CHARACTERIZATION OF AQUIFER HETEROGENEITY IN A COMPLEX FLUVIAL HYDROGEOLOGIC SYSTEM TO EVALUATE MIGRATION IN GROUND WATER: FIELD AND MODELING STUDIES

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ABSTRACT

The hydrogeology and extent of ground water contamination were characterized at a federal Superfund site located in Northern California. Wood preserving compounds, primarily pentachlorophenol (PCP) and creosote have been detected in the soil and ground water. A plume of dissolved PCP up to approximately 1.5 miles long has been identified in ground water south of the plant.

The aquifer consists of a complex multizonal system of permeable gravels and sands composed of units from four geologic formations deposited by the ancestral Feather River. Fluvial channel gravels form the principal aquifer zones and contain overbank clay and silt deposits which locally form clay lenses or more continuous aquitards. Two incised paleochannels of the Laguna Formation are inset into the older Mehtren Formation near the site, complicating the aquifer stratigraphy. The geometric mean horizontal hydraulic conductivities for channel gravels range between 120 to 530 feet/day. Mean vertical aquitard hydraulic conductivity is 0.07 feet/day. Ground water flow is generally southward with a velocity ranging from 470 to 1,000 feet/year.

The spatial distribution of dissolved pentachlorophenol in the aquifer documents the interactions between major permeable zones. Hydrostratigraphic evidence pointing to the separation of aquifer zones is supported by the major ion chemistry of ground water. The sodium and calcium-magnesium bicarbonate-rich water present in the upper aquifer zones is significantly different in chemical composition from the predominantly sodium chloride-rich water present in the deeper permeable zone. This indicates that hydrodynamic separation exists between the upper and lower zones of the aquifer, limiting the vertical movement of the PCP plume. A numerical ground water model, based on this conceptual hydrogeologic model was developed to evaluate ground water model, based on this conceptual hydrogeologic model was developed to evaluate ground water transport pathways and for use int he design of ground water extraction and treatment system.

INTRODUCTION

During a recent environmental investigation involving a heterogeneous sand and gravel aquifer, a detailed ground water flow and solute transport model was developed to describe the movement of a dissolved chemical plume in ground water. The site is located along the eastern margin of the Sacramento Valley, in the floodplain of the Feather River which is bounded by Plio-Pleistocene fluvial terraces rising 50 to 120 feet above the valley floor (Figure 1). Here, soil and ground water contamination in the vicinity of a wood treatment plant have contributed to the migration of dissolved chemical constituents into ground water offsite. The primary chemicals of concern are wood preservatives such as pentachlorophenol (PCP) and polynuclear aromatic hydrocarbon (PAH) compounds. Due to the complexity of the local aquifer system, early hydrogeologic investigations produced conflicting interpretations of the uniformity of ground water flow and the magnitude of pentachlorophenol plume migration near the site.

The fluvial aquifer system was found to be composed of apparently discontinuous channel deposits and overbank clays, which in combination, resulted in a complex aquifer system. It became clear during the investigation that the complex nature of the heterogeneous system made the identification of ground water flow pathways and the description of contaminant plume distribution difficult. Further, in order to develop a ground water flow and solute transport model, the interrelationships between aquifer high and low permeability units and transport parameters had to be quantified. In such an aquifer system involving large scale heterogeneity, it was essential that the ground water hydrodynamics be well defined, so that ground water pathways, velocities and ground water mixing could be described. Unless the hydrodynamics were well described in the conceptual and numerical models, the other transport processes and associated parameters could not be reliably obtained.

The hydrogeologic study summarized here investigated the nature of the heterogeneous aquifer system, estimated the influence of heterogeneity on ground water flow in the vicinity of the wood treatment plant, and evaluated the distribution and transport of PCP throughout the aquifer system. Detailed information was collected to characterize the physical properties of the aquifer and the extent of contamination in ground water (Dames & Moore, 1988a and b). Subsurface information obtained included geologic logs from 32 newly-constructed monitoring wells and exploration test holes. In addition, ground water quality data were obtained from water samples collected from over 100 wells and test holes (see Figure 1). The resulting description of the aquifer system and its behavior served as the basis for development of a three dimensional ground water flow and solute transport model of the site (Dames & Moore, 1988a). The transport model wa used to simulate the spatial distribution of the dissolved PCP plume in ground water and to predict the rate and extent of movement of PCP in ground water under "no-action" conditions, for use in risk evaluation and in the feasibility study. In addition, the model was used for preliminary evaluation of possible ground water recovery and treatment alternatives (Dames & Moore, 1989).

The purpose of this paper is to present a case study in which a heterogeneous fluvial sand and gravel aquifer system has been characterized in some detail. This study helps demonstrate the importance of an adequate understanding of aquifer hydrostratography and hydrodynamics in the investigation of solute transport. Specific objectives of the study include: (1) description of the nature, distribution and hydrogeologic interrelationships of the principal hydrostratographic units that make up the large scale heterogeneity of the aquifer; (2) characterization of the hydraulic properties of the principal permeable units of the aquifer; and (3) development of a three-dimensional numerical model to describe ground water flow and solute transport.

