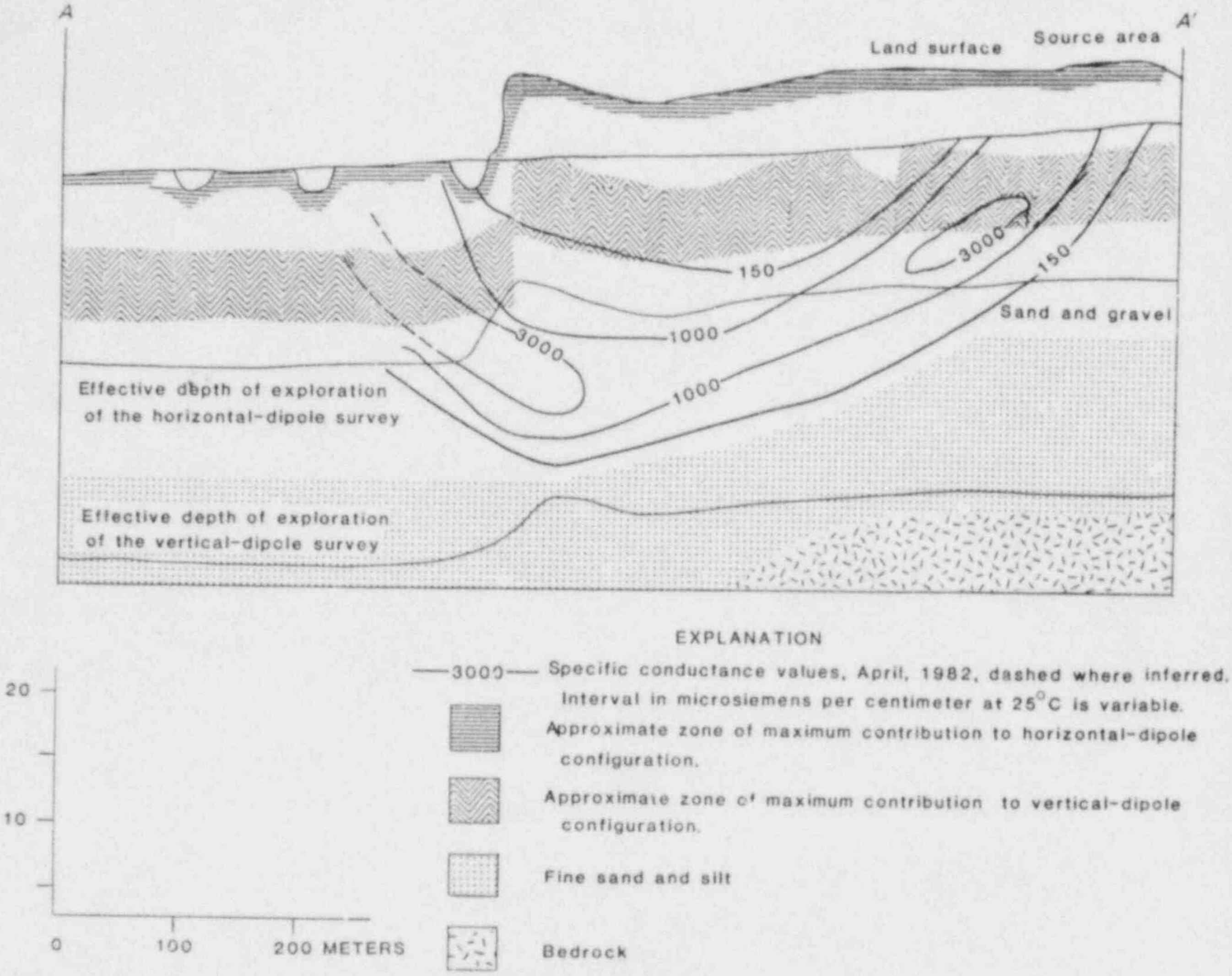

Figure 6. Section showing effective depths of penetration and plot comparing relative responses for horizontal and vertical dipoles.

interval of the aquifer that contributes most to the vertical-dipole configuration (fig. 6)].

Vertical-dipole values remain high (5 mS/m at 25°C) from the plant to within about 100 m of the Pawcatuck River and indicate that some ground-water contamination has occurred of 6 to 12 m below land surface. However, specific conductance values indicate that the most contaminated ground water is present 13 to 20 m below land surface near the river (fig. 5). Because the maximum contribution to the vertical-dipole configuration occurs in the depth interval between 0.3 and 0.6 percent of the intercoil spacing, the vertical-dipole configuration has not sensed fully this high-conductivity zone. A greater intercoil spacing (such as 40 m), however, may have sensed this zone. Vertical-dipole values increase from 4 to 6 mS/m at 25°C on the western side of the Pawcatuck River, which suggests that contamination may occur within the 6- to 12-m interval in this swampy area.

On the contrary, however, horizontal-dipole measurements (fig. 8) remain low (2–3 mS/m at 25°C) to the east of the Pawcatuck River but increase to between 4 and 8 mS/m at 25°C to the west of the river in the swampy area. Because the greatest contribution to horizontal-dipole measurements is from near-surface electrical conditions (fig. 6), elevated conductivity measurements in the swamp may result from (1) the absence of a resistive, unsaturated layer in the area, (2) the variation in grain size from unconsolidated sand and gravel east of the river to silt and organic matter in the swamp, or (3) a rise in the electrical conductivity of the ground water. Although the absence of a resistive, unsaturated layer in the swampy area probably adds to the overall increase in

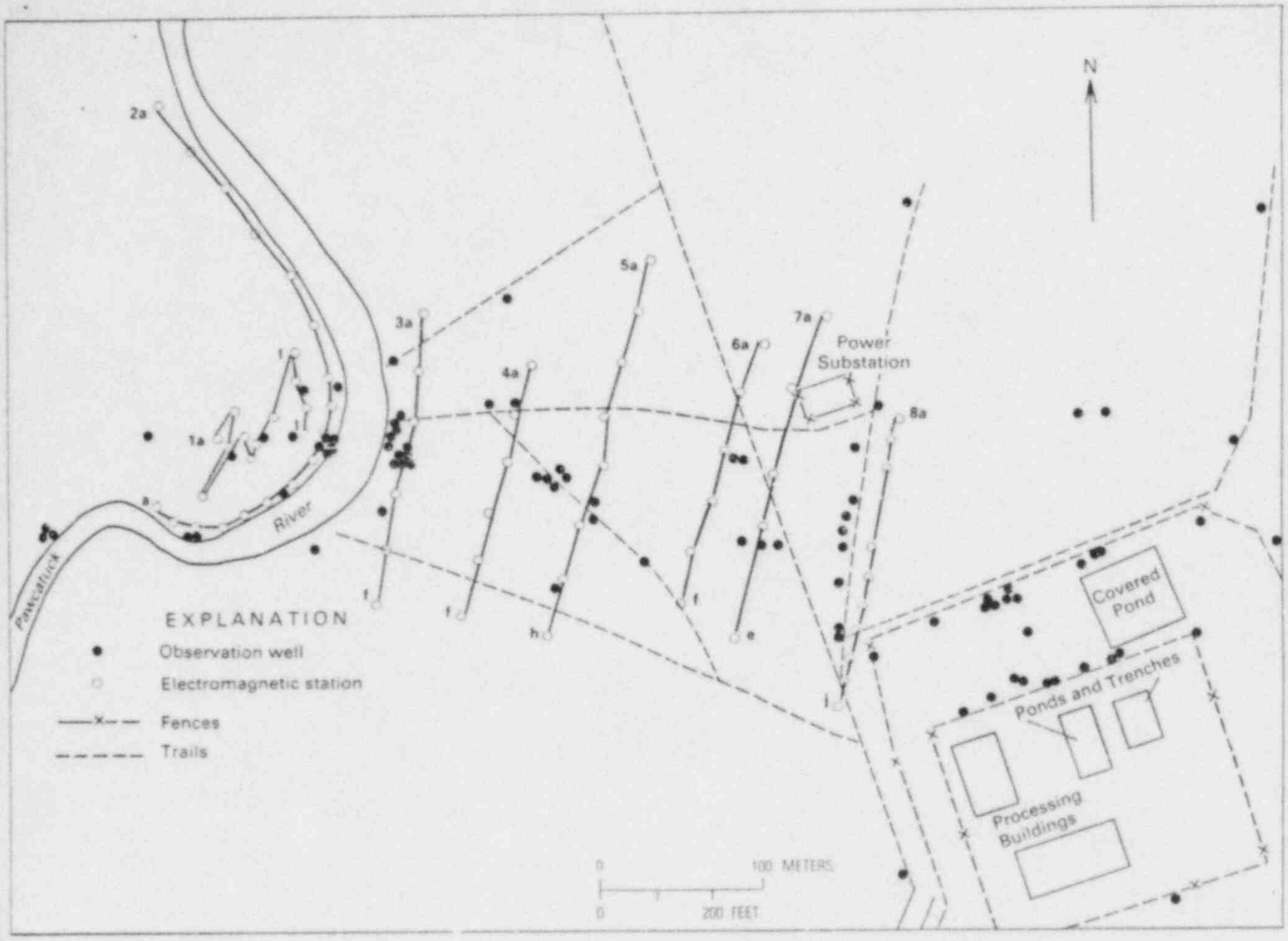

Figure 7. Numbering system of electromagnetic stations.

conductivity levels there, elevated levels of ground-water contamination are suspected. Horizontal- and vertical-dipole linear contouring of EM data show clustering of contour lines in this area (figs. 8, 11).

Logarithmic contouring schemes (figs. 9 and 10, 12 and 13) were obtained by first assigning background values to the logarithmic equation given by Greenhouse and Slaine (1983). Background values at the study site were obtained in the following ways: (1) By averaging the low apparent-conductivity values for those stations which are believed to reflect uncontaminated terrane conductivities and (2) by subjectively setting a background apparent-conductivity value below which contamination does not seem likely.

Background values are determined more easily if the lithology of the study site is known. In the present study, the presence of a conductive, saturated, swampy zone to the west of the Pawcatuck River, consisting of silt, clay, and organic material, resulted in a higher range of background apparent-conductivity values than to the east of the river, which consists of unconsolidated sands and gravels. To bring the western and eastern areas of the site into a common range of decibel values, higher values were assigned to the western side of the river than to the eastern side.

Differences in the ranges of apparent-conductivity values for the horizontal-and vertical-dipole modes also necessitated the use of two background apparent-conductivity values (one for the horizontal and one for the vertical configuration) in each area of the site to the east and to the west of the river.

Table 2 summarizes background apparent-conductivity values used in this study.

Contours of logarithmic data reflect above background conductivities from the plant to the river in the vertical and horizontal modes. Contours of horizontal-dipole values converted to averaged background apparent-conductivity levels (fig. 6) show

Table 1. Electromagnetic data from horizontal and vertical dipoles at study area
[Data in millisiemens per meter at 25°C.; ---, no measurement]

Electromagnetic station	Dipole	
	Horizontal	Vertical
Line 1:		
A	3.9	5.1
B	3.9	3.5
C	4.4	5.5
D	3.3	---
E	4.2	4.3
F	6.3	4.3
G	4.9	6.4
H	3.5	3.7
I	3.9	3.3
J	4.1	4.1
K	4.6	6.3
L	8.4	4.8
Line 2:		
A	2.3	3.4
B	2.3	3.2
C	2.6	3.3
D	2.4	3.0
E	2.4	2.5
F	2.9	3.0
G	4.6	6.0
H	6.6	4.9
I	9.0	6.0
J	8.5	5.7
K	7.2	6.5
L	9.7	3.4
M	7.2	5.8
N	6.2	7.2
O	3.7	5.5
P	3.5	3.5
Q	3.4	3.4
Line 3:		
A	1.8	2.0
B	2.3	3.4
C	4.8	4.8
D	2.6	4.6
E	1.8	3.3
F	---	2.5
Line 4:		
A	1.9	2.1
B	3.2	4.8
C	2.9	3.7
D	3.1	3.3
E	1.7	2.6
F	---	2.6
Line 5:		
A	1.8	2.3
B	1.8	1.7
C	3.0	2.4
D	2.8	3.4
E	3.0	5.0
F	3.5	4.8
G	2.0	2.6
H	---	2.6
Line 6:		
A	1.9	2.6
B	1.9	3.4
C	2.2	3.2
D	2.9	5.4
E	3.2	5.0
F	1.9	2.6
Line 7:		
A	1.4	2.5
B	1.9	5.2
C	2.6	4.0
D	2.5	5.0
E	1.5	2.8
Line 8:		
A	1.6	1.9
B	2.8	2.7
C	1.0	1.8
D	3.3	5.0
E	3.2	5.6
F	4.4	7.5
G	3.3	8.4
H	4.4	13.0
I	3.2	6.2
J	1.8	2.6

higher decibel levels (8 db) in the swamp than to the east of the river (as they did in the linear-contouring scheme). Because lithologic variations have been masked deliberately in the logarithmic ratios, higher decibel levels probably reflect increased ground-water contamination, which was suggested by the clustering of linear contours in the swamp. However, if contamination has occurred in the swamp, it has been masked slightly by the second scheme of contouring logarithmic ratios in which a subjectively assigned background apparent-conductivity value was used (fig. 10).

