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GROUND WATER MONITORING AND RECOVERY SYSTEM DESIGN IN A LOW-YIELD CRYSTALLINE ROCK AQUIFER IN SOUTHWESTERN SOUTH CAROLINA

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ABSTRACT

The monitoring and recovery of contaminated ground water a Resource Conservation and Recovery Act (RCRA) site in South Carolina was complicated by the hydrogeologic conditions existing in the site area. The area is characterized by a subsurface of Paleozoic Age biotite gneiss overlain by varying thicknesses of clay-rich residuum consisting of saprolite and clayey silt. The bedrock surface was found to undulate throughout the study area, forming troughs of weathered residual material that grade in composition with depth from iron-stained decomposed rock to hard, component biotite gneiss. Ground water in this setting was found to exist under unconfined conditions with the water table generally occurring within the overlying residuum. The saturated zone was found to extend into bedrock through sparse secondary openings (fractures and foliation planes). Well yields in the residuum were achievable up to 2.5 gallons per minute (gpm), whereas bedrock yields were less than 1.0 gpm due to the sparse secondary openings. The aquifer thickness extends to an undefined depth within the biotite gneiss. The base of the aquifer occurs at a depth at which secondary partings remain closed due to the surrounding pore pressure of the rock matrix.

The problems encountered during the study include: defining the hydraulic connection between the residuum and sparsely fractured biotite gneiss, effectively monitoring the two aquifer media for contamination, determining useful aquifer parameters from pumping tests, defining aquifer boundary conditions, and designing an effective recovery system for the low-yield aquifer. The techniques used to solve the encountered problems include: installing well nests to define water quality and potentiometric surface in the residuum and biotite gneiss, developing a flow net schematic to predict movement of contaminants, exploiting bedrock trough areas for effective ground water recovery, and performing long-term pumping tests to determine recovery potential and to define boundary conditions.

KEY WORDS: Low-yield aquifer, residuum, bedrock troughs, secondary partings, aquifer boundary conditions, well nests, pumping tests

INTRODUCTION

A hydrogeologic investigation of a former industrial impoundment area was conducted to define the extent of ground water contamination resulting from the facility and to satisfy RCRA compliance monitoring requirements. The investigation consisted of monitoring well installation, aquifer testing, and ground water sampling. The contaminants of concern consisted of industrial solvents (trichloroethene [TCE] and 1,1,1-trichloroethane [1,1,1-TCA]) and their derivatives as well as chromium and nickel.

A ground water extraction system was, in part, defined based on the information developed during the study. An existing well was found to capture approximately 40 percent of shallow ground water contamination occurring at

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the site. Additional wells are required to capture the remaining downgradient portion of the plume. Studies are currently in progress to define new recovery well locations to complete the extraction system.

Site Description

The area of concern occurs adjacent to an active industrial manufacturing facility. Past manufacturing processes incorporated metal finishing procedures such as grinding, polishing, cleaning, and chromium and nickel electroplating.

Process wastewaters from the manufacturing facility were retained in unlined surface impoundments. One impoundment was used for the equalization and settlement of chromium and nickel electroplating wastewater and another was used for the containment of polishing grit slurries, which were found to be laden with chlorinated solvent sludges and residues. Figure 1 is a base map of the site depicting the manufacturing facility and the former impoundment locations. The impoundments were utilized up until 1977 at which time the waste treatment area was reconfigured and the polishing grit impoundment was backfilled with soil and graded to conform to the surrounding land surface. These structures exhibited the greatest potential for a contaminant release to ground water.

Physiographic and Geologic Setting

The site occurs within the Piedmont Physiographic Province at the edge of a broad, flat plateau. The plateau is incised by several small tributaries that flow to a large nearby stream. Maximum relief within the site area does not exceed 75 feet. A small, incised, unnamed tributary occurs approximately 500 feet east of the source areas.

Regionally, the hydrogeologic setting of the site suggests that the former impoundments are located along the edge of a broad plateau that acts as a recharge area for the precipitation infiltrating the subsurface into the aquifer. The incised stream valley that occurs downgradient of the source areas acts as a discharge area for shallow unconfined ground water.

The subsurface in the site vicinity is characterized by high-grade Paleozoic metamorphic gneiss and schists. In the site area, biotite gneiss is present (Overstreet and Bell, 1965). The bedrock is typically overlain by a variable interval of regolith, generally less than 50 feet thick, composed of red-brown clayey silt and yellow-gold saprolite derived from the chemical weathering of the metamorphic parent material. The biotite gneiss is very hard, dense rock consisting primarily of plagioclase feldspar, quartz, and biotite mica. Secondary openings in the rock occur sparsely and are usually openings along foliation planes. Extensive regional joint systems appear lacking in the site area (Griffin, 1981). Bedrock outcrops in the site vicinity are very sparse and are limited to a few very weathered exposures within the incised valley of the unnamed tributary.