HYDROGEOLOGY

Aquifer Units

The principal stratigraphic units in the Oroville area include the Eocene age Ione Formation, the Oligocene-Pliocene age Mehrten Formation, the upper Pliocene Nomlaki Tuff, and the upper Pliocene - Holocene Laguna Formation (Blair and Baker, 1990). Locally, the aquifer system near the plant can be generalized into four major hydrostratigraphic zones: A, B, C and D (Dames & Moore, 1988a). The characteristics and stratigraphic relationships of these zones are summarized in Table 1 and in a series of simplified stratigraphic cross-sections (Figures 2 and 3) the locations of which are shown in Figure 1. The A zone is a permeable gravelly unit of the Laguna Formation (Table 1) found south of the plant site. It is not present in the vicinity of the plant due to the presence of a marked stratigraphic transition that occurs at the margin of the present Feather River floodplain. In most areas south of the plant, the A zone is underlain by the Nomlaki Tuff (unit AB in Table 1), which acts as a major aquitard to confine the B zone. In general, the shallow gravels of zone A are relatively unimportant for assessing contaminant migration from the site because they occur only sparingly and are water bearing only in the southern portion of the study area where sources of contamination are not known to occur. The highly permeable gravelly units of the B and C hydrostratigraphic zones comprise the uppermost aquifer of interest to this study. Depending on location, B and C zone gravels and sands can belong to either the Laguna, Mehrten or Ione Formations which are interwoven in a relatively complex and highly variable stratigraphic environment (Figures 2 and 3). The B and C zones are separated in many areas by interbedded clay units which locally form the BC aquitard. The upper aquifer forms the major potential pathway for transport of dissolved chemicals offsite, and elevated concentrations of PCP occur in ground water samples collected from both the B and C zones.

Two paleochannels of Laguna age have been identified in the study area (Blair and Baker, 1990). One channel is located in the area occupied by the current Feather River floodplain, (Section B''-B''', Figure 2) and the other occurs in the area south of the plant site. In addition, older Mehrten channel gravels have been identified south of the plant. The Laguna paleochannels cut through permeable units of the Mehrten, juxtaposing Laguna channel gravels against gravels of the Mehrten Formation.

A generalized hydrostratigraphic interpretation of the site is presented in cross-sections B-B'-B''-B''' and E-E' (Figures 2 and 3). Figure 2 illustrates the complex stratigraphic relationships that exist between the principally channel-fill deposits of the Laguna Formation onsite and the older Ione, Mehrten and Nomlaki units (where they occur) south of the site. The cut-and-fill morphology typical of channel deposits can be seen quite clearly in the B''-B''' transect (Figure 2), where Laguna gravels wedge out sharply to the south between test hole F (TH-F) and ground water monitoring well MW-22, decreasing in thickness from approximately 270 feet at TH-F to only 30 feet at MW-22.

In general, ground water flowing south from the plant moves through Laguna gravels in hydrostratigraphic zones B and C and enters the permeable units of adjacent formations (Figure 2). Ground water in zone B moves from relatively less permeable Laguna gravels found onsite into somewhat more permeable Mehrten gravels; ground water in Laguna gravels found onsite in hydrostratigraphic zone C flows into the permeable units of the Ione Formation in the vicinity of MW-22 and into Mehrten gravels and less permeable Ione sandstone units to the east. As shown in section B''-B''' (Figure 2), the BC aquitard is formed by low permeability interbeds of the Laguna and Ione Formations juxtaposed against each other along the side wall of the paleochannel. This juxtaposition of sediments provides hydraulic continuity between permeable units across the channel boundary but it also prevents the mixing of B and C zone ground water. The permeable gravels of hydrostratigraphic zone B comprise the principal aquifer along which dissolved pentachlorophenol was able to migrate.

A different perspective on the hydrostratigraphy of the site can be seen in cross-section E-E' (Figure 3) which traverses the plant site from west to east. The BC clay thins and pinches out to the east allowing direct communication between B and C gravels in the vicinity of the wood processing area. During the drilling of monitoring well ML-2 shown on the west side of the cross section, a thick sequence of Mehrten gravels and sands was encountered juxtaposed against channel-fill deposits of the Laguna Formation. The Nomlaki and Mehrten Formations were both encountered at shallow depths in well LF-2 indicating that gravels of the Mehrten Formation are in direct hydraulic contact with gravels of the Laguna Formation at this location. Mehrten gravels also define the eastern margin of the incised Laguna paleochannel seen near this well.

Hydraulic Properties

The hydraulic properties of the B and C aquifer zones were measured in eighteen aquifer pumping tests (Dames & Moore, 1988a). The hydrostratigraphic units in which aquifer tests were conducted are clayey sands and gravels that contain a significant fine particle fraction. The silt, clay and fine sand fractions of these geologic materials appear to reduce the effective permeability of the observed formations, perhaps reducing aquifer permeability to the lower end of the range of hydraulic conductivities expected in fluvial sand and gravel deposits. Based on the pumping test results, the B and C hydrostratigraphic zones appear to be semiconfined. The aquitards that act to confine the permeable zones are leaky, and results from the pumping tests have been used to estimate the vertical permeability of these aquitards. Because of leaky aquitard conditions, most pumping test analysis methods used are those that can be applied to tests in semi-confined aquifers. These methods include the Hantush inflection point method (Hantush, 1956), the Walton method (1962), and the Jacob straight-line method under specific conditions (Cooper and Jacob, 1946).

Aquifer test results are summarized in Figure 4 where they are grouped according to the hydrostratigraphic unit in which the test wells were completed. Observed log-transformed hydraulic conductivity values are plotted on the normal probability graph presented in Figure 4a, which shows that the populations representing hydraulic conductivity data from all tests K(all) and data from three individual groups of tests, [K(Mehrten), K(Laguna south), and K(Laguna plant)] all plot in a nearly linear fashion. The close-to-linear fit indicates that the observed hydraulic conductivity distribution is approximately log-normal. It should be noted that the three sub-datasets plotted in Figure 4a, representing three distinguishable hydrogeologic units, appear to form overlapping subdistributions which, when superimposed, form a nearly log-normal combined distribution (black dots). Because the three subdistributions partially overlap, there does not appear to be a clear distinction between the hydraulic conductivity range of one hydrostratigraphic unit versus that of another.

Based on the pumping test data, transmissivity (T) estimates for Laguna channel gravels on the plant site range from 100 to 18,000 ft^2/day, with a geometric mean value of 3,100 ft^2/day. The geometric mean hydraulic conductivity value (Kg) measured in the Laguna Formation onsite is 150 ft/day, ranging between 10 and 670 ft/day. Storativity (S) for Laguna gravels on the plant site average 0.0025 as a whole, but estimates cover a broad range from 0.011 to 0.00002.