DISCUSSION

The principal advantage of plotting terrane conductivities in dimensionless logarithmic ratios is that it is possible to mask the contribution of background noise to the survey results; that is, local lithologic variations, differences in the apparent and terrane conductivities resulting from variations in depth to the water table due to topographic variations, cultural interferences, and inaccurate measurements. With the data converted, identification of contaminated zones is easier, inasmuch as any increase in the deci-

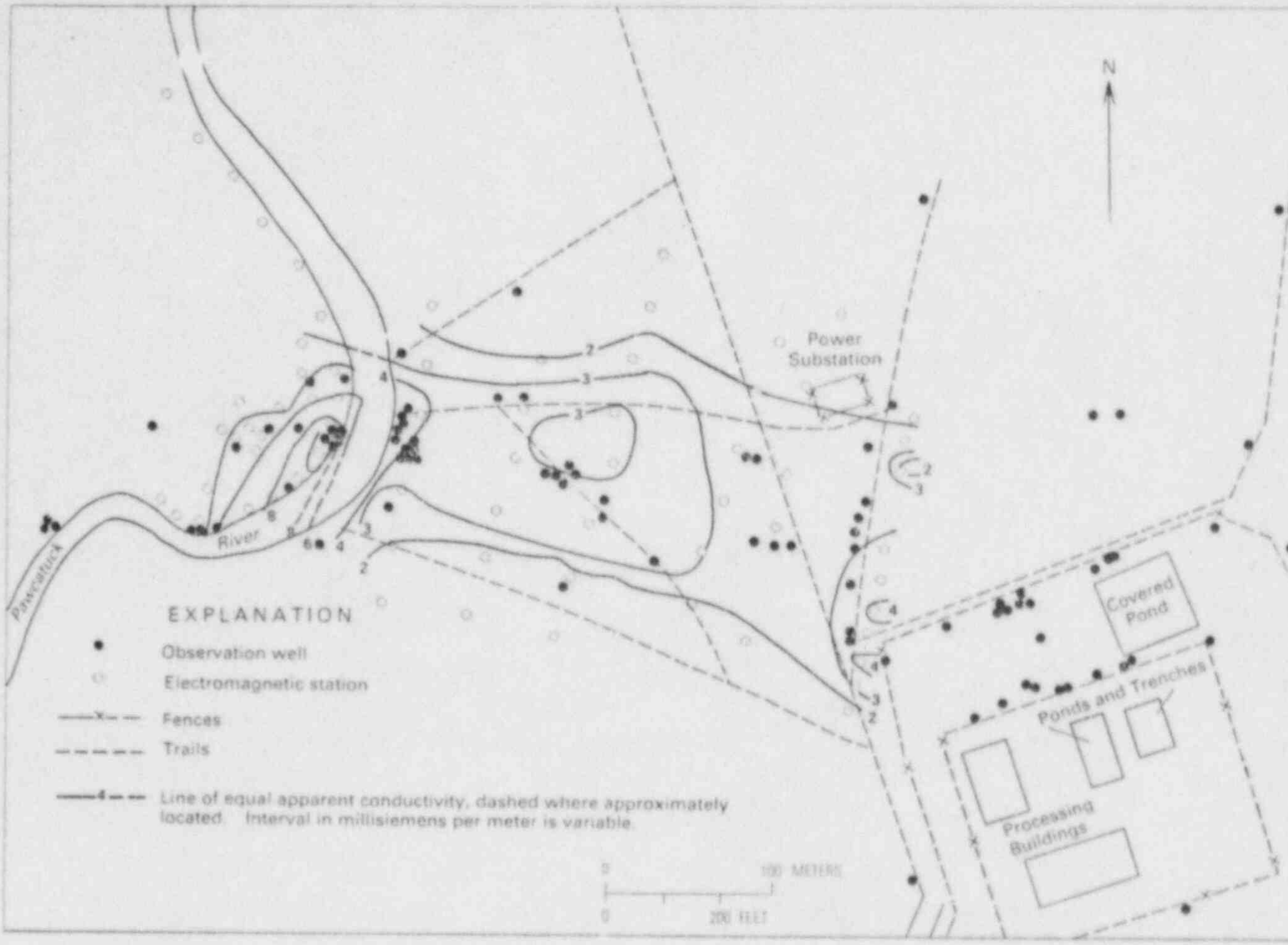

Figure 8. Linear contouring of horizontal-dipole electromagnetic data.

bel level indicates an increase in the apparent conductivity over and above what might be caused by background noise.

The selection of a background apparent conductivity value for contours of logarithmic ratios, however, is quite subjective (Greenhouse and Slaine, 1983, p. 49) and presents the greatest drawback to this method of data presentation. Difficulties were found with both techiques for determining background values used in this study. If too low a background value is used, local lithologic variations may obscure the hydrogeologic interpretation (as with contouring of linear values). Conversely, too high a background value will not give sufficient definition of the boundaries of the plume, thereby masking areas of potential contamination. The authors propose that both methods of determining background apparent-conductivity values be used in the contouring of logarithmic ratios. Low background values will then aid in the delineation of the boundaries of the plume, whereas high background values will show most clearly the core of the contamination plume.

Linear apparent-conductivity values are spaced more closely near zones of elevated contamination and suggest that the plume is composed of a broad zone of relatively lower contamination (2–3 mS/m at 25°C in the horizontal-dipole configuration and 3–5 mS/m at 25°C in the vertical-dipole configuration) with zones of relatively higher contamination near the plant and in the swamp. Although linear contouring of apparent-conductivity values does not show a continuous zone of contamination as clearly as does the logarithmic contouring of apparent-conductivity ratios (due to local variations in lithology and cultural interference), linear contours emphasize high levels of contamination, thereby outlining areas of possible importance.

Contours of linear values also portray the differences in vertical and horizontal electromagnetic results more clearly than the logarithmic format. This is especially true west of the Pawcatuck River where linear contours show high levels of conductivity in the upper layers of the aquifer. Differences between horizontal- and vertical-dipole results are not seen as

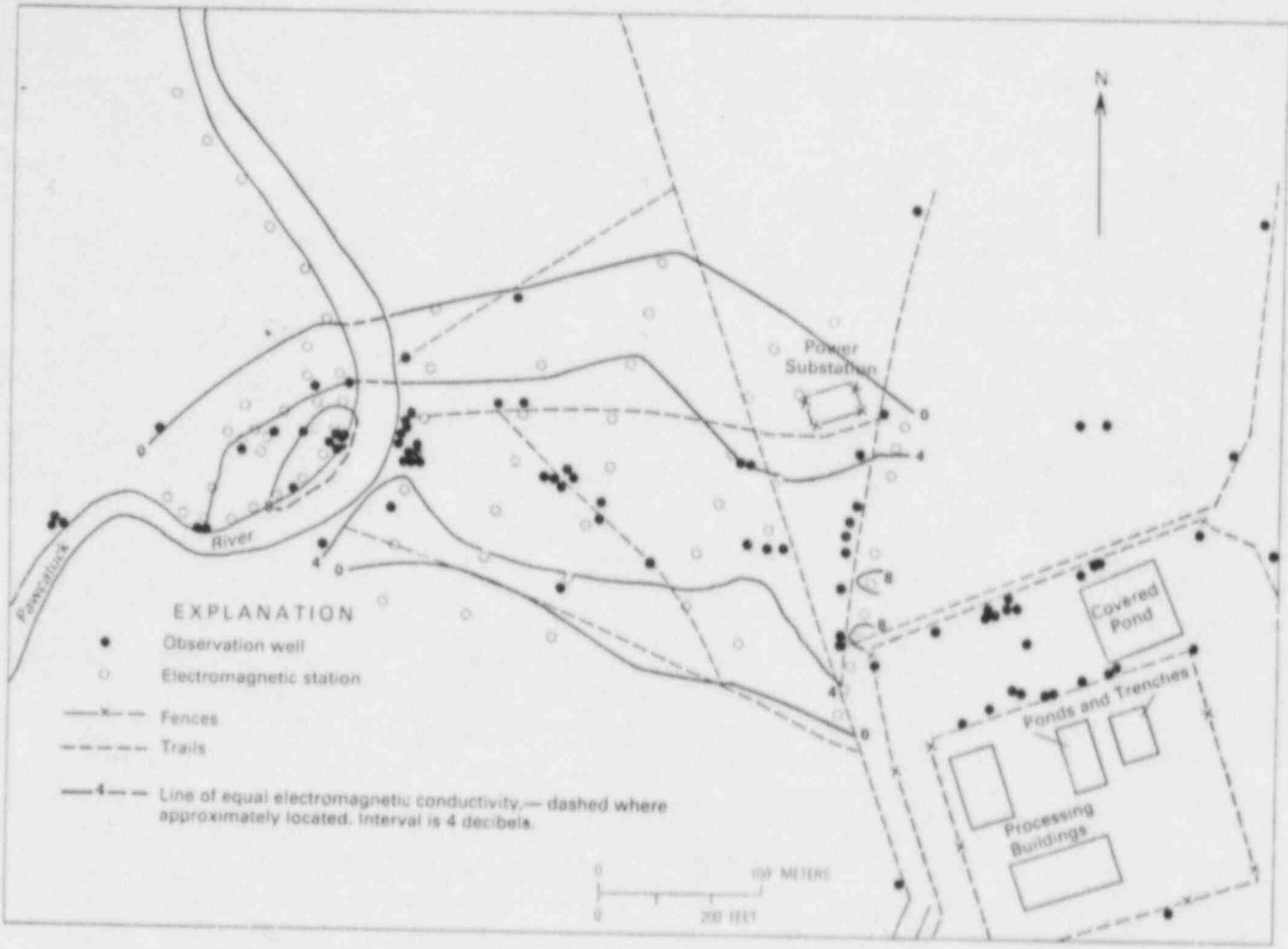

Figure 9. Logarithmic contouring of horizontal-dipole electromagnetic data using averaged background values.

clearly with contours of logarithmic ratios because different background apparent conductivities were used purposefully with horizontal and vertical configurations to put all values at the site into a similar range. As a result, contours of linear values are more helpful in determining the relative depth of contamination than are the contours of logarithmic ratios.

CONCLUSIONS

Results of EM surveys at a low-level radionuclide ground-water contamination site indicate that areas of high apparent conductivity coincide with areas of high specific conductance. Measurements in horizontal- and vertical-dipole configurations indicate chemical stratification that is confirmed by specific conductance samples from wells screened at various depths in the aquifer. Specific conductance results do show, however, that contamination has occurred at greater depth than has been sensed by the 20-m intercoil spacing of the vertical-dipole configuration. The vertical-dipole configuration was helpful in qualitatively determining shallow versus deep levels of contamination.

Contouring of the EM data by linear and logarithmic methods shows that advantages and disadvantages are associated with each method. Advantages to the linear method of contouring include an emphasis on high-conductivity zones that are potential contamination source areas and better depiction of differences in the response of the horizontal- and vertical-dipole configuration with depth. However, interference from background noise and some uncertainty in delineating boundaries between contaminated and uncontaminated areas of the site create problems in the hydrogeologic interpretation of linearly plotted EM data.