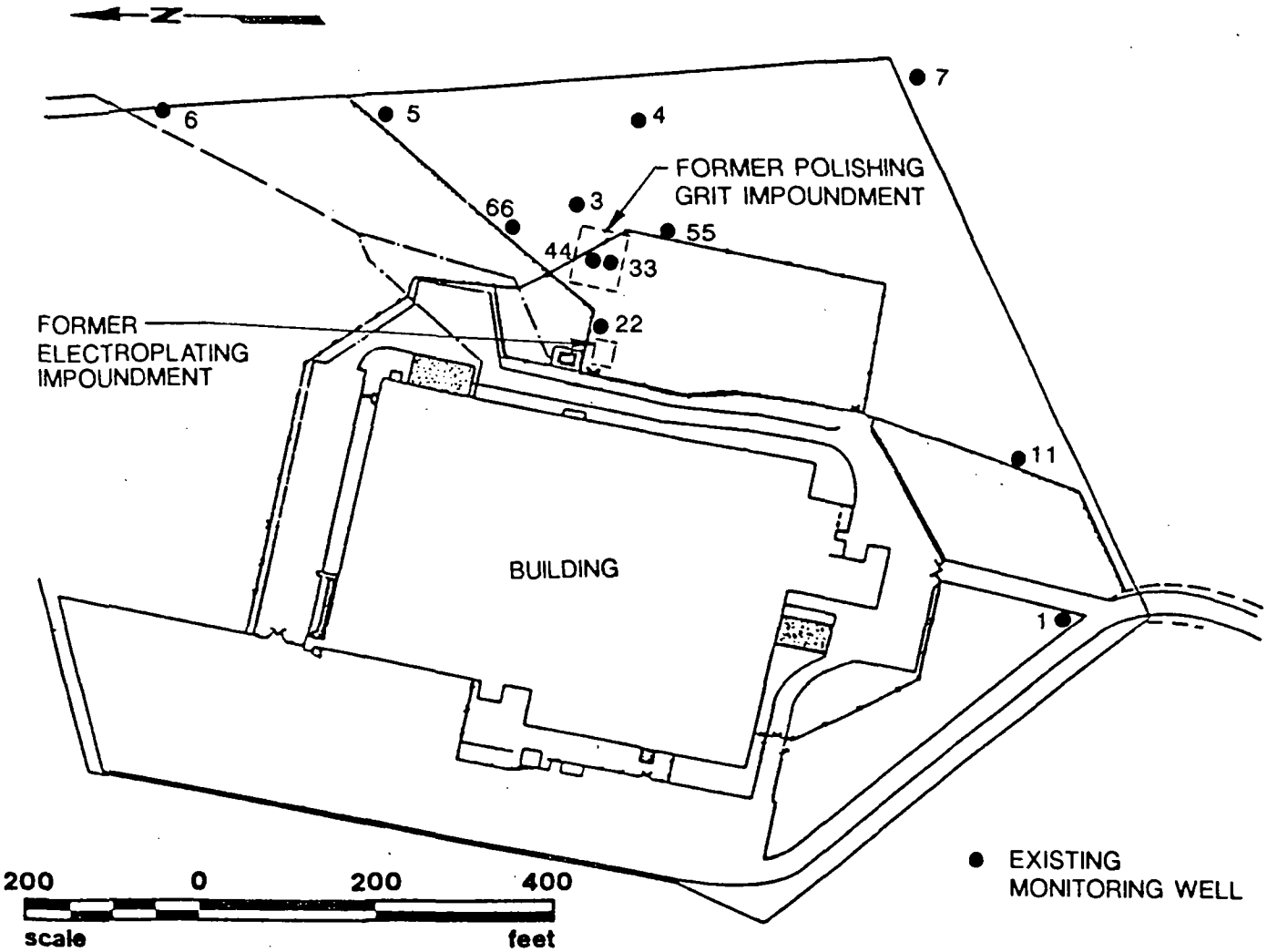

FIGURE 1

FACILITY LAYOUT SHOWING
EXISTING WELL LOCATIONS

Prior Investigations

Two ground water monitoring networks were installed at the site during prior studies. Well locations from these studies are shown in Figure 1. The majority of these wells were drilled to the top of bedrock and installed within the saturated saprolite zone. The thickness of saprolite was found to be highly variable, which caused well depths to range from 12 to 35 feet. The saturated thickness of the saprolite in these wells ranged from approximately 2 to over 20 feet, which created anisotropic flow conditions within the aquifer.

Two of the wells (MW-22 and MW-33) were drilled into the underlying competent biotite gneiss bedrock. Well 22 was cored (3-inch diameter) 10 feet into rock and a 15-foot well screen was subsequently installed into the borehole to monitor both the encountered bedrock and overlying saprolite. Well 33 was cored 20 feet into competent bedrock with a 5-foot well screen set at the base of the boring.

Water level measurements taken on both monitoring well networks indicated an eastward ground water flow direction towards the unnamed tributary. Water levels taken on existing bedrock wells suggested that the saprolite and shallow bedrock were hydraulically interconnected. The construction method (installing 2-inch screen-and-riser inside a 3-inch diameter corehole) of the bedrock wells, however, may not clearly reflect actual hydrogeologic conditions.

Ground water sampling of the two well networks indicated elevated chromium, nickel, TOC, and TOX concentrations downgradient of the impoundment areas. Because of encroaching source remediation activities, Wells MW-22, MW-33, MW-44, and MW-55 were abandoned in October 1987. Additionally, the initial well network (Wells MW-1 through MW-7) was deemed inadequate for sampling by regulatory authorities due to the construction methods utilized.

Subsurface sampling in the polishing grit impoundment encountered solvent-laden sludges and residues that contained significant levels of TCE, tetrachloroethene, vinyl chloride, 1,1,1-TCA, trans-1,2-dichloroethene, 1,1-dichloroethene, and 1,1-dichloroethane. The base of the impoundment was found to be approximately 7 feet above the water table.

Based on the above conditions, additional well installation and more focused ground water sampling were required to further define the extent of ground water contamination. Also, it was not definitely clear whether the saprolite zone comprised a perched water table contained by the relatively impermeable underlying bedrock or whether the saprolite and gneiss were in hydraulic connection and comprise one aquifer.

MONITORING WELL NETWORK DESIGN AND INSTALLATION

Three major considerations were taken into account when developing a site-specific ground water monitoring plan:

- Define the hydraulic relationship between saprolite and bedrock

- Determine appropriate screen placement within the anisotropic aquifer
- Define contaminant distribution and anticipated movement of contaminants within the aquifer.

These factors required definition prior to developing an effective remediation strategy for ground water contamination.

The techniques utilized to generate the required data included: exploratory drilling and rock coring; cluster well installation consisting of a well installed in saprolite and one set into the biotite gneiss; pressure testing of penetrated bedrock; and the development of a flow net schematic from water level data.

The eventual complete ground water monitoring well network installed at the site monitored both the impoundment area and an adjacent closed hazardous waste management area and consisted of four cluster well locations, eight shallow wells, two deep wells, and four piezometers in addition to the existing wells from the prior study. The resultant ground water contour map for the new and existing wells was found to corroborate prior studies, as illustrated by Figure 2.

The following sections describe the resolution of each of the major considerations identified above.

Defining the Hydraulic Relationship Between Saprolite and Bedrock

Standard exploratory drilling procedures (e.g., split-spoon sampling, rock coring) were utilized to define site conditions. The saprolite was found to be a heterogenous mix of clay, silt, and occasional quartz sand that contained a phreatic water surface. Saturated thickness varied from 2 to over 15 feet thick. Rock coring did not reveal any significant fracture zones within bedrock, only minor foliation partings. No water-producing zones were observed during coring.

Air hammer drilling was attempted to ream the corehole and advance other deep wells under a dry drilling process. No observable water-bearing zone was again encountered; however, slight water seepage into the boreholes was observed after drilling. Comparison of eventual static head levels of the air hammer borings set into rock and adjacent shallow wells set into saprolite suggested that the two media were interconnected. Static levels revealed a higher head (from 0.1 to 0.75 foot) at each downgradient deep location when compared to its shallow counterpart. This finding was consistent with the premise that the downgradient area was situated in a discharge zone, where deeper portions of the aquifer would have a higher head level.

Pressure testing, using a double-pneumatic packer system, subsequently verified the hydraulic connection between bedrock and saprolite. The testing indicated sparse water-bearing zones in bedrock, which indicated a stabilized head consistent with the overlying saprolite.