The geometric mean transmissivity based on three aquifer pumping tests performed in Laguna Formation channel gravels south of the plant site is 26,800 ft^2/day. The corresponding geometric mean hydraulic conductivity for Laguna gravels in this area is 530 ft/day ranging from 210 ft/day to 850 ft/day. No estimates of storativity could be made from observation wells completed in Laguna gravels south of the plant site.

The results of aquifer pumping tests performed in wells that are completed in permeable units within the Mehrten Formation yield a geometric mean transmissivity of 10,000 ft^2/day and a geometric mean hydraulic conductivity of 220 ft/day. Storativities measured in the Mehrten Formation average 0.00017. The average storativity in the Mehrten is lower than that observed in the nearby Laguna Formation, confirming the influence of the Nomlaki confining unit on the Mehrten gravels.

As mentioned previously, comparison of hydraulic conductivity estimates obtained for the Laguna and Mehrten Formations suggests that, in general, the three aquifer pumping test groups yield a similar range of values (Figure 4a). The similarity in hydraulic conductivity between formations is important because it indicates that hydrostratigraphic units which are juxtaposed against each other along the sides of paleochannels are in hydraulic communication. This implies that a given permeable zone can act as a continuous hydraulic unit and conduct ground water flow even though there may be some local differences in the sedimentary composition of the zone.

The aquifer pumping test data also provide useful information about the hydraulic properties of aquitards that confine the principal aquifer zones. In this case, leakance (L) and hydraulic conductivity (K') values were calculated for selected aquitards using the Walton method (Walton, 1962). Test results from the Laguna BC aquitard located on the plant site, the uppermost Laguna aquitard located south of the plant site, and the Nomlaki aquitard are shown in Figure 4b. Leakance estimates plotted in the log probability graph approximate a straight line, suggesting that the data are log-normally distributed. In general, K' values estimated for the three aquitards are relatively similar: 0.10 ft/day (3.5 x 10^{-5} cm/sec) for the Laguna BC aquitard on the plant site, 0.13 ft/day (4.6 x 10^{-5} cm/sec) for the uppermost Laguna aquitard south of the plant site, and 0.04 ft/day (1.4 x 10^{-5} cm/sec) for the Nomlaki Tuff. The overall mean K' is 0.07 ft/day (2.4 x 10^{-5} cm/sec) which is approximately three orders-of-magnitude lower than the hydraulic conductivity (K) of the permeable gravel units.

Ground Water Conditions

Ground water in the study area flows generally southward through the permeable gravels of the B and C aquifer zones. Hydraulic gradients throughout the area are relatively uniform except in the immediate vicinity of the wood treatment plant (Figure 5). Within aquifer zone B, the hydraulic gradient ranges from 0.0013 to 0.0028 and ground water velocity ranges from 1.3 ft/day to 2.8 ft/day southward. Gradient and velocity estimates are based on a mean hydraulic conductivity of 300 ft/day estimated south of the plant, and an effective porosity of 0.3. These parameters appear to vary little based on a measurement period of 2.5 years. From the above data, the estimated rate of ground water movement in the southern portion of the study area ranges from 470 ft/year to 1000 ft/year southward.

Vertical hydraulic gradients have been evaluated at eleven locations in the vicinity of the plant, in areas where well clusters provide water level measurements in more than one aquifer zone. In general, hydraulic gradients within the B aquifer are downward west of the plant site, possibly in response to recharge from irrigation ditches and ponds. Vertical gradients in the aquifer B zone on site are generally upward, with occasional fluctuations in magnitude and direction probably caused by the strong influence of local pumping wells. Although observed vertical gradients may help to explain the distribution of pentachlorophenol in ground water in some areas, in general, transport across aquitards does not appear to be an important factor in PCP movement in to offsite areas.

Pentachlorophenol Distribution In Ground Water

During the RI/FS program conducted at the wood treatment site, ground water quality conditions were monitored in 39 onsite and 105 offsite monitoring wells. As a result, the concentrations of a broad spectrum of chemical constituents of ground water, including PCP and PAH compounds, were determined providing a thorough description of the overall water chemistry of aquifer zones A, B, C, and D.

Analysis of water quality data collected during the RI/FS program indicates that aquifer zone B is the major pathway for movement of the PCP plume in ground water. Zone C gravels appear to contain dissolved PCP to a lesser extent, primarily near the plant site. The spatial distribution of pentachlorophenol detected in onsite and offsite monitoring wells screened in aquifer zone B is shown in Figure 6. The outermost PCP concentration isopleth shown in the figure represents a concentration of 30 μg/L which is the California Drinking Water State Action Level for PCP in ground water. The direction of PCP movement is generally to the south in a well-defined plume that appears to exhibit little transverse dispersion. This is consistent with the advection-dominated transport conditions observed in the study area.

GROUND WATER FLOW AND SOLUTE TRANSPORT MODELING

The site investigation provided sufficient information for the formulation of a detailed conceptual model of the heterogenous aquifer system. This conceptual model served as the basis for development of a three-dimensional numerical model of the aquifer system in which a large measure of the aquifer heterogeneity could be retained. The key elements of the conceptual model included the spatial location of permeable aquifer zones, spatial distribution of aquitards, hydraulic properties of the geologic materials, ground water elevation data, hydraulic inputs and outputs to the system (such as well use, irrigation, rainfall, and stream losses), aquifer boundary conditions, and contaminant source information. The above elements were subsequently integrated into the three dimensional numerical ground water flow and solute transport model that was developed to describe the aquifer system (Dames & Moore, 1988a). The numerical code selected for model simulations was TARGET-3DS, a three-dimensional, saturated, density-coupled, transient ground water flow and solute transport model developed by Dames & Moore (Dames & Moore, 1985). This model employs an integrated finite-difference solution technique which utilizes a hybrid differencing formulation of the advection-dispersion equation. All model runs were performed on a Compaq 80386 microcomputer.