The ability to mask the contribution of background noise to EM survey results, thereby outlining more accurately areas of contamination, is the principal advantage to logarithmic contouring. The selection of background apparent-conductivity values at the study site posed the greatest drawback to logarith-

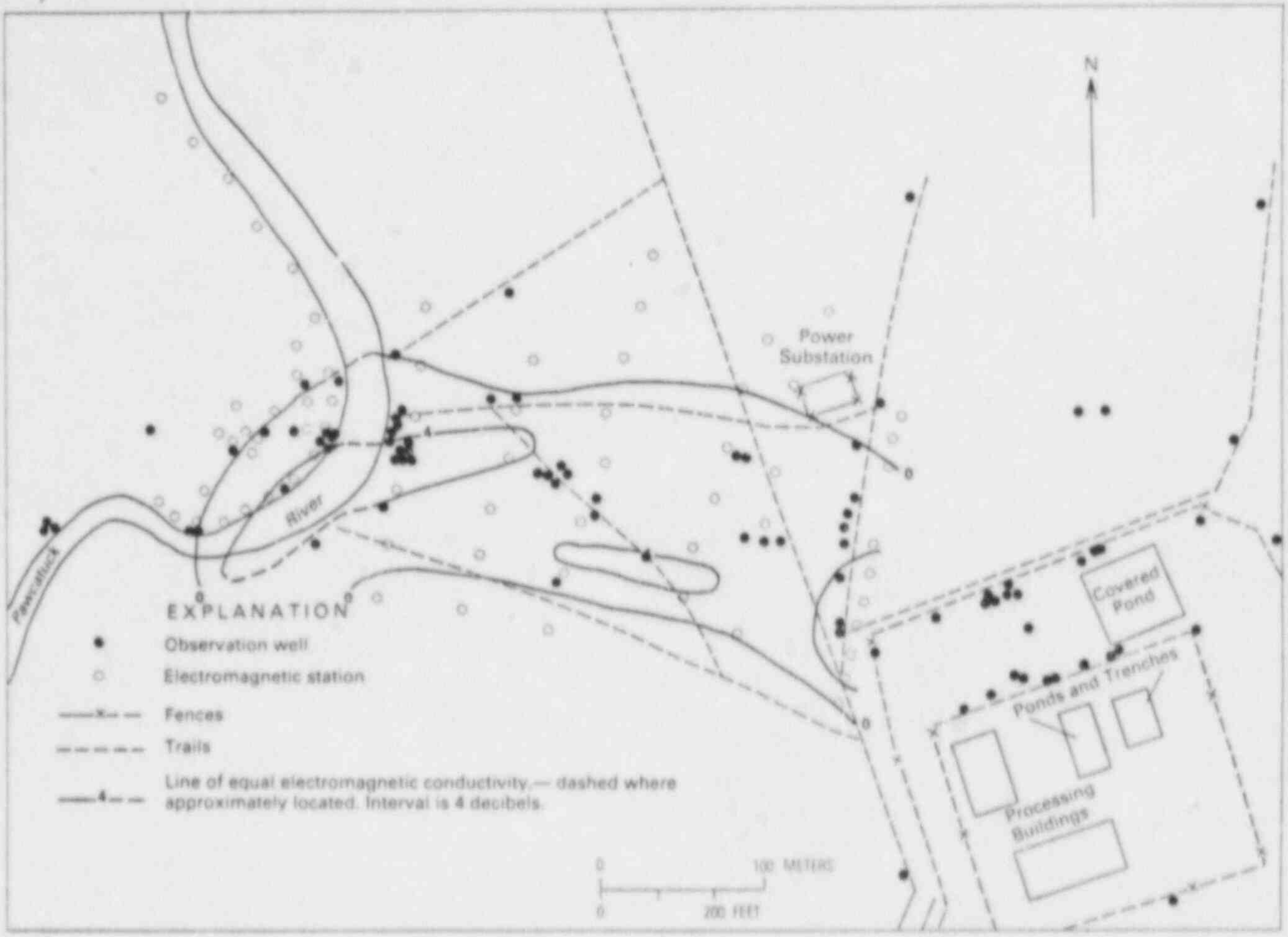

Figure 10. Logarithmic contouring of horizontal-dipole electromagnetic data using assigned background values.

mically contoured data. Background values that were too high caused an unreal reduction in the boundaries of the contamination plume, whereas low background apparent-conductivity values allowed interference from background noise to bias the hydrogeologic interpretation.

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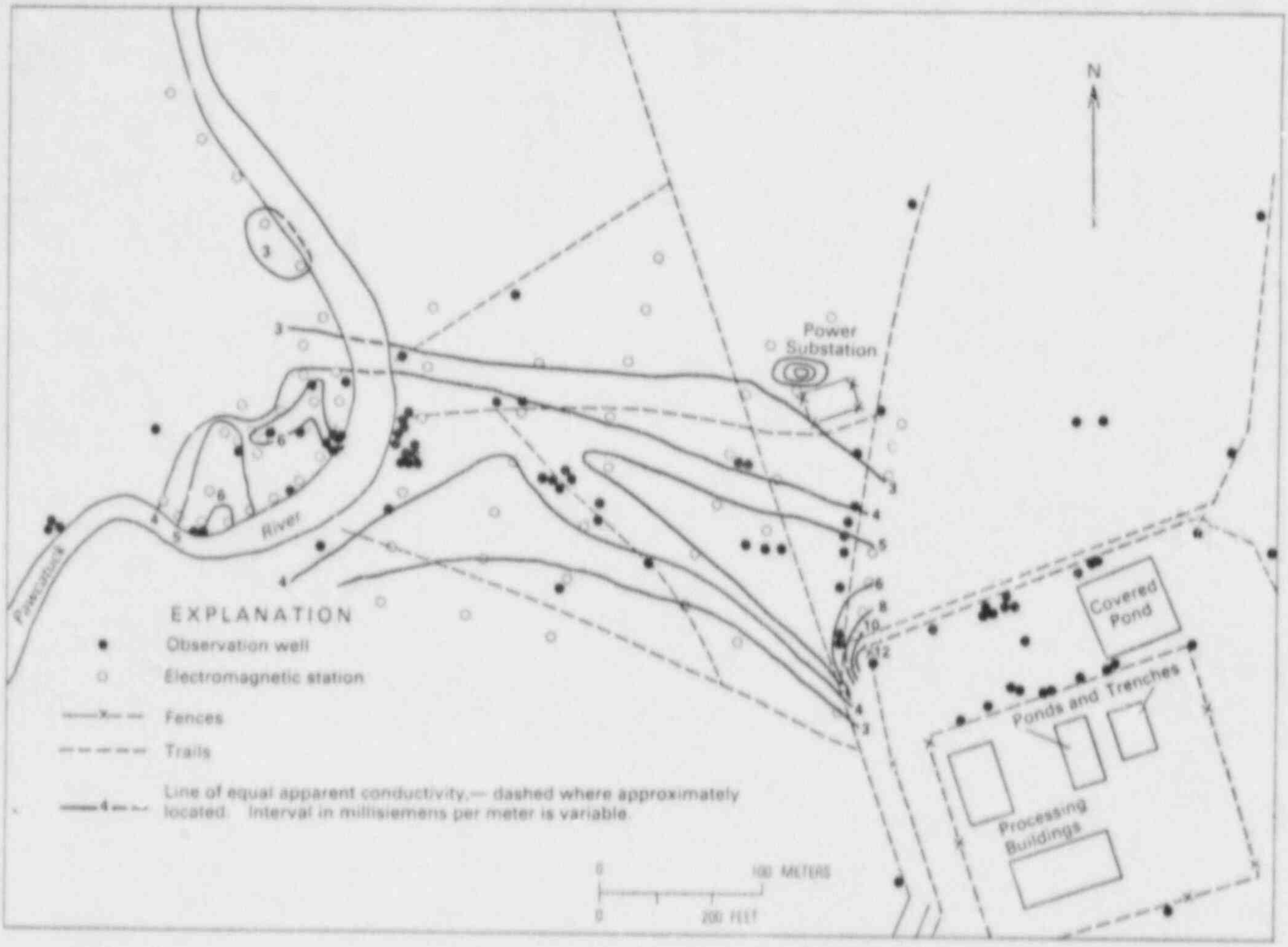

Figure 11. Linear contouring of vertical-dipole electromagnetic data.

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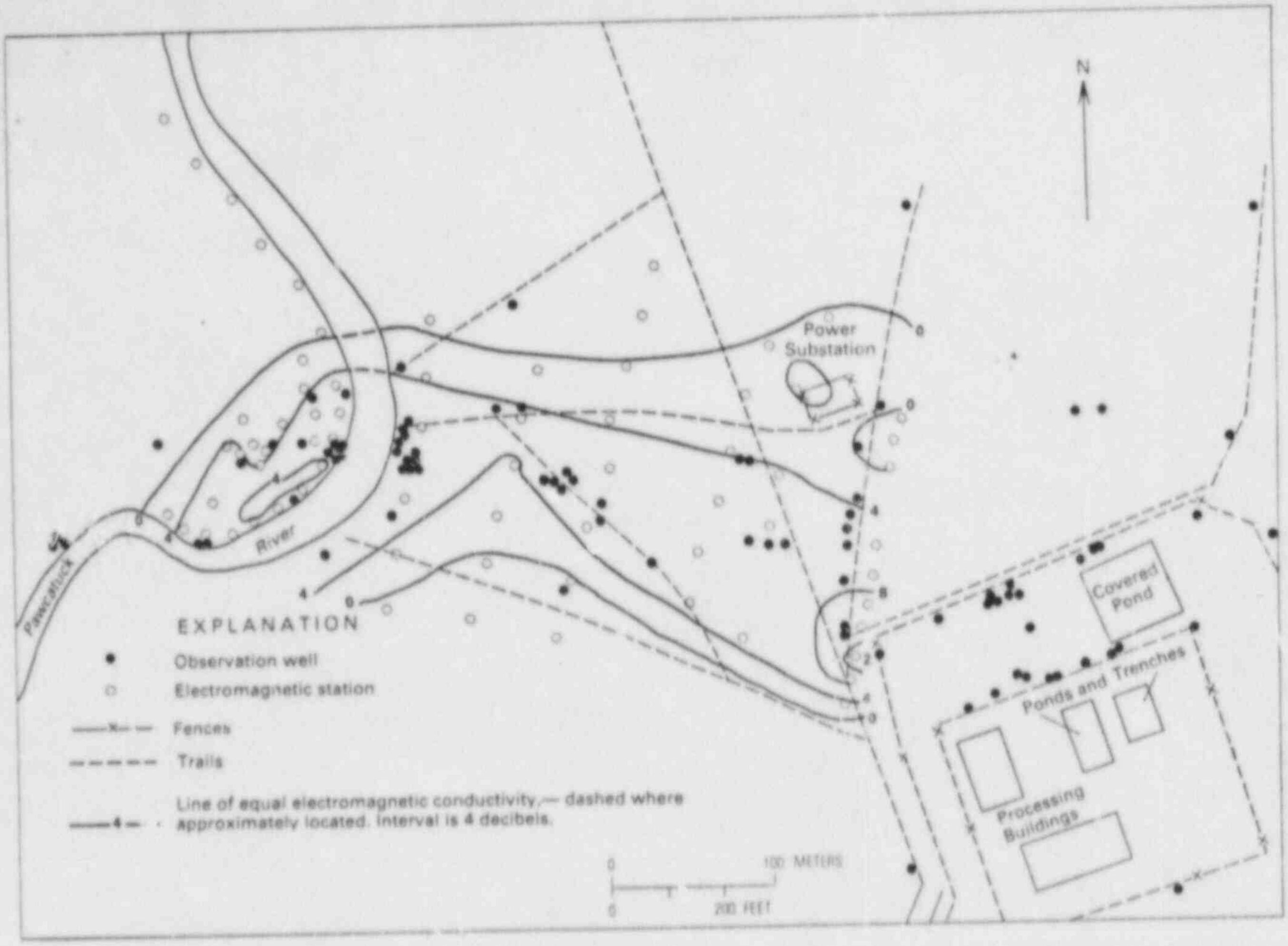

Figure 12. Logarithmic contouring of vertical-dipole electromagnetic data using averaged background values.