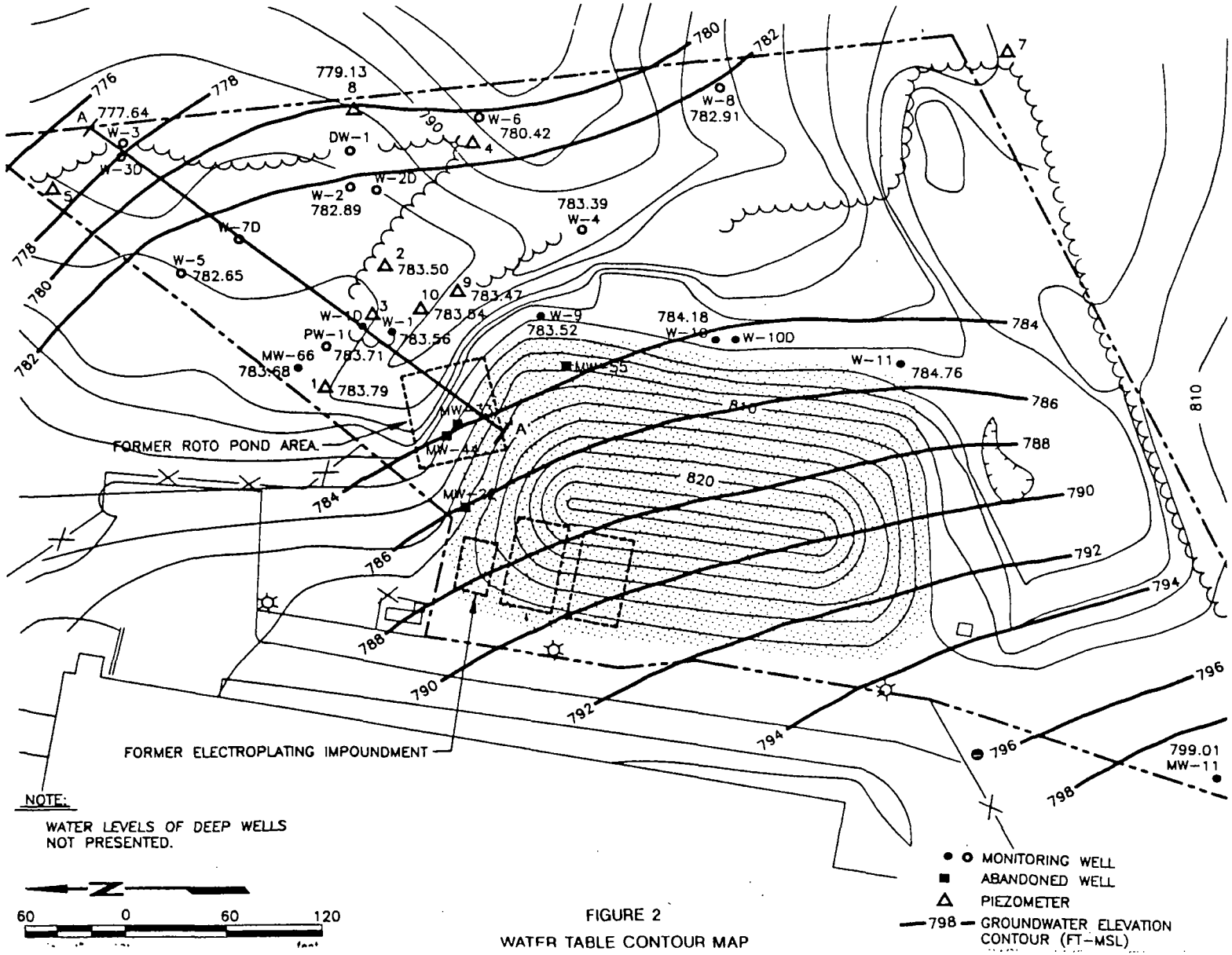

FIGURE 2

WATER TABLE CONTOUR MAP

Determining Appropriate Screen Placement

To determine representative water quality, appropriately screened monitoring wells were necessary. The heterogeneity of the aquifer complicated screen placement. Specifically, the variability of saturated saprolite caused by the undulating bedrock surface created the greatest complexity. Figure 3 is a cross section through the site area depicting the undulating surface of bedrock.

Ground water flow through the saprolite occurs through void spaces occurring within the material due to its noncompacted nature as well as because of any relic secondary features (joints, foliation, planes, fractures) remaining from the parent material. Ground water flow within the biotite gneiss occurred exclusively because of the sparse secondary openings within the rock matrix. Accordingly, aquifer transmissivity and storage were found to be both greater in the saprolite than in the encountered bedrock. The permeability difference of the two materials was thought to be a potential influence on contaminant distribution within the aquifer.

Where saturated saprolite was thin, a 5-foot screen was emplaced at or near the top of bedrock. Where thicker saturated deposits were encountered, a larger screen was employed and centrally located within the unit. Bedrock wells were installed with a more consistent approach with respect to elevation. Generally, bedrock monitoring wells were screened or opened between 745 to 765 feet above sea level (Figure 3), with some minor exceptions to allow for water-bearing intervals and, in one case, because no ground water was encountered within the saprolite. Screening of the bedrock wells to a more-consistent interval enabled construction of a flow net schematic for the aquifer.

Defining Contaminant Distribution and Anticipated Movements of Contaminants

Sampling of the monitoring wells for the appropriate parameters (volatile organic compounds [VOCs], selected metals) defined contaminant distribution throughout the aquifer in both the horizontal and vertical directions. Relating the sampling data to the source areas and constructing a flow net schematic (from available head level data) of the area of concern provided insight into the contaminant flow path and anticipated future movements.

The chromium and nickel contamination was found to correspond to aquifer flow lines (Figure 4) indicating the dissolved nature of these elements. Initially, these compounds were found near the shallow portion of the aquifer in the impoundment source vicinity. In this area, aquifer recharging conditions were found to occur, which created downward movement within the aquifer as the plume moved downgradient from the source area. This is particularly evident at the W-1 cluster area where the deeper bedrock well revealed a greater concentration of these parameters than the shallow well. This area occurs very near the projected vertical equipotential line indicating the transition between aquifer recharge and discharge conditions. Downgradient of the W-1 location, a marked upward gradient is evident within the aquifer due to discharge conditions that causes the metals contamination to occur within the shallow location at the W-2 cluster with no elevated levels within the deeper