The primary purpose of the modeling analysis was to develop a numerical model that realistically represented past and present ground water flow and contaminant transport for the heterogeneous aquifer system. The transport model was used to simulate the spatial distribution of PCP contamination and to predict the rate and extent of movement of PCP and other compounds in ground water under "no-action" conditions, for use in risk evaluation and for preliminary evaluation of possible ground water recovery and treatment alternatives (Dames & Moore, 1989). Specific objectives included:

- Calibration and evaluation of the sensitivity of the simulated hydrogeologic system to variations in key hydraulic and transport parameters;

- Prediction of the current and future extent of ground water contamination for use in evaluation of remedial alternatives; and

- Evaluation of the effectiveness of ground water remediation alternatives.

A brief summary of the modeling analysis and simulated results for hydrodynamics and PCP transport are briefly discussed below.

The model grid was oriented over the study area (Figure 7a) and aligned with the predominant ground water flow direction. The western boundary of the grid was set along the Feather River while the other boundaries were positioned to include data from ground water monitoring wells located furthest from the site. The dimensions of the grid were approximately 2.8 miles in the i-direction (east-west or x-axis) and 3.8 miles in the j-direction (north-south or y-axis). The bottom of the model grid was defined at a depth where a substantially thick clay unit of the Ione Formation provided a convenient natural boundary (no flow boundary) for the bottom of the grid, thus creating a vertical grid dimension of 260 feet. A minimum grid spacing equal to 200 feet in the i and j directions and 20 feet in the vertical (k-direction) grid was selected. This resulted in a grid with dimensions of 33 by 56 by 15 feet in the i, j, and k dimensions. Based on modeling requirements and on numerical constraints, a time step of one year was selected for all model runs.

During the course of the site investigation, ground water monitoring data indicated that ground water levels vary uniformly across the modeled area and horizontal hydraulic gradients do not appear to vary seasonally across the domain. The Feather River, located in the northwest portion of the grid, was modeled as a constant fixed-head boundary since variations in river stage do not influence water levels in the area of interest. Other ground water flow boundaries were also treated as fixed head boundaries based on observed field data.

Ground water withdrawals due to well pumping were accounted for through use of annual average pumping rates obtained from public records and documents. Recharge from rainfall, irrigation, rivers, streams and impoundments were allocated as annual averages and distributed spatially based on land use and natural processes.

The naturally-occurring aquifer units were classified into six hydraulic material types that were used to define the hydrostratigraphy of the model domain (Dames & Moore, 1988a). They are: (1) highly permeable gravels (Laguna and Mehrten Formation gravels off-site, represented by hydrostratigraphic units B and C); (2) medium permeability gravels (Laguna gravels located in zones B and C); (3) dredge tailings; (4) Ione sandstone (zone C); (5) low permeability Nomlaki Tuff (the AB aquitard); and (6) low permeability clays of Laguna and Mehrten channel deposits off-site. Based on the results of aquifer and physical tests, the hydraulic properties of the low permeability clays were found to be similar, justifying their representation as a single material type in the model. The hydraulic conductivities of all six material types were assumed to be isotropic in the horizontal plane.

For each of the six materials described above, the numerical model required input data to define horizontal and vertical hydraulic conductivity, storativity, porosity, and longitudinal and transverse dispersivity. The values used in the model were initially derived from field and laboratory measurements (Dames & Moore, 1988b) and from the literature. Estimates of a few of these properties were later modified during calibration to optimize the model fit to observed hydraulic gradients and solute transport rates.

Retardation parameters and degradation rates for the solutes of interest in ground water were estimated from studies reported in the literature. Only values thought to be applicable to conditions at the wood treatment site were selected for input into the model. Criteria used to evaluate the applicability of literature data included site stratigraphy, nature of geologic materials, chemical composition of ground water, total organic carbon content of the aquifer and other aquifer properties. The transport parameters selected for pentachlorophenol as a result of model calibration were: retardation factor R = 1.11 and degradation half-life $t_{1/2}$ = 12 years. The degradation half-life based on observed field conditions was more than an order of magnitude greater than the values reported from laboratory studies. The laboratory defined values from the literature were not used because they were thought to be unrepresentative of actual field conditions.

Significant areas of ground water contamination identified on the plant site were represented in the model by grid cells in which solute-laden infiltration water was introduced into the uppermost saturated cell of the aquifer. The areas of ground water contamination represented by the model were approximately proportional to the total estimated area of the sources of contamination observed in the field. The rate and duration of releases of contaminants from each source area during the predictive runs were estimated from observed concentrations, infiltration rates, and chemical solubility data (Dames & Moore, 1988b).

The numerical flow and solute transport model was initially calibrated for hydrodynamics to match water level and flow conditions and then for solute transport based on the spatial distribution of the PCP plume. The best match between simulated results and observed data was obtained when PCP was introduced into ground water twenty-five years into the past (in

1963). Simulations of the pentachlorophenol plume after the 25 year calibration period (Figure 7a) compared favorably with the observed present-day pentachlorophenol plume (presented in Figure 7b at the same scale). In addition, the vertical distribution of PCP in the heterogeneous aquifer was quite representative of the distribution observed in the field.

CONCLUSIONS

The results of the hydrogeologic investigation demonstrate that ground water movement through the aquifer system is governed to a great extent by large-scale heterogeneities. Ground water flow and the resulting dissolved chemical plume movement is primarily through the highly permeable channel-gravel deposits. Overbank clays and the Nomlaki Tuff act, in general, as barriers to water movement on a large scale. This appears to also be true for solute movement, in part due to the relative dominance of advective processes and the apparently minor role of diffusion in transport.