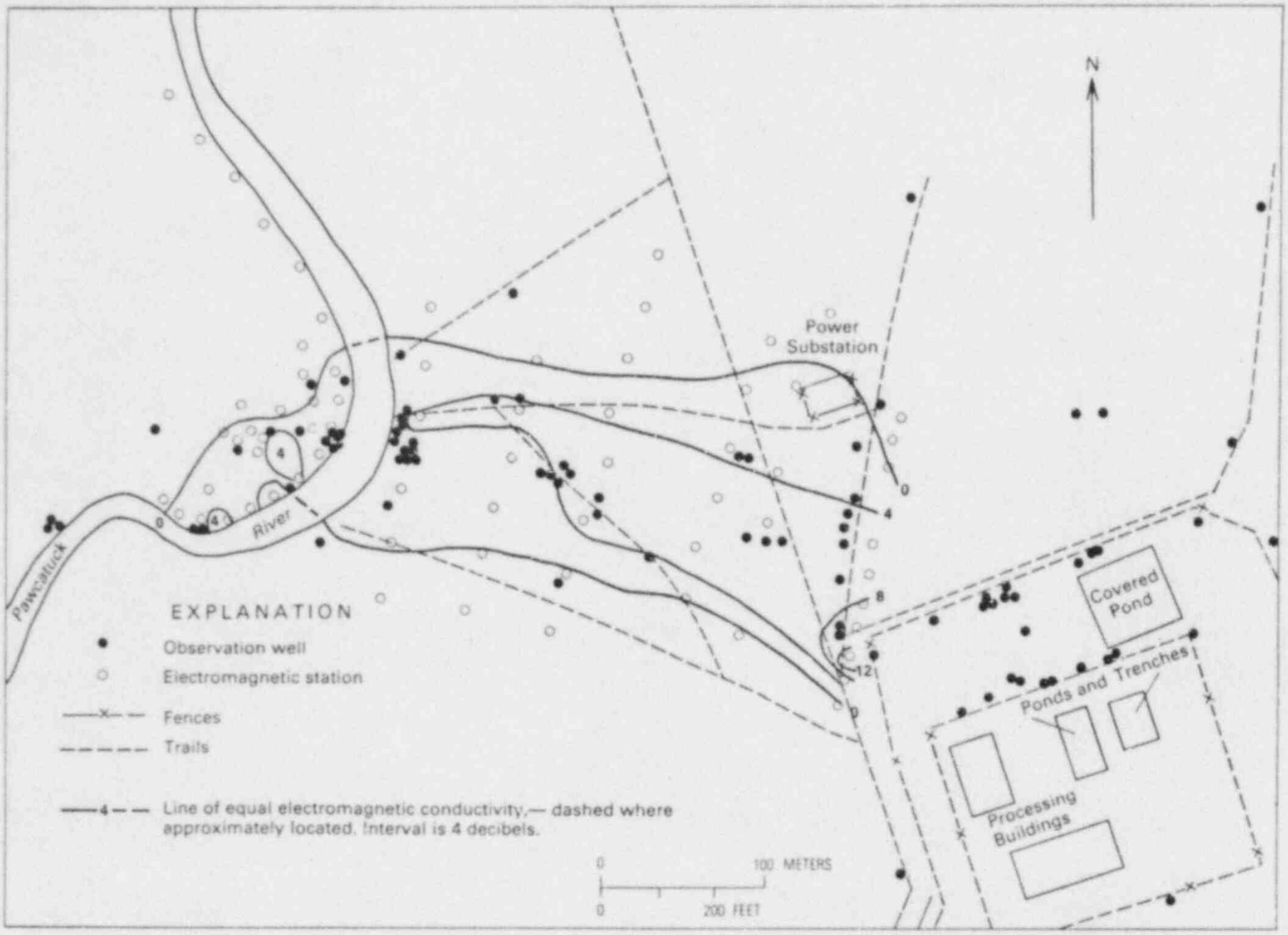

Figure 13. Logarithmic contouring of vertical-dipole electromagnetic data using assigned background values.

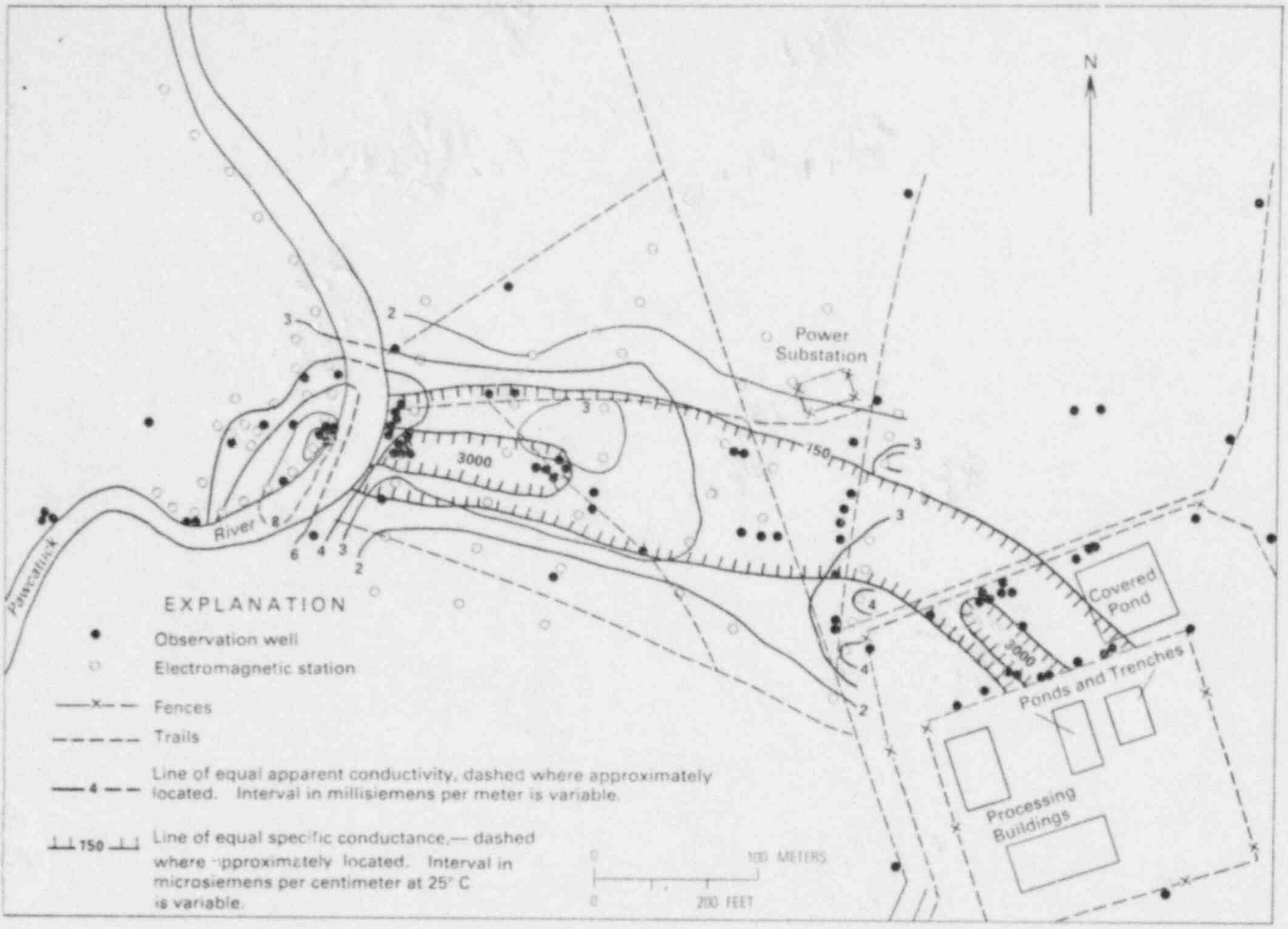

Figure 14. Comparison of specific conductance in ground water to linear horizontal-dipole electromagnetic data; April 1982.

Table 2. Background apparent-conductivity values used to normalize the electromagnetic data
[All values in millisiemens per meter at 25°C]

Values	Dipole orientation			
	Vertical		Horizontal	
	East	West	East	West
Averaged	2.4	3.3	1.7	3.3
Assigned	3.0	4.0	2.0	4.0

Low-Level Radioactive Ground-Water Contamination From a Cold-Scrap Recovery Operation, Wood River Junction, Rhode Island

By Barbara J. Ryan *and* Kenneth L. Kipp, Jr.

Abstract

In 1981, the U.S. Geological Survey began a 3-year study of ground-water contamination at a uranium-bearing cold-scrap recovery plant at Wood River Junction, Rhode Island. Liquid wastes from this industrial site were discharged to the environment through evaporation ponds from 1966 to 1980. Leakage from the polyethylene- and polyvinylchloride-lined ponds resulted in a plume of contaminated ground water that extends from the ponds northwestward to the Pawcatuck River through a highly permeable sand and gravel aquifer of glacial origin.

Electrical conductivity, determined by electromagnetic methods, was used to delineate the plume areally before observation wells were installed. These data, combined with water-quality data from more than 100 observation wells, indicate that the plume is approximately 2,300 feet long and 300 feet wide and is confined to the upper 80 feet of saturated thickness where sediments consist of medium to coarse sand and gravel. No contamination has been detected in fine sands and silts underlying the coarser materials. Piezometric head and water-quality data from wells screened at multiple depths on both sides of the river indicate that contaminants discharge to the river and to a swampy area at the west edge of the river. Dilution precludes detection of contaminants once they have entered the river, which has an average flow of 193 cubic feet per second.

Water-quality data collected from April 1981 to June 1983 indicate that strontium-90, technetium-99, boron, nitrate, and potassium exceed background concentrations by an order of magnitude in much of the plume. Concentrations of gross beta emitters range from 5 to 500 picoCuries per liter. No gamma emitters above detection levels have been found. Electrical conductivity of the water ranges from 150 to 4,500 micromhos per centimeter at 25 degrees Celsius. Water-quality sampling shows zones of concentrated contaminants at both ends of the plume, separated by a zone of less contaminated water. Laboratory tests for exchangable cations indicate little capacity for uptake by the coarse sediments. In the swamp, reducing conditions may promote observable solute interaction with sediments or organic material.

INTRODUCTION

Liquid wastes containing radionuclides and other chemical solutes from an enriched ura[illegible] cold-scrap recovery plant have leaked from polyethylene- and polyvinylchloride (PVC)-lined ponds and trenches into a highly permeable sand and gravel aquifer in southern Rhode Island. The resultant plume of ground-water contamination extends about 2,300 ft from the ponds and trenches to the Pawcatuck River and the contiguous swamp into which ground-water discharge occurs. In 1981, the U.S. Geological Survey began a 3-year study of this ground-water contamination at a plant at Wood River Junction, Rhode Island (fig. 1). The objectives of the study are to (1) identify constituents in the plume, (2) determine solute interaction with aquifer materials, (3) model ground-water flow and solute transport in the study area, and (4) use the model to predict residence times in the aquifer and fate of contaminants in the plume.

Contaminated ground water at this site moves through a highly permeable glacial outwash aquifer that yields water readily to wells. The Rhode Island Water Resources Board has conducted test drilling around Wood River Junction and has considered developing ground water from the Meadow Brook Pond area for use both within and outside the basin. The possibility that supply wells developed in the area might be contaminated as a result of migration of contaminated water beneath the Pawcatuck River is of concern to the Water Resources Board.

By October 1982, most of the data collection network for the investigation was in place, and routine water-level measurements, water-quality sampling, and precipitation measurements were begun. This paper describes geohydrologic conditions at the site, the source of ground-water contamination, and presents preliminary findings based on data collected through June 1983. National Geodetic Vertical Datum of 1929 is referred to as sea level in this report.

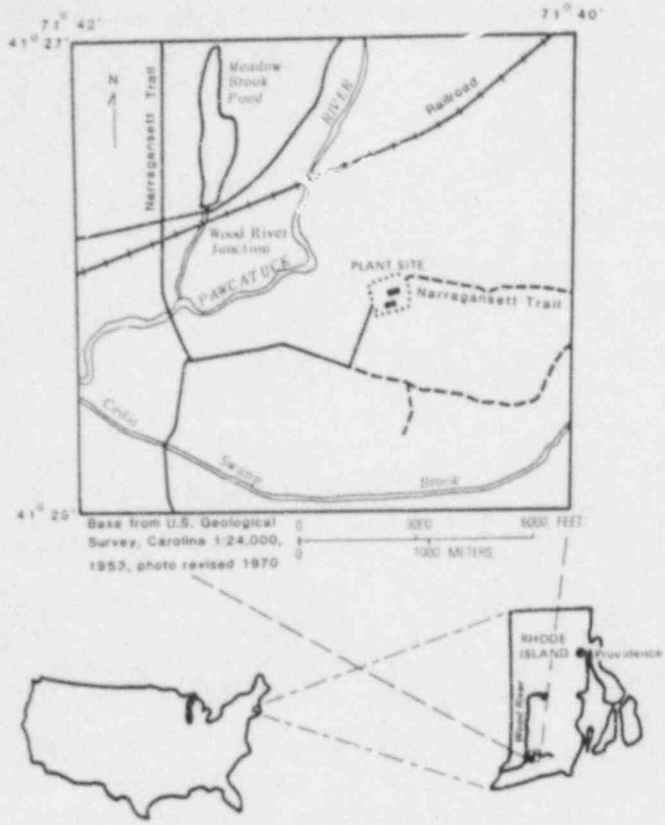

Figure 1. Location of study area.

PLANT HISTORY AND CONTAMINATION SOURCE

From 1964 to 1980, an enriched uranium cold-scrap recovery plant was operated (fig. 2) at Wood River Junction, Rhode Island. Acid digestion with hydrofluoric and nitric acids and organic separation with tributyl phosphate and kerosene were used in the process. Solid wastes from the process were shipped offsite, and liquid wastes were discharged to the Pawcatuck River through a drain pipe from 1964 to 1966 and to uncovered "evaporation" ponds and trenches from 1966 to 1980.

In southern Rhode Island, however, average annual precipitation is much greater than average annual evaporation; for example, from 1950 to 1970, precipitation at the National Weather Station at Kingston, Rhode Island, 9 mi northeast of the study area, averaged 46.06 in/yr while estimated annual free water surface evaporation for the same period was only 29 in/yr (National Oceanic and Atmospheric Administration, 1982). This and the fact that highly permeable sediments occur beneath the ponds and trenches indicate that much of the liquid waste discharged to the ponds and trenches did not evaporate but rather percolated into unconsolidated deposits beneath the site.