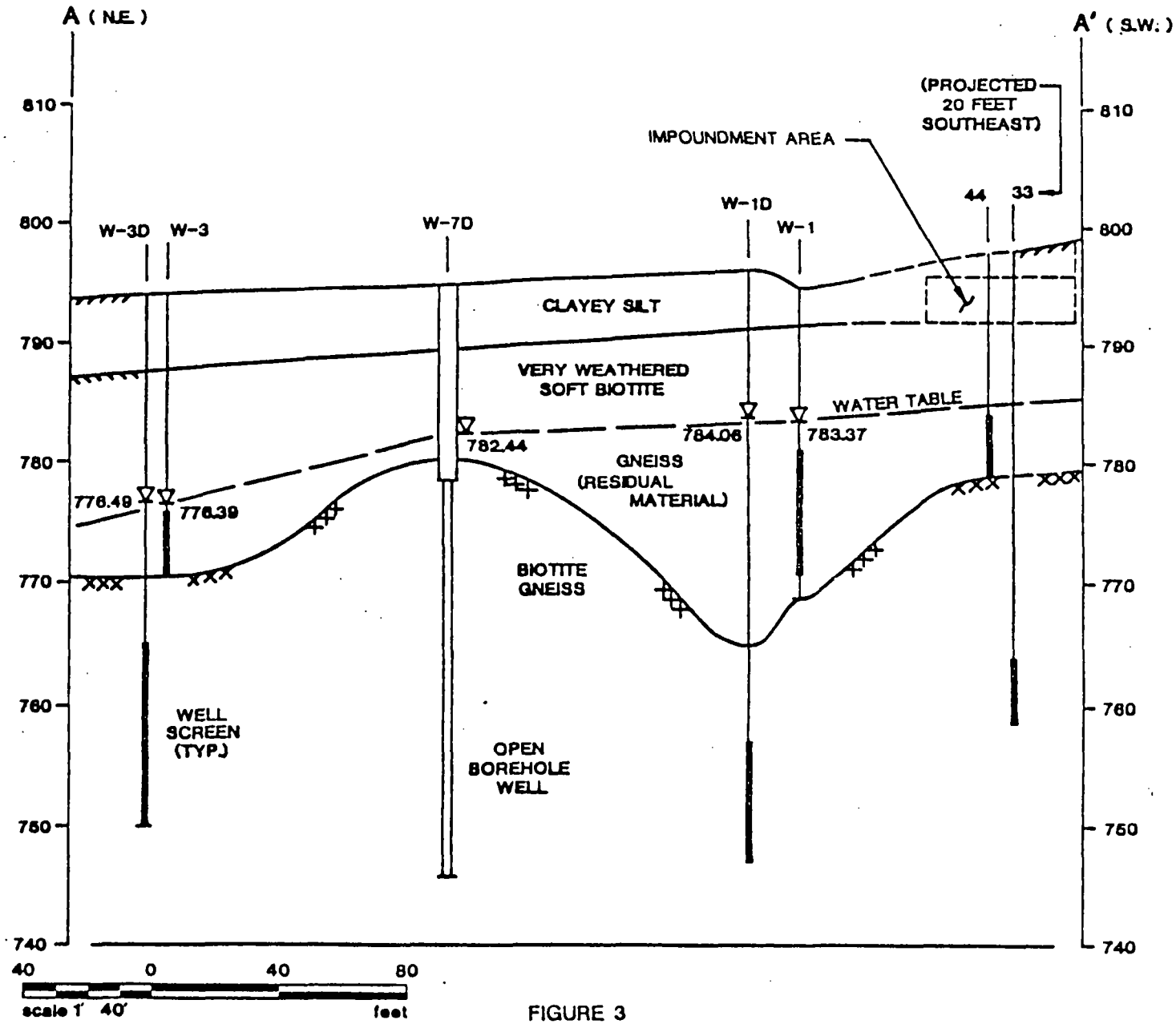

FIGURE 3

CROSS-SECTION A-A'