Hydraulic gradient, ground water flow, and water chemistry data suggest that within permeable aquifer zones, ground water moves relatively freely across formational and incised paleochannel boundaries. Hydraulic conductivities of Laguna and Mehrten gravels support field observations of free ground water movement across the Laguna/Mehrten geologic contacts. This finding is significant because it helps to explain why the ground water regime in the study area is not dominated by flow parallel to the axes of the gravelly paleochannels, but instead contains a much more uniform flow field than might otherwise be expected. If the gravels were of significantly differing hydraulic conductivities, then a preferred pathway would have resulted in a paleochannel-controlled flow and plume distribution.

The ground water modeling analysis resulted in the development of a numerical ground water flow and solute transport model that realistically represents the movement of ground water and pentachlorophenol in the heterogeneous hydrogeologic system associated with the wood treatment site. The calibrated model yields predictions which compare favorably with field observations of hydraulic gradients and PCP concentrations. Predictions of solute movement are consistent with the observed hydrostratigraphy and behavior of the hydrogeologic system; therefore, the underlying conceptual model upon which these predictions were made is believed to be valid.

Modeling results suggest that predictions of PCP solute transport are sensitive to the degradation rate of the compound in ground water. Review of laboratory studies reveals that relatively short degradation half-lives of a few months have been reported for pentachlorophenol under controlled conditions. Modeling results, however, indicate that a realistic half-life is on the order of 12 years in the ground water environment encountered on this site. The apparent differences between literature and modeled degradation rates may be due to the media and other conditions under which the rates were estimated. The calibrated model of pentachlorophenol movement is believed to be representative of actual degradation of PCP under field conditions for this site.

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TABLE 1
GENERALIZED HYDROSTRATIGRAPHIC UNIT CHARACTERISTICS

Unit	Description
A	Permeable, gravelly unit of the Laguna Formation (upper Pliocene-Holocene). Found south of the plant site. Water bearing only in southern portion of the study area.
AB	Nomlaki Tuff, aquitard (upper Pliocene age). Spatially significant confining unit in the south and southwest.
B	Highly permeable gravel units of the Mehrten Formation (Oligocene-Pliocene) in the southern and western part of the study area. Also comprised of highly permeable gravels of the Laguna Formation on the southeast side of the study area where a paleochannel has been incised into the Mehrten Formation gravels. Contains discontinuous clay lenses. Composed of a thick accumulation of Laguna Formation gravels onsite which wedge out along a paleochannel wall just south of the plant site.
BC	Aquitard unit or series of discontinuous low-permeability units. Between MW-22, P-1, EH-1, and RI-5, this is a thick siltstone of the Ione Formation (Eocene). Further south, it is apparently discontinuous, composed of clayey, silty lenses in the Mehrten and Laguna formations. In the far south (near P-2 and RI-15) tuffaceous and siltstone units form a locally continuous stratum. Onsite it forms a substantial Laguna Formation clay layer that is juxtaposed against the BC siltstone of the Ione, maintaining separation between the B and C zones.
C	Permeable gravels of the lower Mehrten, lower Laguna, and Ione formations south of RI4 and RI-5, and the B and C aquifer zones appear to form a thick gravel unit separated by discontinuous clay lenses. Further south, they are apparently separated again by the BC aquitard. It is composed of lower Laguna gravels onsite. It appears that the B and C gravels combine to form a locally thick permeable unit in the northern portion of the site, where no intervening clay is found.
CD	Deep, largely continuous, low permeability stratum composed of Ione Formation clays and silts (Eocene).
D	Deep sandstone in Ione Formation (Eocene) at well P-1.