The depth of the ponds and trenches ranged from 3 to 15 ft below land surface; the bottoms of the ponds were 9 to 13 ft and the bottoms of the trenches were 1 to 3 ft above high water table.

From 1964 to 1966, liquid wastes were discharged to the Pawcatuck River through a buried drain 1,500 ft in length. Beginning in 1966, liquid wastes were discharged into a pond approximately 5,000 ft^2 in area and 6 ft in depth (fig. 2). Pond capacity or overflow problems due to precipitation and disposal flow rates (estimated by plant officials to have averaged about 400 gal/d) led to periodic construction of additional ponds and trenches. In 1967, a second pond (8,400 ft^2 in area and 4 ft in depth) was used as a replacement, and, in 1972, a new pond was constructed in the same area as the original pond. A series of trenches were built to replace the first and second ponds in 1977 and were used until 1979. The liquid waste disposal ponds and trenches encompassed approximately 25,000 ft^2. These disposal sites are considered to be the source of the contaminated liquid percolation to the water table. In 1979, a covered tank with a double polyethylene liner was constructed 50 ft north of the original pond area (fig. 2) to hold the liquid waste during evaporation and concentration processing. To date, no evidence exists for ground-water contamination from the covered tank storage area.

Because data on chemical composition and physical properties of the liquid wastes are limited and concentrations of chemical and radiochemical constituents in waste discharges changed with time, defining the actual source loadings is not possible. In addition to hydrofluoric and nitric acids, tributyl phosphate, and kerosene, the following chemicals were used in the recovery process and were present in the liquid wastes in varying concentrations: aluminum nitrate, calcium hydroxide, mercury, sodium carbonate, sodium hydroxide, and potassium hydroxide. Although primarily nonirradiated fuel elements were processed from 1964 to 1980, slightly irradiated fuel elements from test reactors were processed from 1967 to 1980. This could account for the strontium-90 and technetium-99 that are in the contaminated water.

Processing at the plant, which ended in August 1980, currently is being decommissioned. Material from the bottom of the ponds and trenches and sediment from below the ponds and trenches were removed and combined with a cementlike mixture and shipped offsite for burial. Sediments in the unsatu-

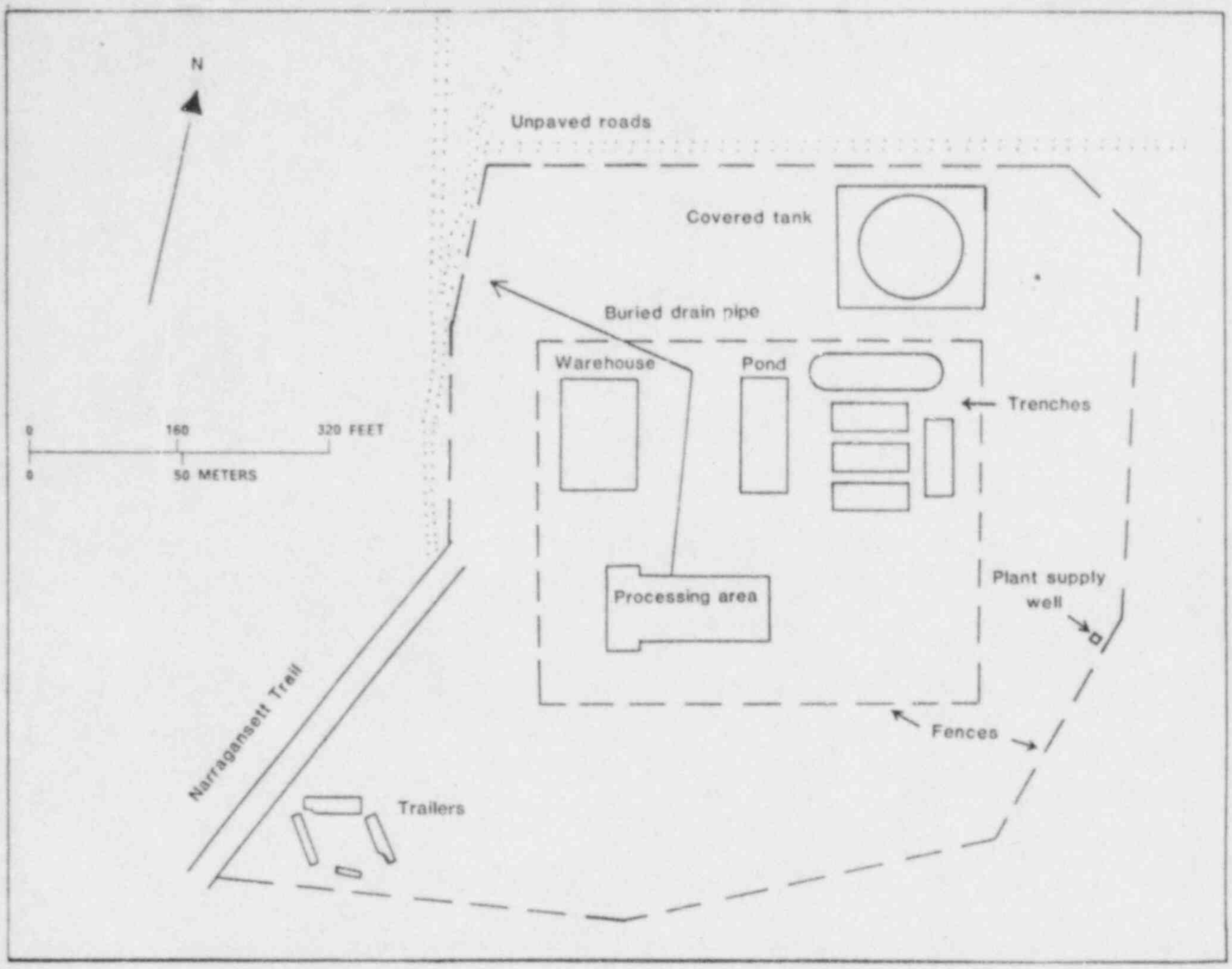

Figure 2. Location of processing area, evaporation pond, trenches, and covered tank in 1979.

rated zone between the pond and trench bottoms and the water table were not sampled.

PREVIOUS SITE INVESTIGATIONS

From 1974 to 1977, the Rhode Island Water Resources Board drilled approximately 20 test holes on the plant property to obtain lithologic and water-quality data for evaluating potential areas for ground-water development. Water-quality data obtained as part of the Water Resources Board investigation indicate ground water of high conductivity (5,500 µmho/cm at 25°C), high nitrate (225 mg/L), and significant gross alpha (43 pC/L) and gross beta (489 pC/L) emitters 1,100 ft from the source area (Dickerman and Silva, 1980, p. 177–178). In 1977, the company installed 10 observation wells between the plant and the river that ranged in depth from approximately 50 to 80 ft. Water-quality data obtained by the company from one of these wells indicate ground water of high conductivity (14,500 µmho/cm at 25°C), high nitrate (2,200 mg/L), and significant gross beta emitters (1,518 pC/L) 200 ft from the source area (Dickerman and Silva, 1980, p. 177–178).

In 1977, resistivity surveys were conducted by David Huntley, University of Connecticut, and by Daniel Urish, University of Rhode Island. Results of these surveys indicated a plume of ground water with high conductivity between the plant site and the Pawcatuck River. Adjacent to the source area, depth below land surface of the highest conductance water was estimated to be 40 ft (David Huntley, written commun., 1981). Maximum known extent of contamination at the start of the present study (October

1982) was approximately 1,200 ft from the source area.

STUDY AREA DESCRIPTION

Geology

The study area is underlain by the Hope Valley Alaskite Gneiss, a metamorphic rock unit of Late Proterozoic age (570–900 million years old). The gneiss was an igneous rock unit that underwent one and possibly two episodes of metamorphism (Moore, 1959). The bedrock crops out east, northeast, west, and southwest of the study area, and unconsolidated glacial deposits of Pleistocene age (less than 1 million years old) have been deposited on top of the bedrock.

Glacial till deposits (poorly sorted clays, silts, sands, gravels, and boulders) form a relatively thin (less than 20 ft) mantle over the bedrock (LaSala and Hahn, 1960) and appear at land surface east of the plant site (fig. 3). Glacial outwash deposits (well-sorted silts, sands, and gravels) were deposited in the bedrock valley (fig. 4) and range in thickness from 0 to 300 ft in some parts of the valley.

In the bedrock valley, the outwash deposits consist of predominantly medium to coarse sands and gravels to a depth of about 80 ft below land surface and mostly fine sands and silts below a depth of 80 ft (fig. 4). A glacial terminal moraine (till with some stratified deposits) approximately 3 mi south of the study area may be responsible for the fine sands and silts at depth. Slow-moving glacial meltwater flowing into a lake behind the moraine apparently resulted in the deposition of the fine-grained sediments.

The fine sands and silts are cohesive in places; however, few clay-sized particles have been found to date. Clay-sized particles from two split spoon samples taken from the fine sand and silt unit were 2.94 and 3.07 percent. Clay-sized particles taken from seven split spoon samples from the coarse sand and gravel unit ranged from 0.12 to 7.60 percent, with an average value of 1.53 percent and a median value of 0.38 percent. In two locations (one approximately 100 ft south of Meadow Brook Pond and one between the plant site and river) where test holes have exceeded 150 ft in depth, a zone (5–15 ft) of coarse sands has been encountered below the fine silts and sands and above the bedrock surface. The mineralogy of the outwash deposits is predominately quartz and feldspars; dark minerals (biotite and hornblende) are generally more abundant in the finer sediments (F. T. Manheim, written commun., 1983).

Hydrology

The plant site, located within the lower Pawcatuck River basin, is approximately 2 mi east of the junction of the Pawcatuck and Wood Rivers. Unconsolidated deposits near the junction of these two rivers comprise the most extensive accumulation of sediments in the lower Wood aquifer (Gonthier and others, 1974, p. 7). The aquifer is approximately 8 mi in length and ranges from 2,000 to 8,000 ft in width with the majority of it extending north, northwest, and west of the plant site. Saturated thickness in the Ellis Flats area exceeds 290 ft. Swamp and till deposits form the southern and eastern limits of the aquifer, respectively.

The aquifer is unconfined with a water table that slopes westward from the plant site at an average gradient of 28 ft/mi. The lower boundary of the aquifer is the bedrock surface (fig. 4). Generally, ground-water movement in the aquifer is from the lateral boundaries or till upland areas toward the Pawcatuck River (fig. 5). Ground water discharges to the Pawcatuck River, which is the major surface water drainage from the study area. Ground-water potentials (fig. 6) show upward vertical movement of water into the Pawcatuck River and contiguous swampy area west of the river.

Water enters the ground-water system through infiltration of precipitation (rainfall or snowmelt). Overland runoff and some ground-water flow from adjacent till-covered bedrock areas also enter the aquifer. Based on annual average runoff of 27.51 in from 1966 to 1980 upstream of the U.S. Geological Survey gage on the Pawcatuck River at Wood River Junction and a relation developed by Mazzaferro and others (1978, p. 45), long-term average annual recharge to the aquifer is estimated to be 26 in/yr. Assuming ground-water outflow is a conservative estimate of the amount of natural recharge, Mazzaferro and others (1978) related ground-water outflow to the percentage of stratified drift in a drainage basin. The relation developed by linear regression is described by the equation,

$$Y = 35 + 0.6X,$$

where Y equals ground-water outflow as a percent of total runoff and X equals percentage of total basin area underlain by stratified drift. For this case, X = 100.