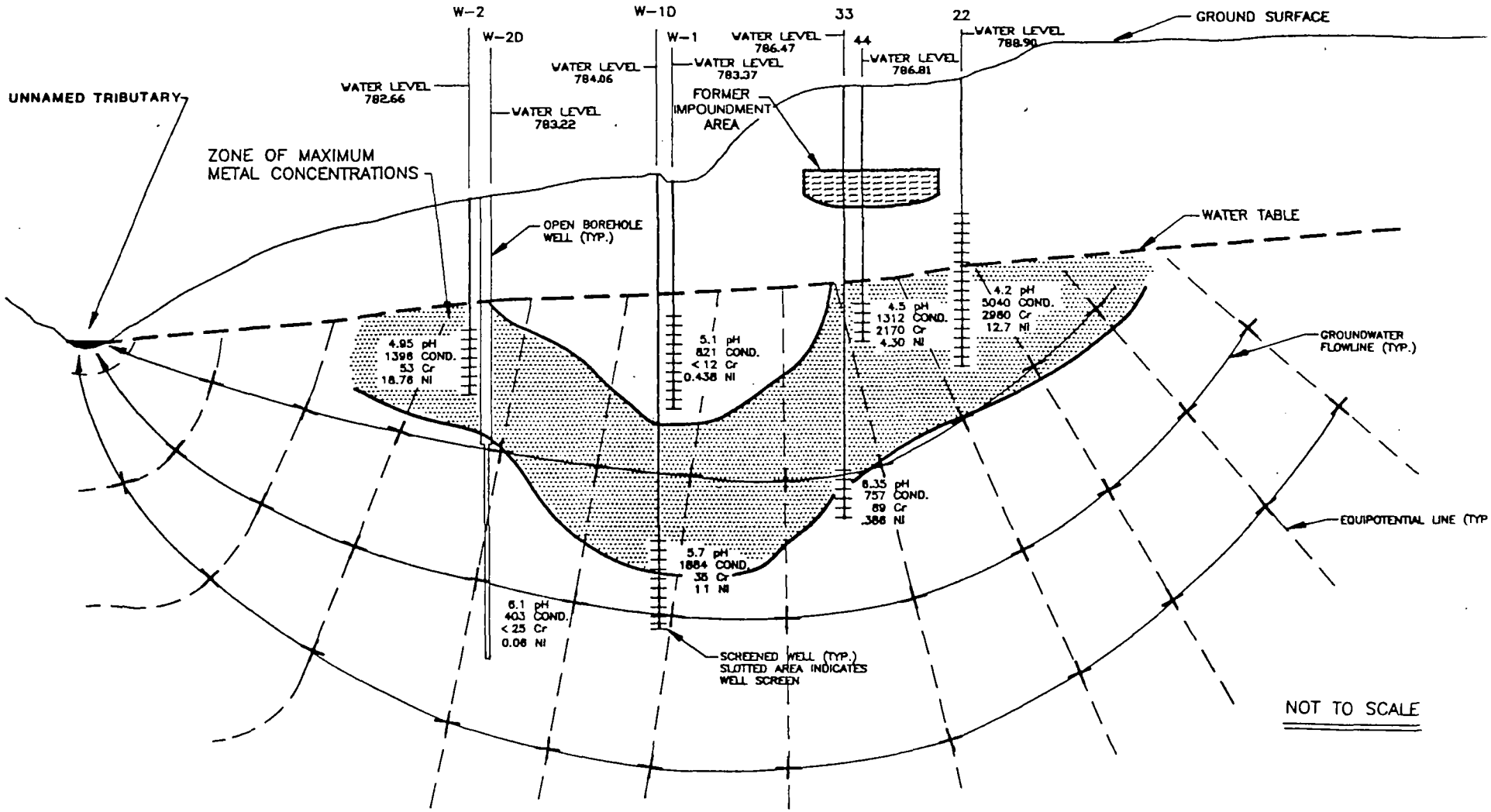

FIGURE 4
CHROMIUM AND NICKEL CONCENTRATION
FLOW SCHEMATIC

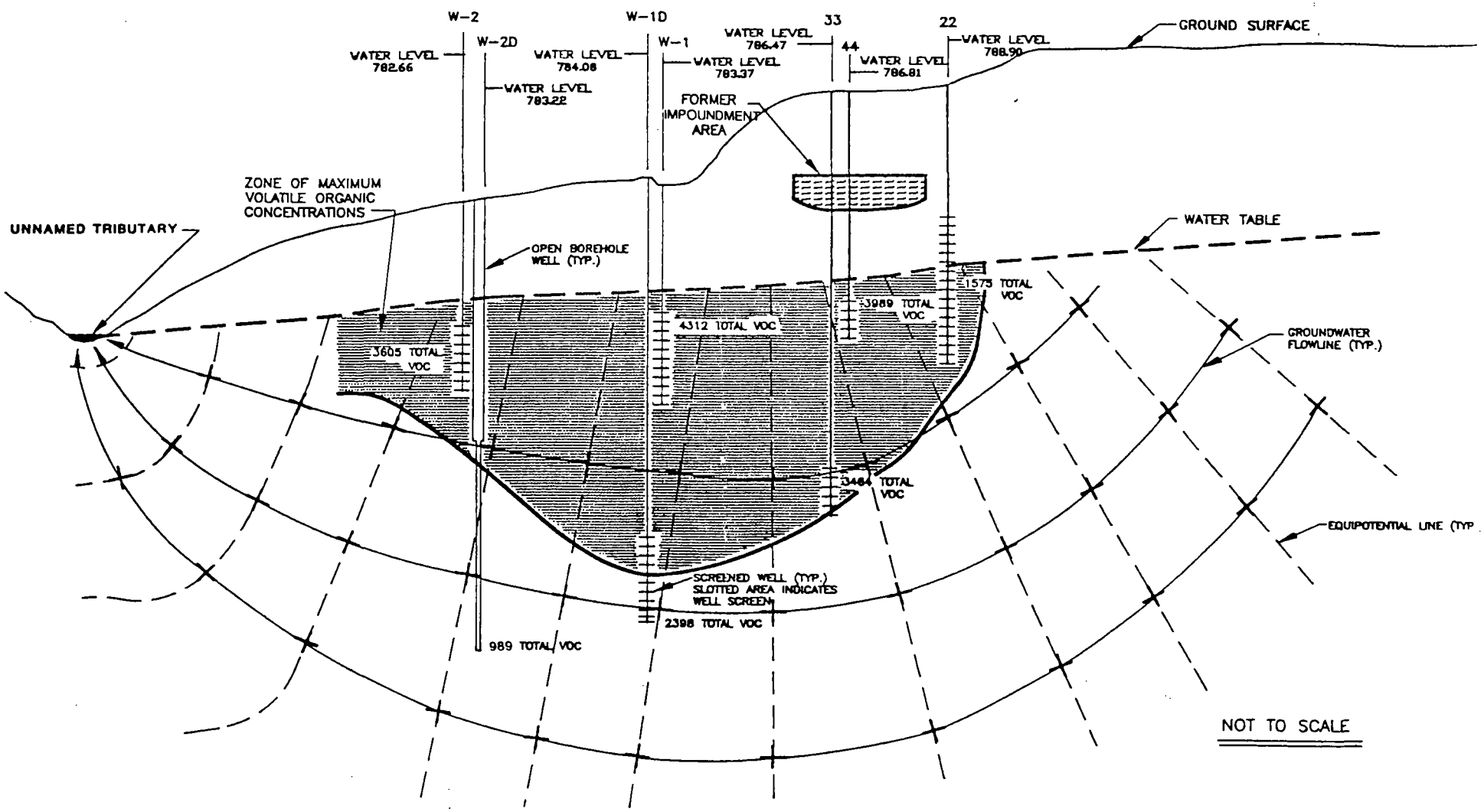

FIGURE 5
VOLATILE ORGANIC CONCENTRATION
FLOW SCHEMATIC

well. It is evident from this condition that downgradient movement of metals contamination (towards the unnamed tributary) will stay within the shallow portion of the aquifer due to the upward vertical gradient.

The resultant volatile organic plume identified was shown to be influenced by the vertical gradient but not completely controlled by it. The VOC levels were found to be about evenly distributed within the shallow and deeper portions of the aquifer near the source area indicating a quick vertical movement in the recharge area (downward gradient) of the aquifer. As the plume progressed downgradient, the VOCs levels were found to be higher in the shallow portions of the aquifer than in the deeper zones; however, relatively significant concentrations of denser chlorinated solvents (TCE) were still found in the downgradient deep wells. Accordingly, the less dense VOCs were consistently found within the shallow portions of the aquifer at greater concentrations regardless of the hydrogeologic setting.

Based on these data, it appears that much of the VOC contamination would be present within the shallow portion of the aquifer as it moved downgradient but a relatively significant portion of the denser VOCs remained within the deep portion of the aquifer. A deeper monitoring well (DW-1) was subsequently installed in the W-2 vicinity and indicated VOC (TCE) contamination but at a level approximately four times less than W-2D. These data suggest that the vertical gradient is retarding downward movement of the denser solvents.

RECOVERY SYSTEM DESIGN

The major consideration in developing a ground water remediation plan for the identified plume area were:

- Determining extraction feasibility
- Defining accurate aquifer parameters
- Identifying capture zone geometry.

The heterogeneous nature of the aquifer complicated defining these considerations.

The techniques utilized to obtain the required necessary data included: conducting long- and short-term pumping tests; installing numerous observation wells (piezometers) in multiple directions to identify aquifer response to pumping; and development of aquifer parameters using various aquifer analysis methods. The following sections describe the resolution of each of the above considerations.

Determining Extraction Feasibility

Because of the heterogeneity of the aquifer, it was not certain if the contaminant plume could be successfully extracted by pumping wells. Slug test data indicated a hydraulic conductivity ranging between approximately 3×10^{-4} to 5×10^{-3} centimeters per second (cm/sec) for saprolite and 1×10^{-4} to 6×10^{-5} cm/sec for bedrock. The areas of thin saturated residuum did not have a high enough transmissivity to sustain pumping. Bedrock was so sparsely fractured that none of the wells could yield in excess of 1/2 gpm.

Based on these initial data, it was decided to attempt a pumping test in the area of the thickest saturated residuum where the potential for effective extraction appeared greatest. The well chosen for the pumping test was Well W-1, which is contained within a trough containing 16 feet of saturated residuum (Figure 3). After preliminary initial testing, a rate of 2.4 gpm was attempted. The well was subsequently pumped for 22 hours. Limited drawdown was observed in nearby observation wells. The maximum drawdown for an observation well was 0.23 foot at Well PW-1, which is located 38 feet from the pumping well. The pumping test results indicate that bedrock troughs containing greater than 15 feet of saturated saprolite are feasible for ground water extraction. Encountered competent bedrock intervals and areas of thin saturated saprolite were not capable of sustaining minimum extraction rates.

Determining Representative Aquifer Parameters

Estimates of transmissivity and storage from the initial pumping test ranged from 3,900 to 8,300 gallons per day per foot (gpd/ft) and 0.015 to 0.038, respectively. Figure 6 is a semi-log plot (Cooper and Jacob, 1946) of distance versus drawdown for Observation Well MW-66. The transmissivity value estimated was higher than anticipated and may not accurately reflect aquifer conditions under long-term extraction because of anticipated boundary and possible undefined drainage delay effects. Additionally, the limited amount of drawdown encountered during the initial test did not define a zone of influence for a pumping well within this area.

To determine representative aquifer parameters that would reflect aquifer performance during sustained withdrawal, a 30-day extraction test was performed. The long-term test was pumped at an average rate of 2.5 gpm for its duration. This test identified significant negative boundary effects occurring within the site area that did not show up during the shorter test. Most observation wells detected the boundary between 1,300 and 2,700 minutes after the start of pumping. Figure 7 is a semi-log plot of Observation Well MW-66 that exhibits the boundary effects. These effects are believed to be the result of the irregular, undulating contact between the sparsely fractured, less-permeable bedrock and the overlying residuum in the vicinity of Well W-1.

Drainage delay effects were not observed in observation wells during the test of the unconfined aquifer. The observed boundary conditions may have masked any drainage effect caused by dewatering of the residuum. Figure 8 is a log-log plot (Theis, 1935) of time versus drawdown for Observation Well MW-66 depicting the boundary effects.