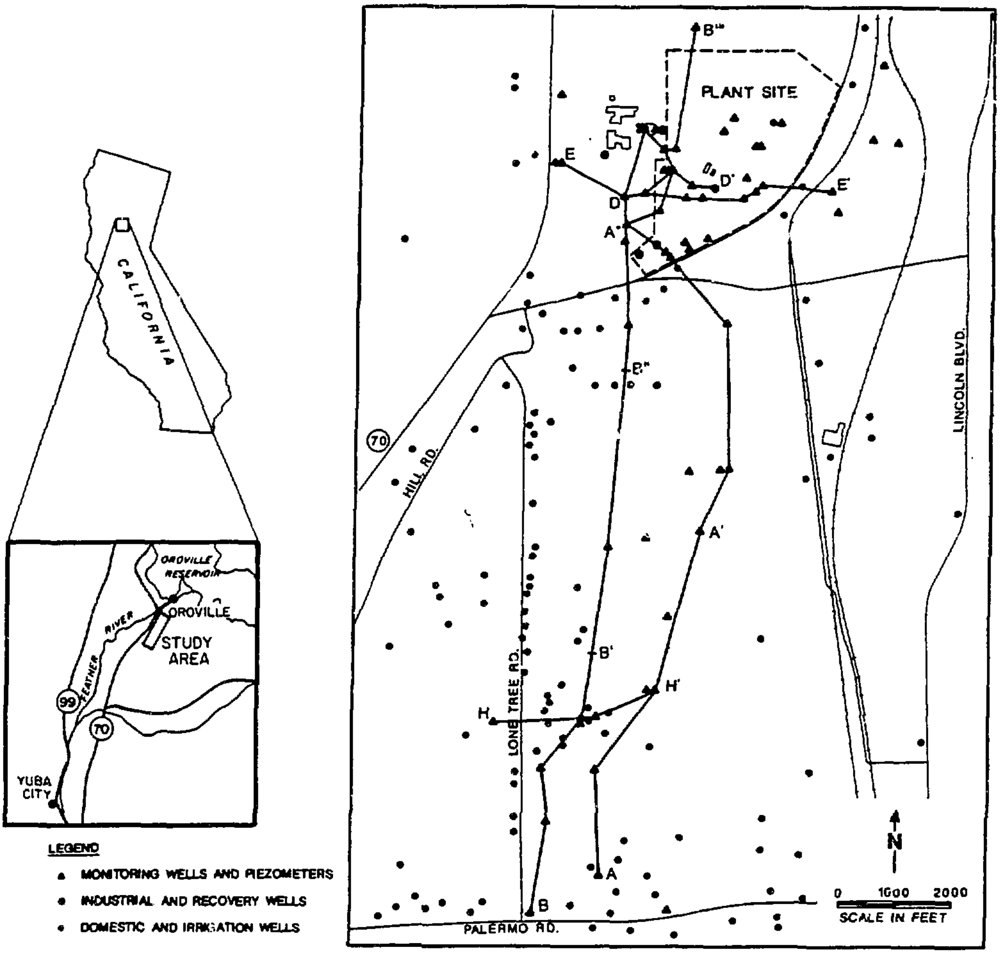


Figure 1. Map of the study area showing plant site, wells and cross-section locations.

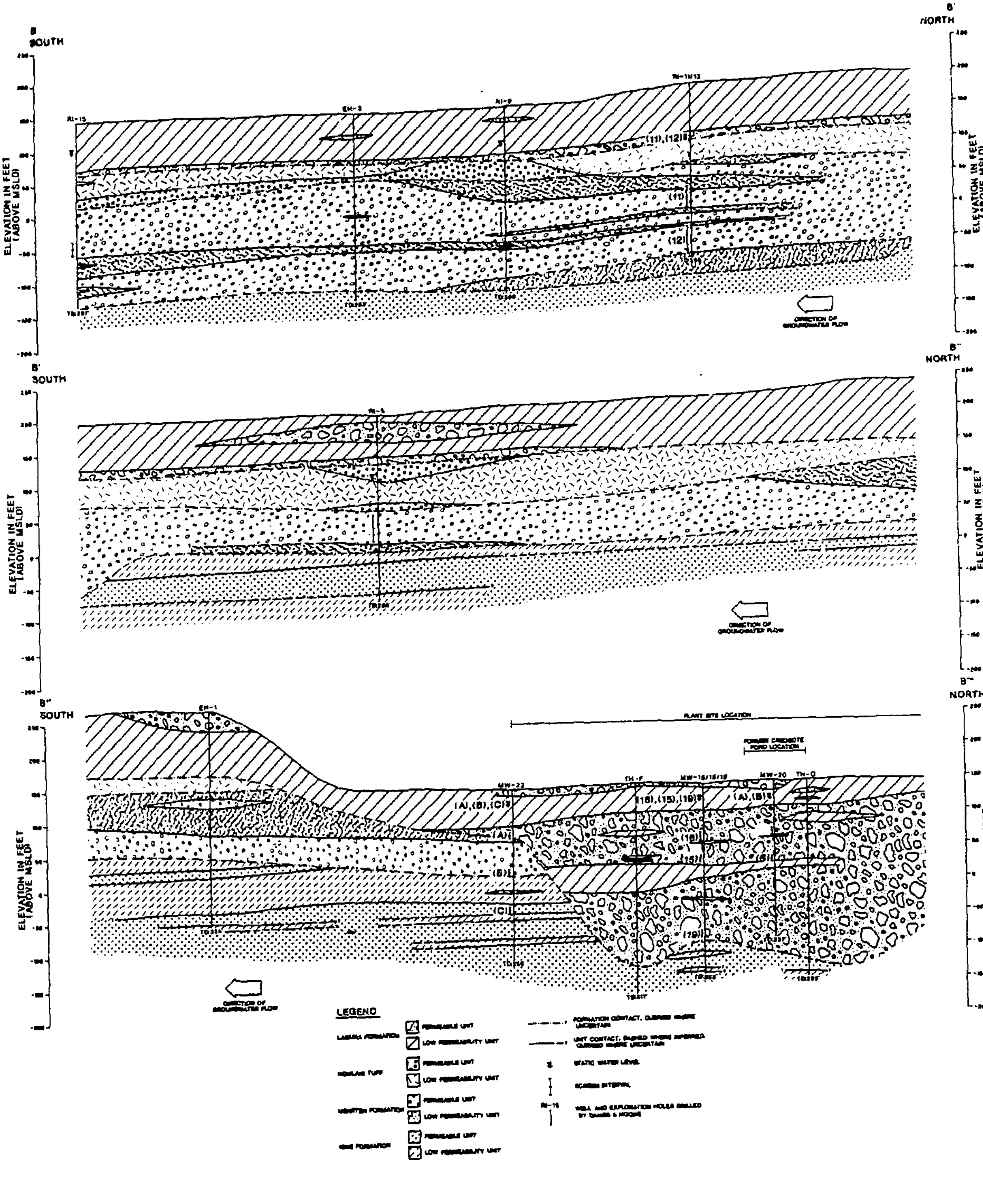


Figure 2. Geologic cross-section B-B'-B''-B'''.