Discharge of water from the aquifer occurs through ground-water runoff and evapotranspiration, primarily where the water table is near the land surface. Hydraulic conductivity of till is estimated to average about 1 ft/d as does the till in the nearby upper Pawcatuck River basin (Allen and others,

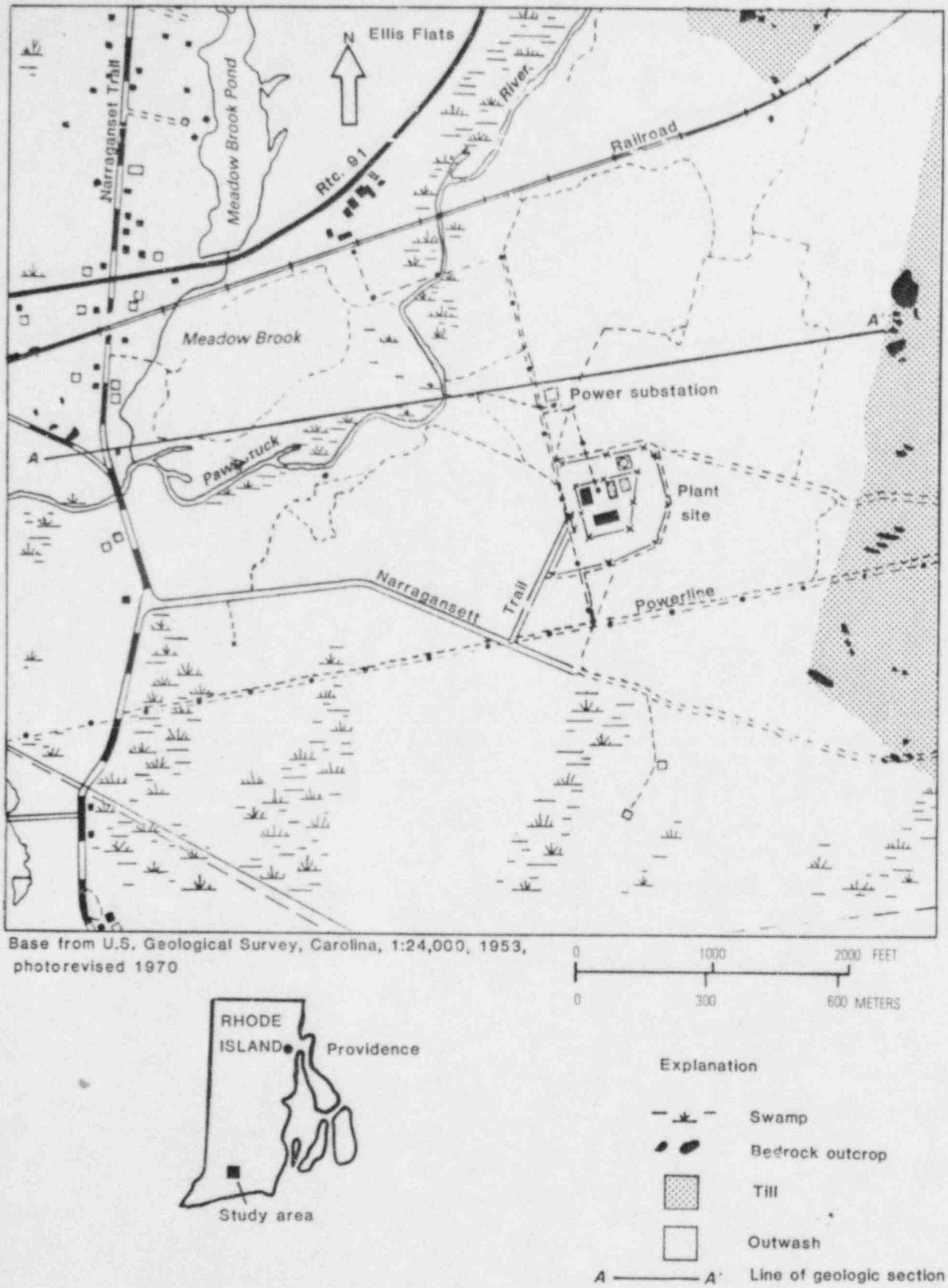

Figure 3. Generalized surficial geologic map of the study area and location of cross-sectional line *A–A′*.

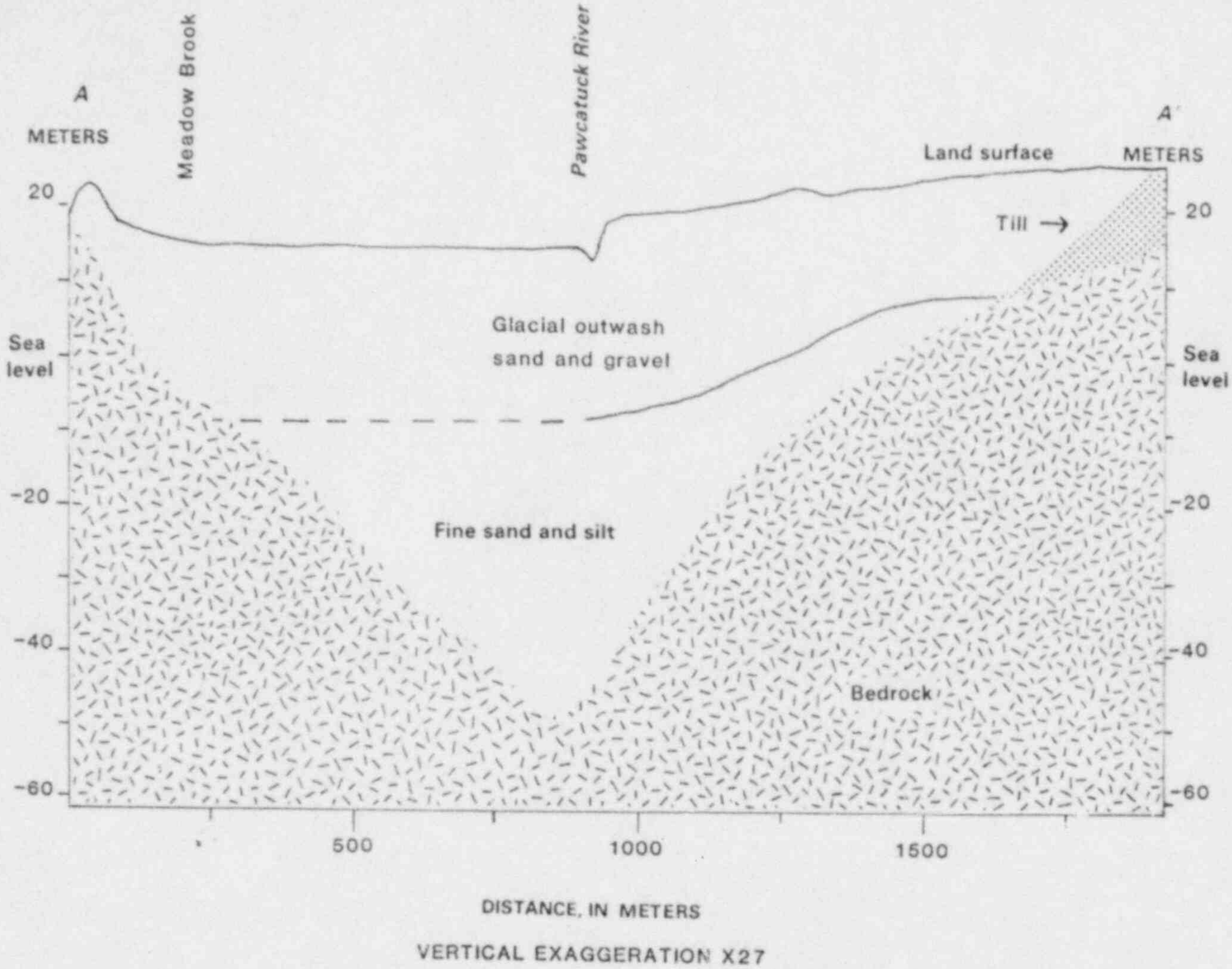

Figure 4. Generalized geologic section along line *A–A'*.

1966, p. 9), whereas hydraulic conductivity of outwash deposits at the plant, estimated from lithologic logs, is about 180 ft/d (Gonthier and others, 1974, plates 2, 4). Hydraulic conductivity determined from analyses of three aquifer tests made within a 1-mi radius of the site, including one on the plant supply well (fig. 2), ranged from 140 to 190 ft/d (D. C. Dickerman, oral commun., 1983). Hydraulic conductivity of the fine sands and silts at depth probably falls somewhere in between those of the tills and coarse outwash deposits. Fractures in the bedrock also yield water to wells but generally only enough for domestic supplies (5 gal/min or less) (Allen, 1953, p. 26). Ground-water flow, which was calculated from a water-table gradient of 28 ft/mi, an estimated aquifer porosity of 0.38 (obtained from averaging porosity values from six sediment samples), and hydraulic-conductivity estimates that ranged from 140 to 190 ft/d, ranged from 1.95 to 2.65 ft/d.

Uncontaminated ground and surface water in the study area generally meet U.S. Environmental Protection Agency (1976) drinking water standards. Specific conductance, an indication of dissolved minerals in the water, is generally less than 100 μmho/cm at 25°C. Principal cations, sodium, calcium, potassium, and magnesium are present in concentrations of 14 mg/L or less; principal anions, sulfate, chloride, and nitrate are present in concentrations of 20 mg/L or less. Some naturally occurring radionuclides, such as potassium-40 (1 pC/L), radium-226 (3 pC/L), radium-228 (2 pC/L), and strontium-90 (3 pC/L), have been detected in ground and surface water in the study area.

EXPLORATION TECHNIQUES

Geophysical techniques and well drilling were used to define the hydrogeologic system and contam-

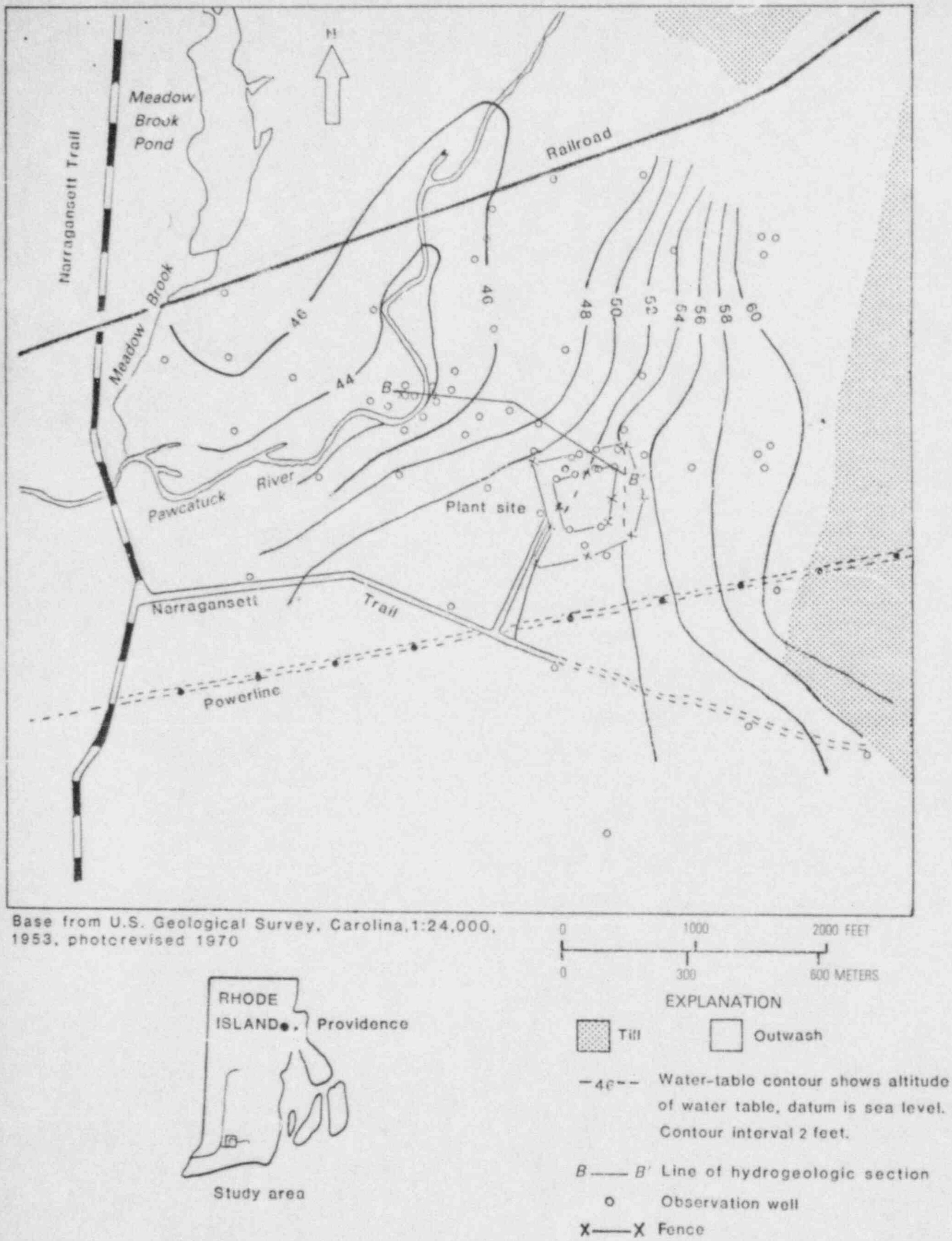

Figure 5. Average water-table altitude from July 1982 to June 1983; location of observation wells and cross-sectional line *B-B'*.