The results of the 30-day test revealed more representative transmissivity and storage values than the initial testing. The time-drawdown data for the observation wells installed in residuum (saprolite) indicate a transmissivity ranging from 2,000 to 2,400 gpd/ft prior to boundary effects. The coefficient of storage ranged between 0.012 to 0.023. The bedrock wells revealed higher transmissivity values ranging from 2,900 to 3,600 gpd/ft with the coefficient of storage ranging from 0.013 to 0.0036. The higher transmissivity values for the bedrock wells appear to be exaggerated, possibly due to a poor hydraulic connection between the water-bearing fractures encountered in the well and the adjacent saprolite.

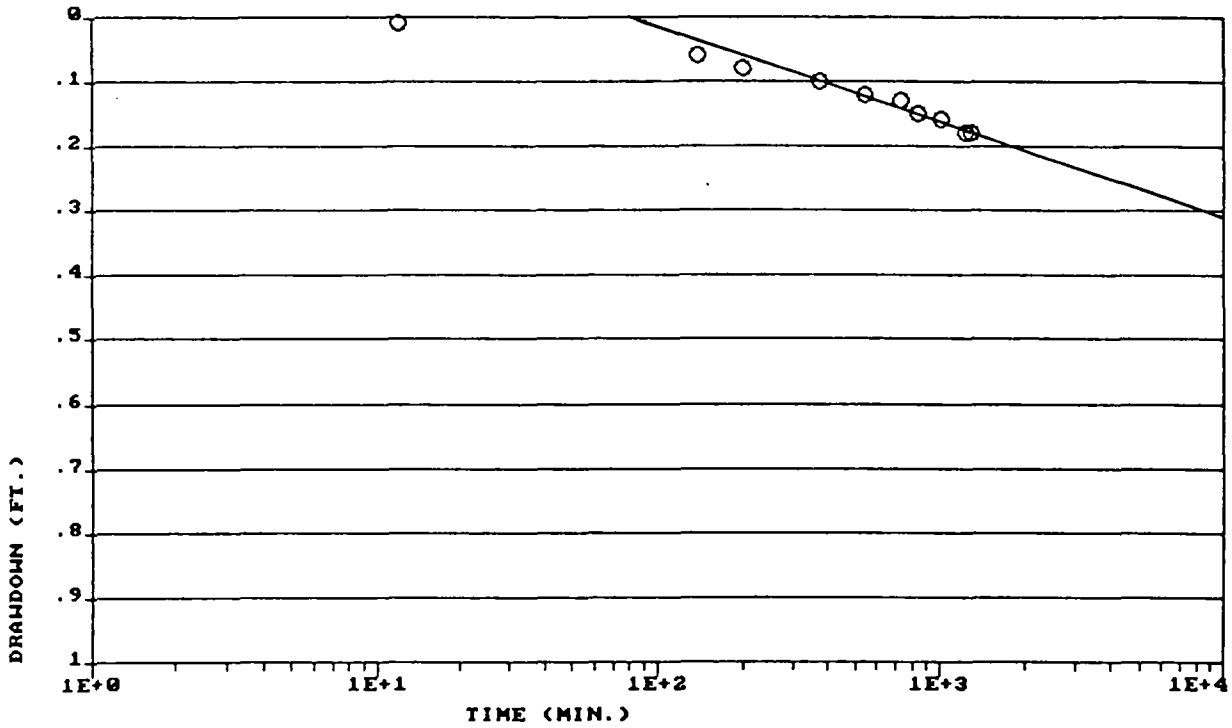

FIGURE 6

MW-66 TIME DRAWDOWN PLOT-22 HR TEST

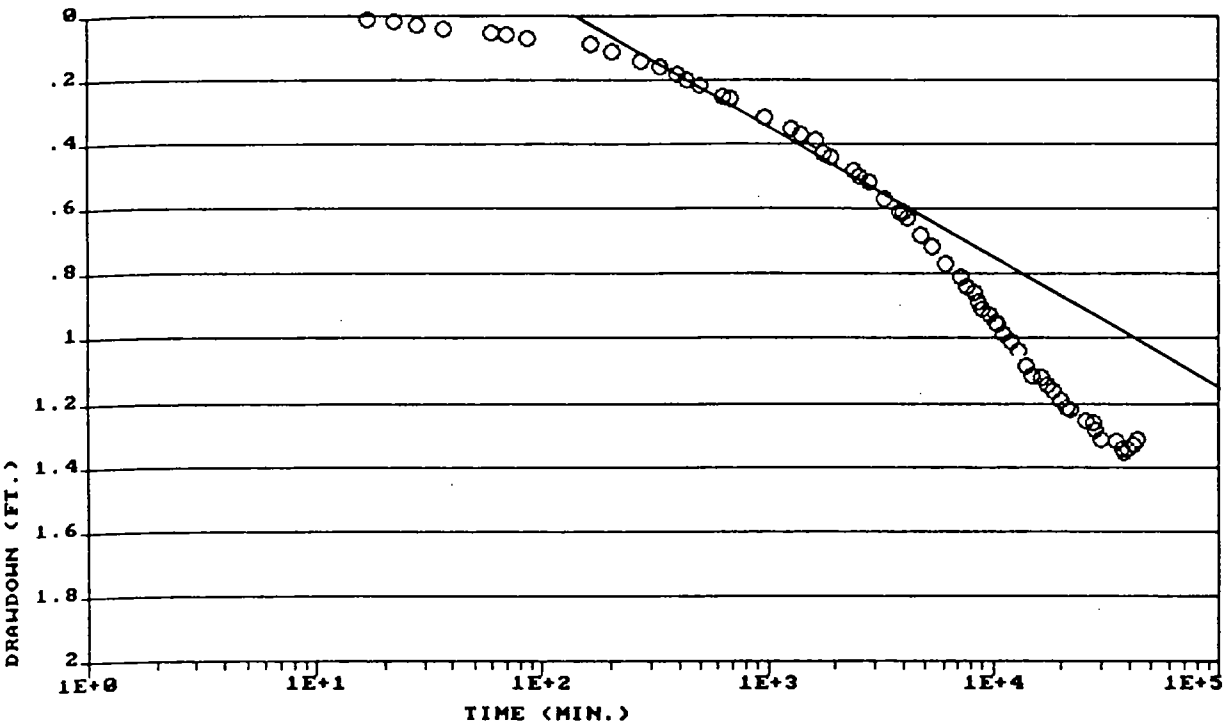

FIGURE 7

MW-66 TIME DRAWDOWN PLOT-30 DAY TEST

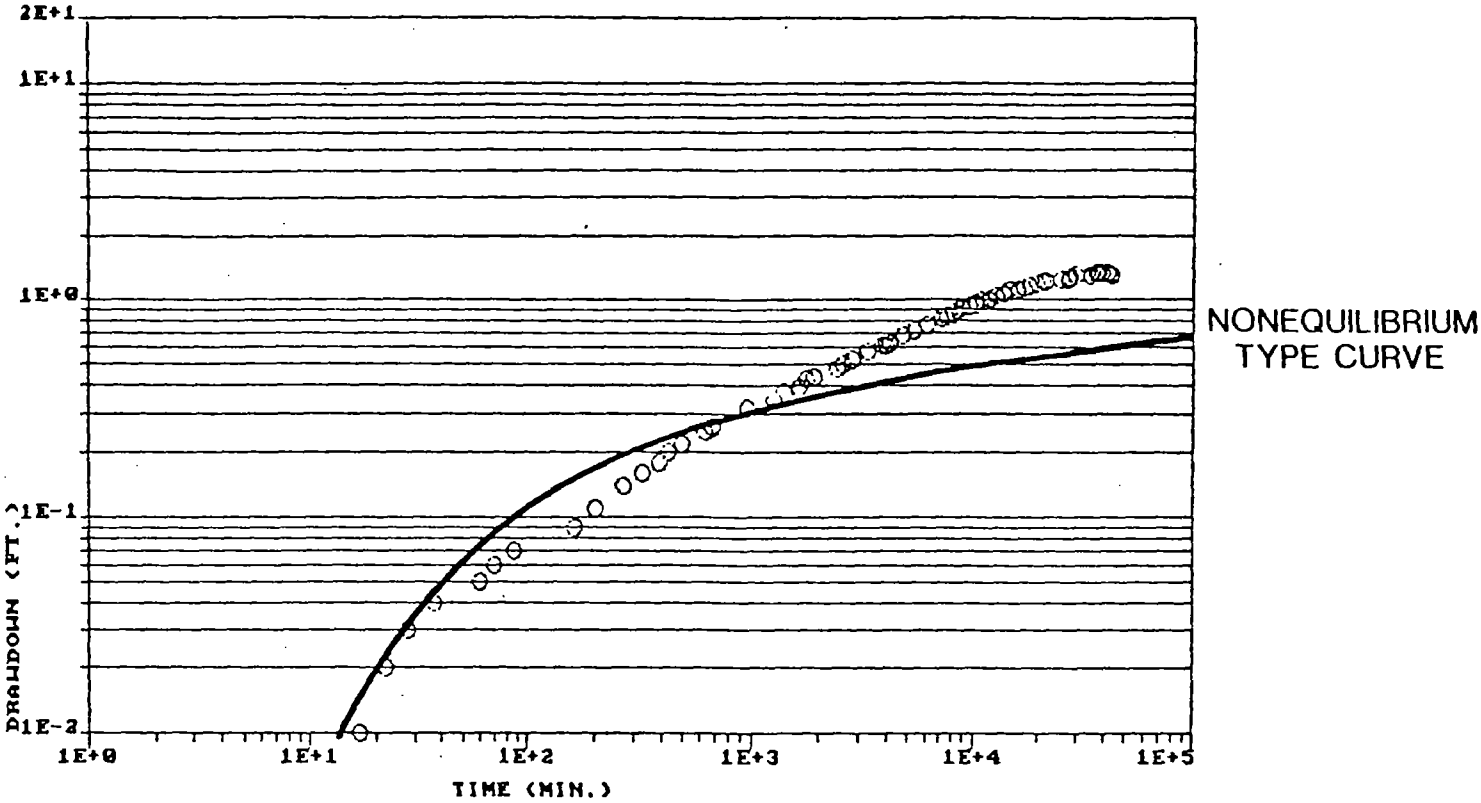

FIGURE 8

MW-66 LOG-LOG TIME DRAWDOWN PLOT-30 DAY TEST

After boundary effects, the time-drawdown plots indicate a consistent transmissivity ranging between 900 to 1,100 gpd/ft for all wells except one bedrock well, which indicated a value of 1,600 gpd/ft. Storage values for the observation wells ranged from 0.027 to 0.057 during this period.

Distance-drawdown analysis (Cooper and Jacob, 1946) was calculated for wells trending southeast and east of the pumping well. Figure 9 is a plot of the southeast alignment for 1, 3, and 25 days into the test. These data show the gradual and continued decreasing aquifer transmissivity as the test progressed.

The distance-drawdown graphs (Cooper and Jacob, 1946) trending southeast from the pumping well indicates a continuing decrease in transmissivity from 3,670 gpd/ft 1 day into the test to a value of 1,269 gpd/ft 25 days into the test. Storage values ranged from 0.015 to 0.03. East of the pumping well, the distance drawdown analysis revealed the transmissivity decreased from 2,205 gpd/ft 1 day into the test to 1,090 gpd/ft 25 days into the test. Storage values ranged from 0.023 to 0.049 during this period.