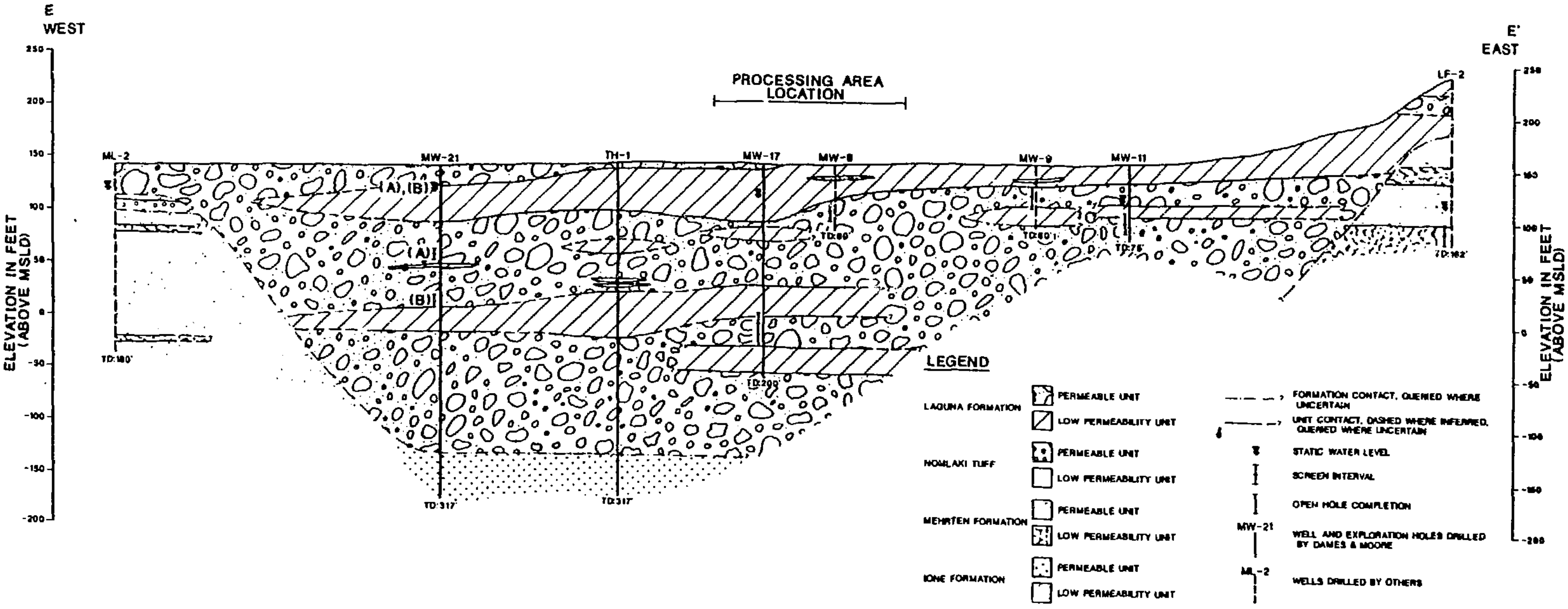
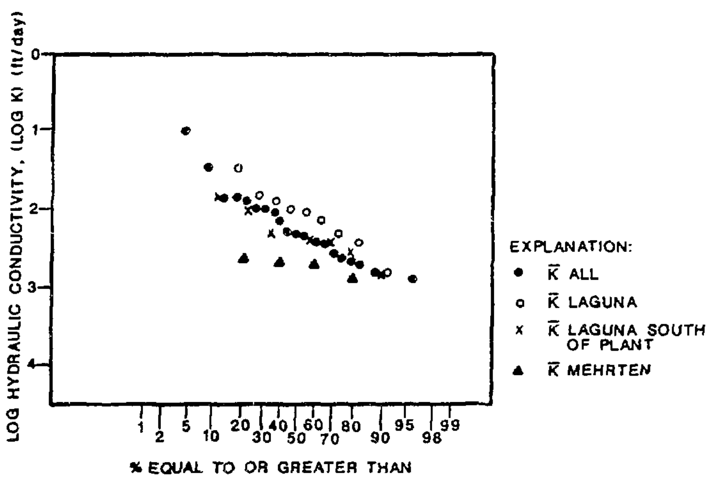


Figure 3. Geologic cross-sections E-E'.



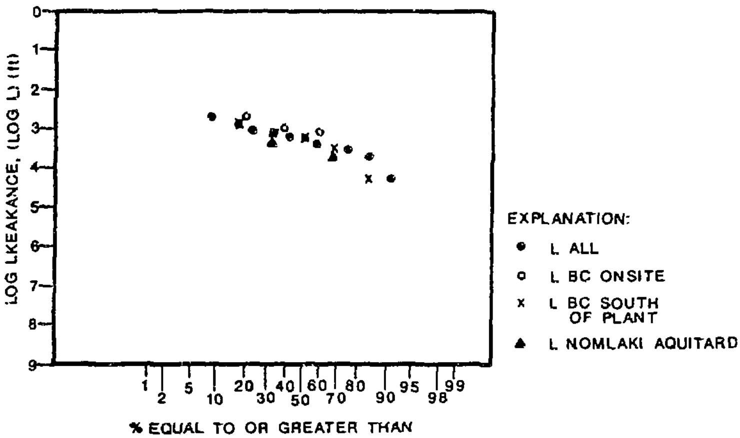


Figure 4. a) Log-probability distribution of hydraulic conductivity of the Laguna Formation gravels at the plant, Laguna gravels south of the plant and Mehrten gravels.

b) Log-probability distribution of leakance of the Laguna Formation clays at the plant, Laguna clays south of the plant and the Nomlaki aquitard.