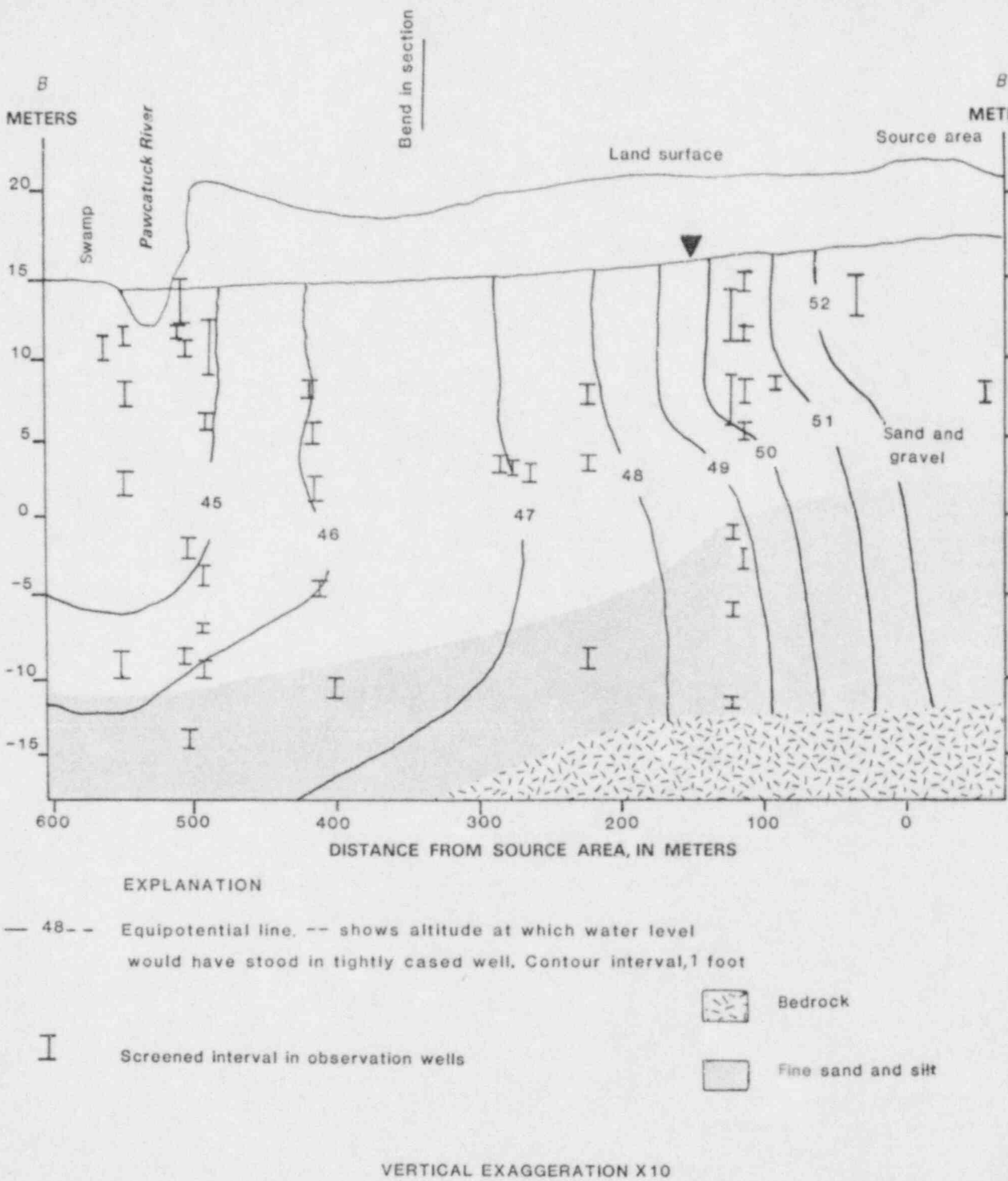

Figure 6. Hydrogeologic section showing average ground-water potential from July 1982 to June 1983.

ination plume. Geophysical techniques included seismic refraction to determine depth to bedrock, geophysical well logging (gamma gamma, natural gamma, and neutron) to determine relative lithologic differences within a given well and from well to well, and electromagnetic (inductive) conductivity surveys to locate areas within the aquifer containing water of high specific conductance.

More than 135 observation wells ranging in depth from 10 to 230 ft were installed during six drilling phases using hollow-stem auger, mud rotary, and drive-and-wash methods. Wells generally were

constructed of 1¼- to 1½-in diameter flexible polyethylene or rigid PVC plastic pipe. Two wells were constructed with 5-in diameter rigid PVC pipe for geophysical logging purposes, and two wells were constructed with 1¼-in diameter galvanized steel for continuous water-level recording. Screened intervals or well points ranged from 2 to 10 ft in length and were either No. 10 (0.010-in) or No. 12 (0.012-in) slot. The first drilling phases were used to install relatively shallow (less than 30-ft) observation wells to determine the water-table configuration. Later phases were devoted to the installation of wells ranging in depth from 10 to 100 ft to locate the contamination plume horizontally and vertically. Ten split spoon samples were taken for such sediment analyses as cation exchange capacities, mineralogic descriptions, porosity tests, and sieve analyses.

CONTAMINATION PLUME

The plume of contaminated ground water extends from the source area northwestward approximately 1,500 ft to the Pawcatuck River and southwestward approximately 800 ft in a downstream direction through the swampy area west of the river, a total distance of 2,300 ft (figs. 7, 8). Dilution precludes detection of contaminants once they have entered the river which has an average discharge of 193 ft^3/s. The plume is approximately 300 ft in width and is confined to the upper 80 ft of saturated thickness (fig. 9) where sediments consist of medium to coarse sand and gravel. The top of the contamination plume is depressed below the water table, and its depth increases as it moves away from the source area. The plume obtains a maximum depth (80 ft below land surface) between 1,400 and 1,500 ft from the source area. Beneath the discharge area (river and adjacent swamp), the plume rises to land surface.

Specific gravity of three samples of contaminated ground water collected in 1981 ranged from 1.000 to 1.001 (Daniel Urish, written commun., 1982). It is assumed, therefore, that freshwater recharge on top of the plume is probably responsible for increased depth of the plume away from the pond area. Seasonal variations in hydrologic conditions may affect dimensions of the plume; for example, high precipitation in the spring of 1983 depressed the contamination plume below the water table at the river-swamp interface (fig. 10).

Chemical and radiochemical constituents in the contaminated water include nitrate (5–600 mg/L), boron (20–400 µg/L), potassium (3–25 mg/L), strontium-90 (4–250 pC/L), and technetium-99 (75–1,350 pC/L). Due to the expense of the analytical proce-

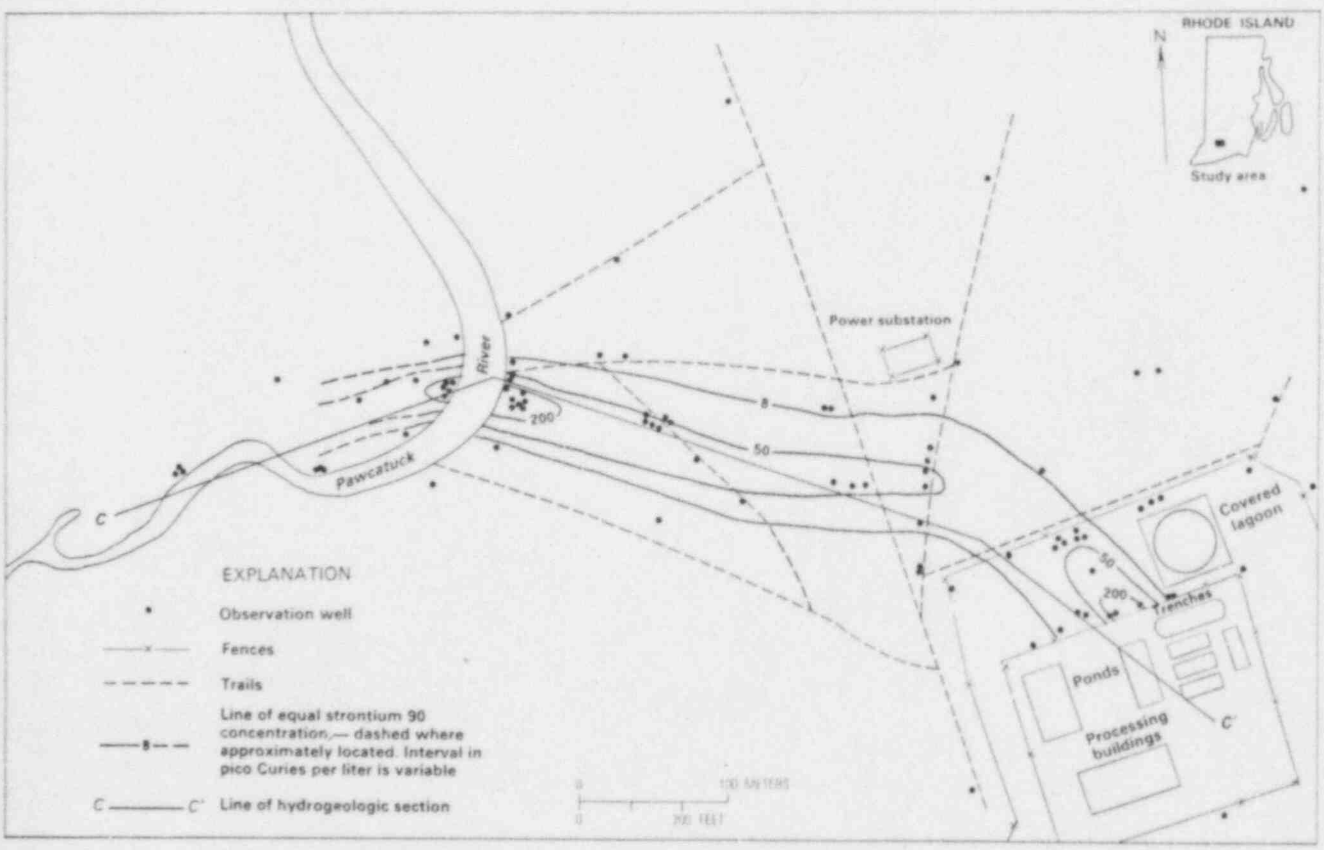

Figure 7. Strontium-90 concentration in ground water at the plant site, October 1982.

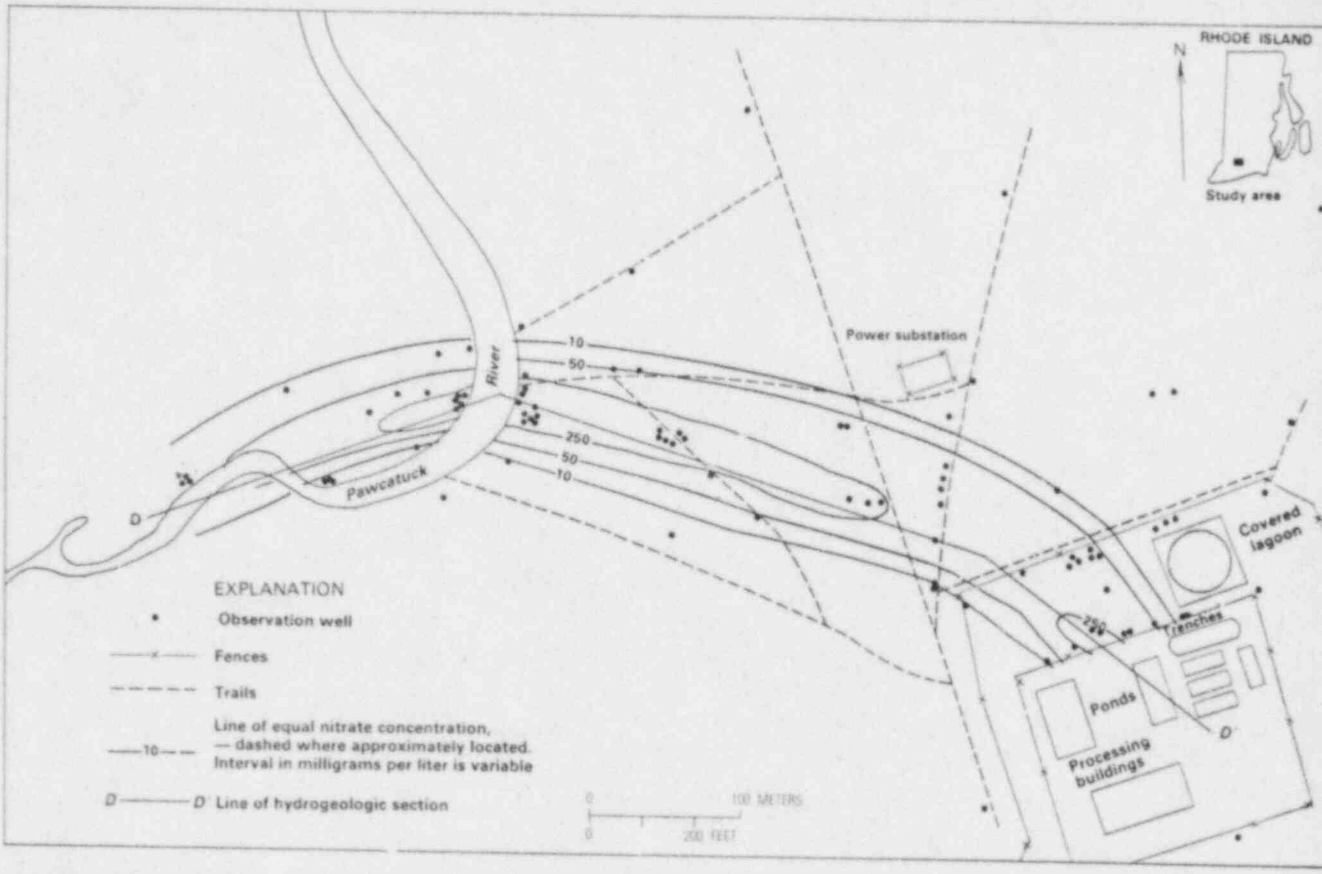

Figure 8. Nitrate concentration in ground water at the plant site, October 1982.