The long-term test provided representative values of aquifer parameters under extended pumping conditions. The distance drawdown plots and calculations indicated that the aquifer continued to decline in transmissivity as the test progressed. This was not readily apparent from time-drawdown semi-log plots of observation wells. The data generated by the distance drawdown analysis depicts aquifer conditions over a relatively large area as opposed to a single observation point. These data enable a more accurate prediction of aquifer response within an anisotropic aquifer.

Identifying Capture Zone Geometry

The capture zone of Well W-1 was easily defined due to the rate of the long-term test and the close proximity of observation points that provided water level elevation data during extraction. The zone indicates an elongated area in the north-south direction (parallel to ground water flow) being recovered by the well as shown in Figure 10. This area is projected to extend to 155 feet south of the well and at least 90 feet north of the well. This north-south elongation will enable Well W-1 to capture essentially all upgradient shallow contaminated ground water remaining to the west of W-1. To the east, the capture zone is projected to extend approximately 65 feet from W-1. The zone is limited in its extent in this direction because of the natural flow gradient occurring across the site.

The developed capture zone of Well W-1 is estimated to be able to collect approximately 40 percent of the contaminated ground water on site. The contributing area will include all contaminated shallow water in the source areas, all contaminated water lateral to and approximately 65 feet downgradient of the extraction point.

SUMMARY AND CONCLUSIONS

Based on this study of contaminant delineation and extraction within the low-yielding anisotropic Piedmont aquifer, the following conclusions can be made:

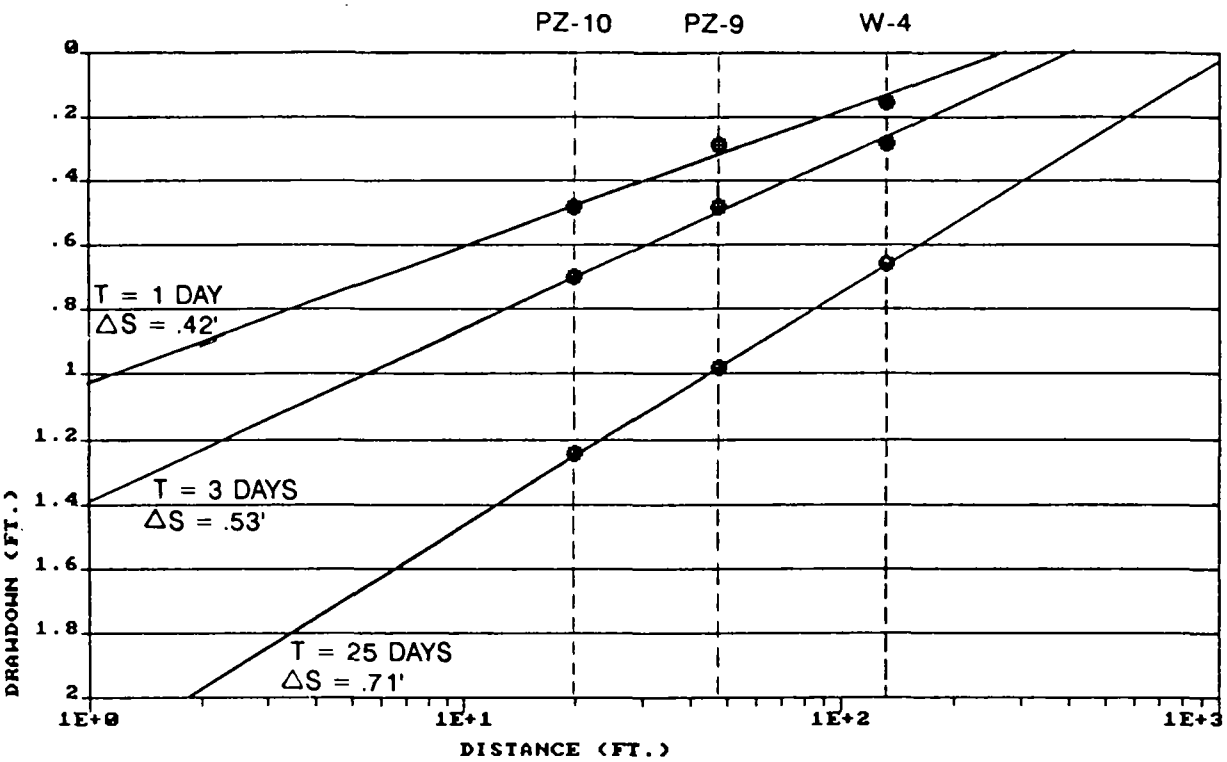

FIGURE 9

DISTANCE DRAWDOWN PLOT FOR WELLS
W-4, PZ-9, PZ-10 30 DAY TEST

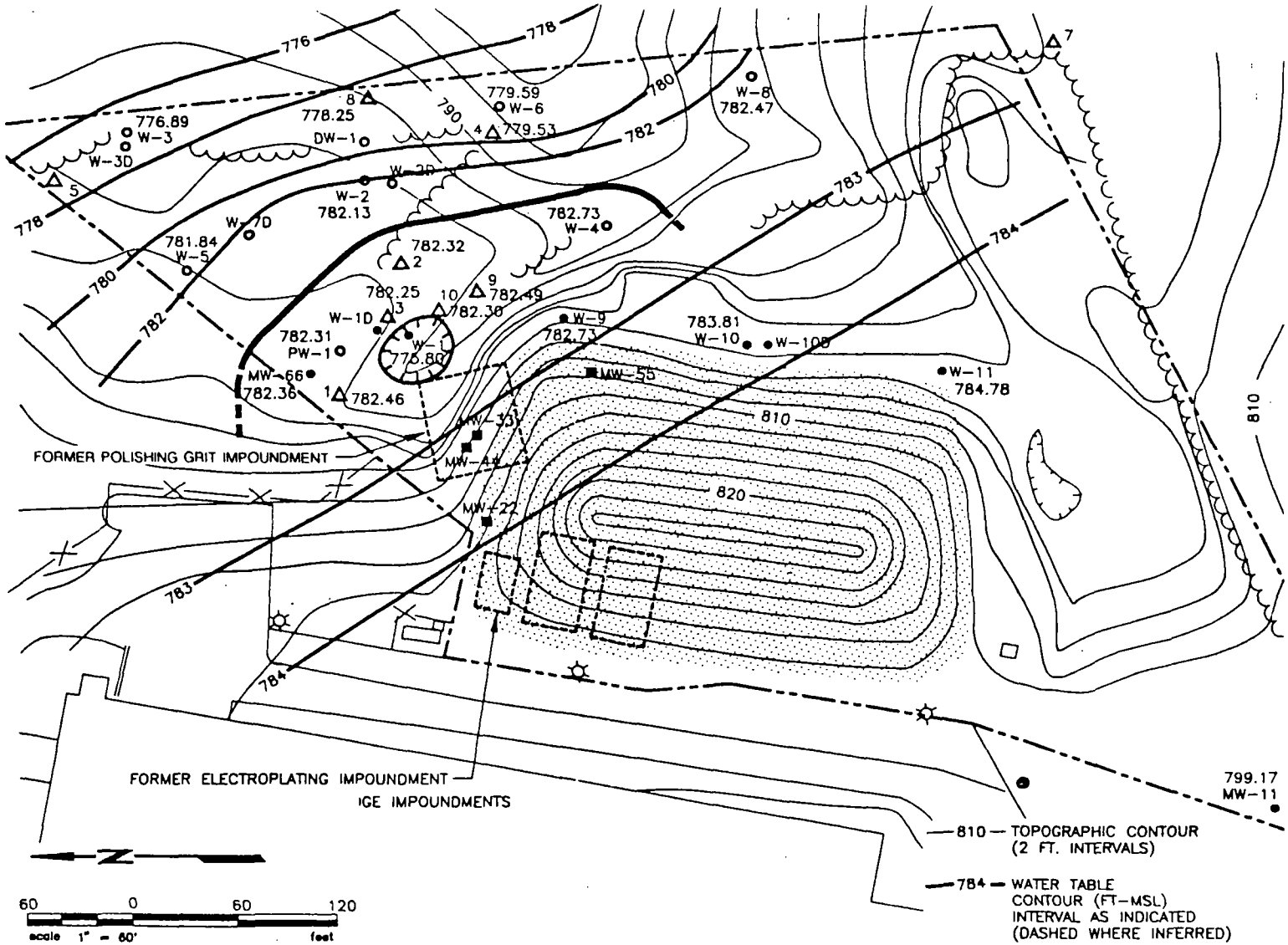

FIGURE 10
CAPTURE ZONE DELINEATION
DAY 25 OF PUMPING

- Defining the hydrogeologic relationship between saprolite and bedrock is necessary so that a monitoring network can be properly installed to define horizontal and vertical contaminant extent.

- Monitoring ground water from within the saprolite exclusively may not be adequate to define contaminant distribution that is caused by vertical gradient and contaminant density factors.

- Properly installed well nests (cluster wells) are effective in defining the number of encountered water-bearing zones, vertical flow gradient, and contaminant distribution trends.

- In the absence of significant fracture systems in bedrock, ground water extraction is most-effectively conducted utilizing bedrock troughs where thick accumulations of saprolite and/or semi-consolidated rock occur.

- Extended term pumping tests (1-week minimum) are highly recommended to develop the site-specific aquifer parameters that define boundary conditions.

- Distance-drawdown analysis data appear to provide the most reliable aquifer parameters in nonhomogeneous aquifer conditions.

- A large network of observation wells enables simple delineation of a capture zone area around an extraction well.

To complete the recovery system, seismic refraction and electromagnetic conductivity geophysical studies were conducted between W-1 and the unnamed tributary to define additional areas of thick saprolite (bedrock troughs) that will be suitable for additional extraction points to collect downgradient and deeper contamination. These studies indicated several potential bedrock trough areas on the property east of the facility, approximately 300 to 400 feet downgradient from W-1.

Subsequent drilling and well installation in these areas revealed three areas of troughs of saprolite and/or weathered semi-consolidated gneiss that contain up to over 40 feet of saturated residuum. Preliminary aquifer testing indicate that each of these areas should be capable of yielding 2 to 4 gpm. Additional testing will be conducted using the techniques described earlier to define accurate aquifer parameters and capture zone delineation in these areas.

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