dure, only five water samples have been analyzed for technetium-99 (two by the U.S. Geological Survey and three by Oak Ridge Associated Universities). In these five samples, strontium-90 accounts for 10 to 30 percent of the gross beta activity; the remainder is attributed to technetium-99. The sums of strontium-90 and technetium-99 actually may exceed the gross beta activity level for a given sample; this is most likely due to the fact that the separation and counting efficiency for individual radionuclide measurements is greater than that of the gross beta counting apparatus. Concentrations of gross beta emitters range from 5 to 500 pC/L. No gamma emitters above detection levels have been found. Electrical conductivity of the water ranges from 150 to 4,500 µmho/cm at 25°C. Dissolved solids have been measured up to 3,500 mg/L, and these concentrations interfere with the detection of alpha emitters. Concentrations of chemical constituents in contaminated water at the plant site, and background concentrations are summarized in table 1.

From 1982 to 1983, two zones of concentrated contaminants were present at both ends of the plume and were separated by a zone of less contaminated water. The zone near the Pawcatuck River resulted from infiltration of contaminants while the plant was processing material (1964–80). The zone near the source area apparently resulted from flushing of additional contaminants from the unsaturated zone while the sediment below the ponds and trenches was being excavated for site-decommissioning.

Sediment- and water-quality analyses from sampling locations from the plant to the river indicate chemical and radiochemical constituents are not being sorbed by aquifer materials. Cation-exchange capacities from five split spoon samples ranged from 0.1 to 4.2 milliequivalent per 100 grams (meq/100 g), with a median value of 0.5 meq/100 g. Technetium-99 and strontium-90 have been detected in water from observation wells that are 1,500 and 2,000 ft, respectively, from the plant. In the swamp, however, reducing conditions may promote observable solute interaction with sediments or organic material once the plume rises to land surface. Additional sediment- and water-quality analyses are being conducted on materials from the swamp.

SUMMARY

Liquid wastes from an enriched uranium cold-scrap recovery plant have leaked into a highly permeable sand and gravel aquifer in southern Rhode Is-

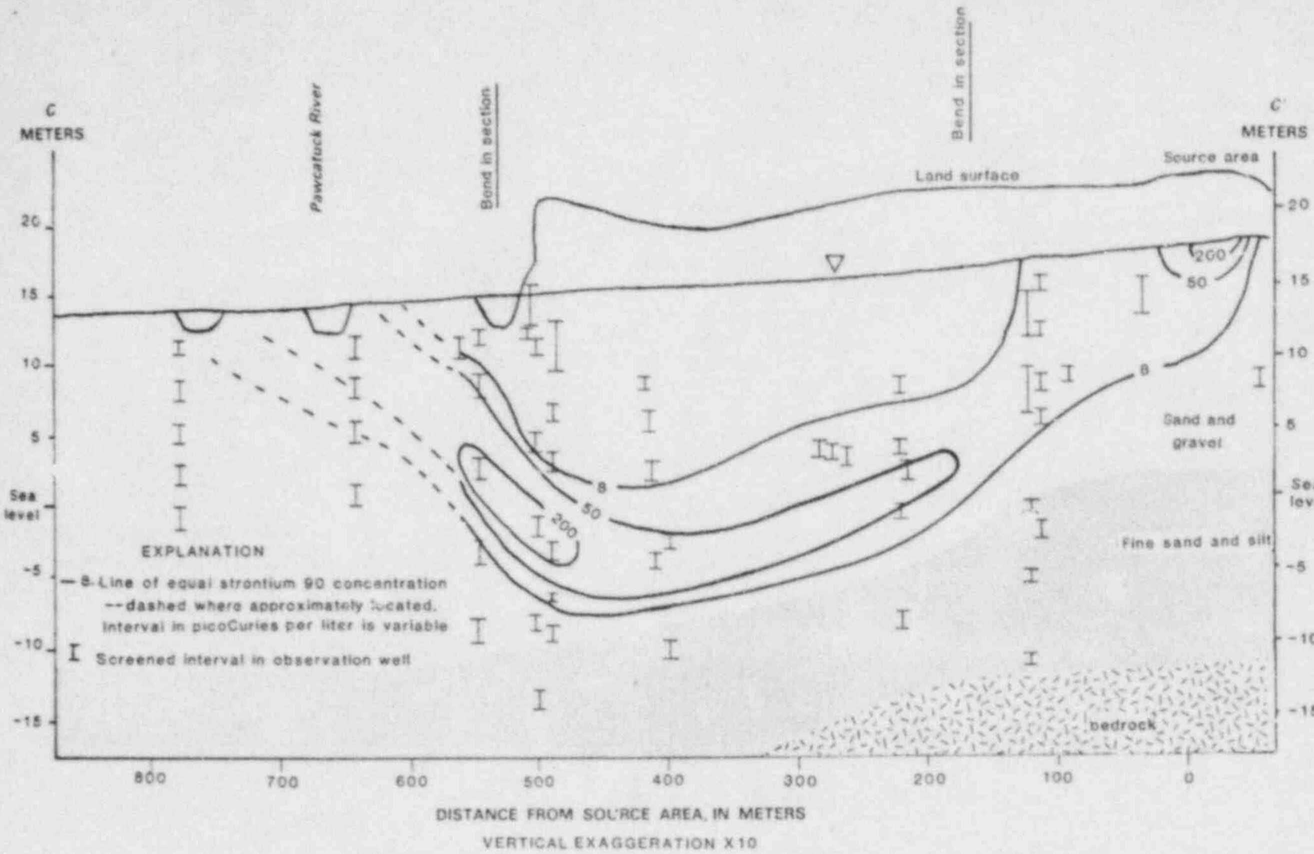

Figure 9. Strontium-90 concentration in ground water at the plant site, October 1982.

land. The resultant plume of contamination extends 2,300 ft from the source area (evaporation ponds and trenches) to the aquifer's discharge area (the Pawcatuck River and swampy area west of the river). Dilution, however, precludes detection of contaminants once they have entered the river. Chemical and radiochemical constituents in the plume include nitrate, boron, potassium, strontium-90, and technetium-99. Unconsolidated deposits comprising the aquifer contain few clay-sized particles, and contaminants do not appear to be interacting significantly with the sediments. In the swamp, reducing conditions may promote observable solute interaction with sediments or organic material.

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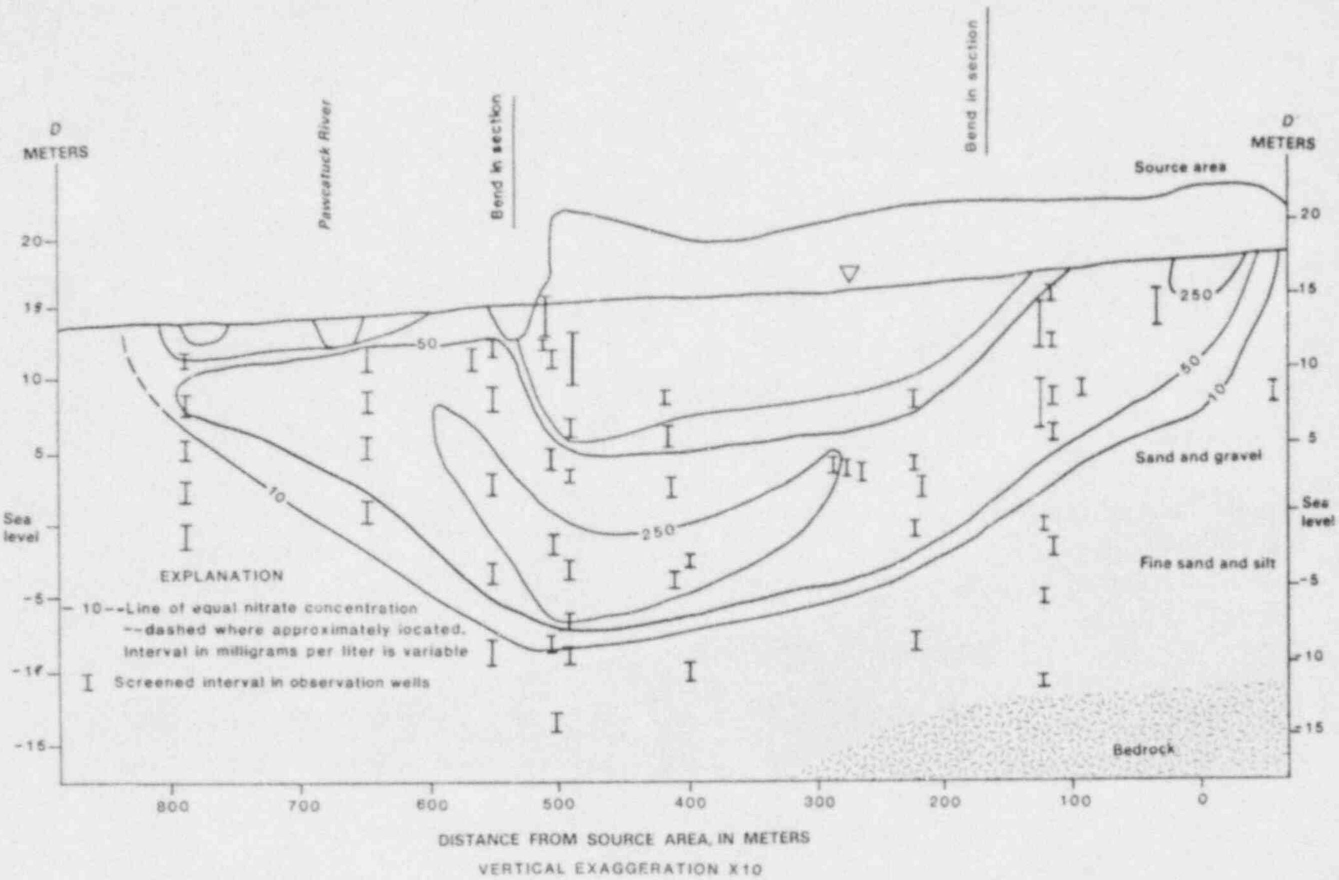

Figure 10. Nitrate concentration in ground water at the plant site, May 1983.

Table 1. Representative chemical analyses of water from observation wells near the middle of, the edge and outside the contaminant plume

[Results in milligrams per liter except as indicated]

Chemical constituent	Observation well in middle of plume, Feb. 17, 1982	Observation well on edge of plume, Feb. 3, 1982	Observation well outside of plume, Dec. 23, 1981
Alkalinity-$CaCO_3$	7	3	9
Boron (µg/L)	230	50	<10
Cadmium (µg/L)	1	2	<1
Calcium	720	50	4.1
Chloride	180	9.2	5.0
Copper (µg/L)	4	2	5
Fluoride	<.1	<.1	<.1
Hardness	1,900	130	16
Iron (µg/L)	250	20	310
Lead (µg/L)	5	6	1
Magnesium	23	1.5	1.4
Manganese (µg/L)	600	67	1,600
Nickel (µg/L)	14	1	2
Nitrate ($NO_2 + NO_3$)	580	37	.18
pH (units)	5.6	5.7	5.6
Phosphorus (ortho as P)	<.01	<.01	<.01
Potassium	21	3.4	2.5
Silica	<.1	11	6.9
Sodium	25	7.8	4.4
Specific conductance (µmho/cm at 25°C)	4,260	376	77
Strontium-90 (pC/L)	222	6.7	2.9
Sulfate	50	14	14
Water temperature (°C)	12.0	11.5	10.5
Zinc (µg/L)	50	11	16

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