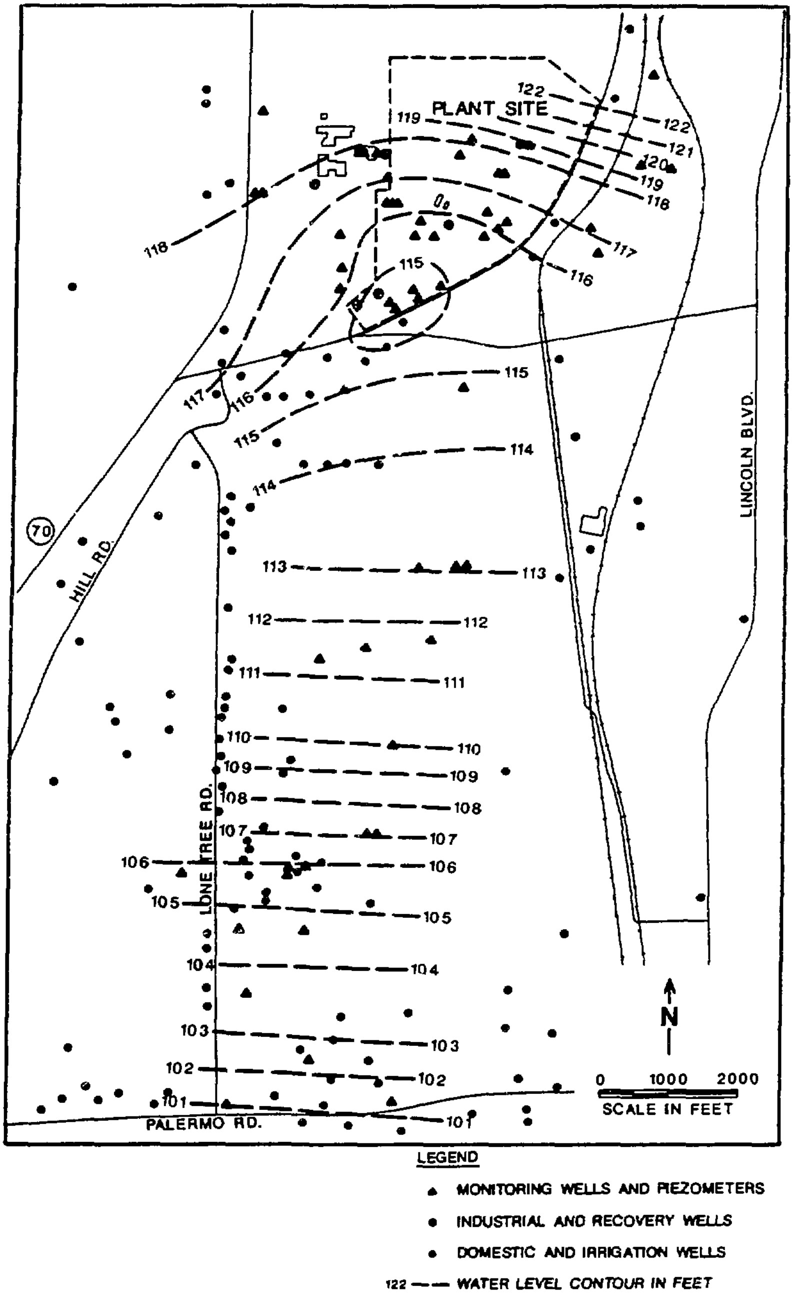


Figure 5. Piezometric head surface contours for the aquifer B zone.

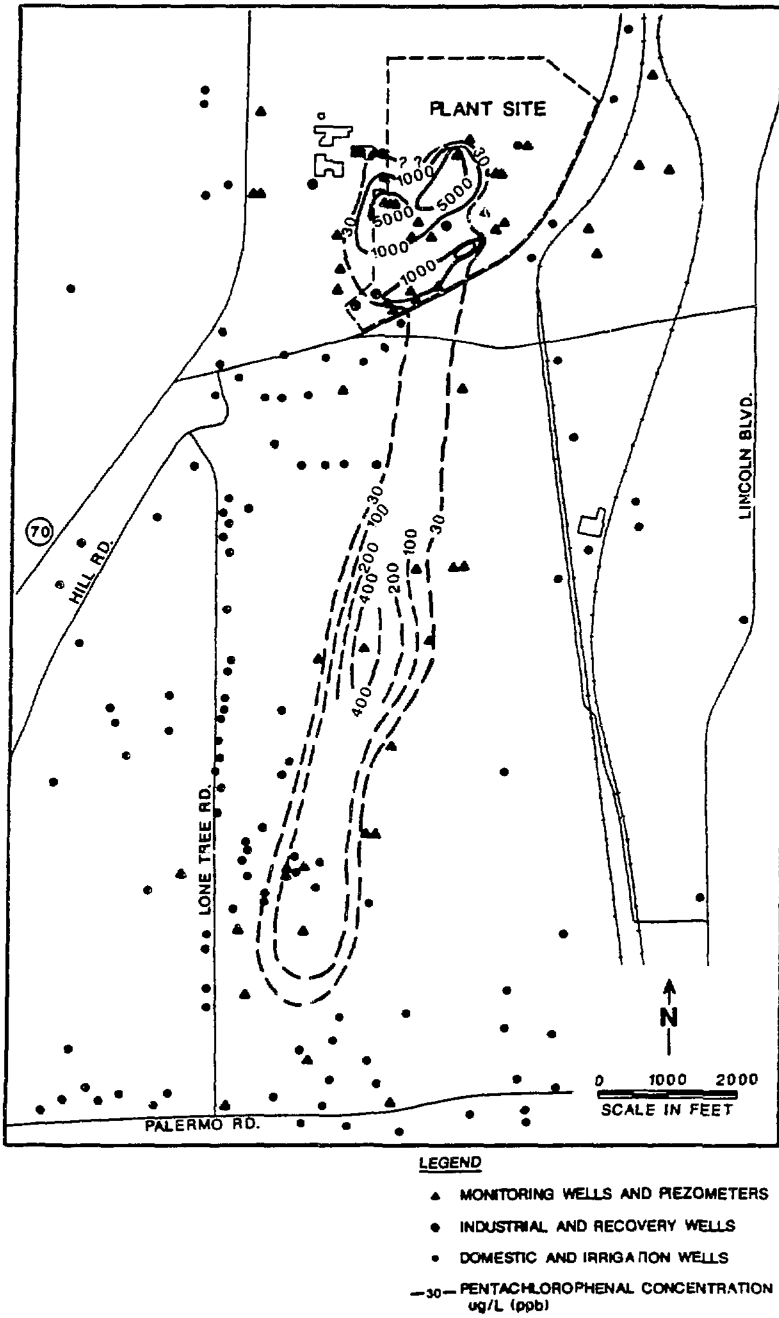
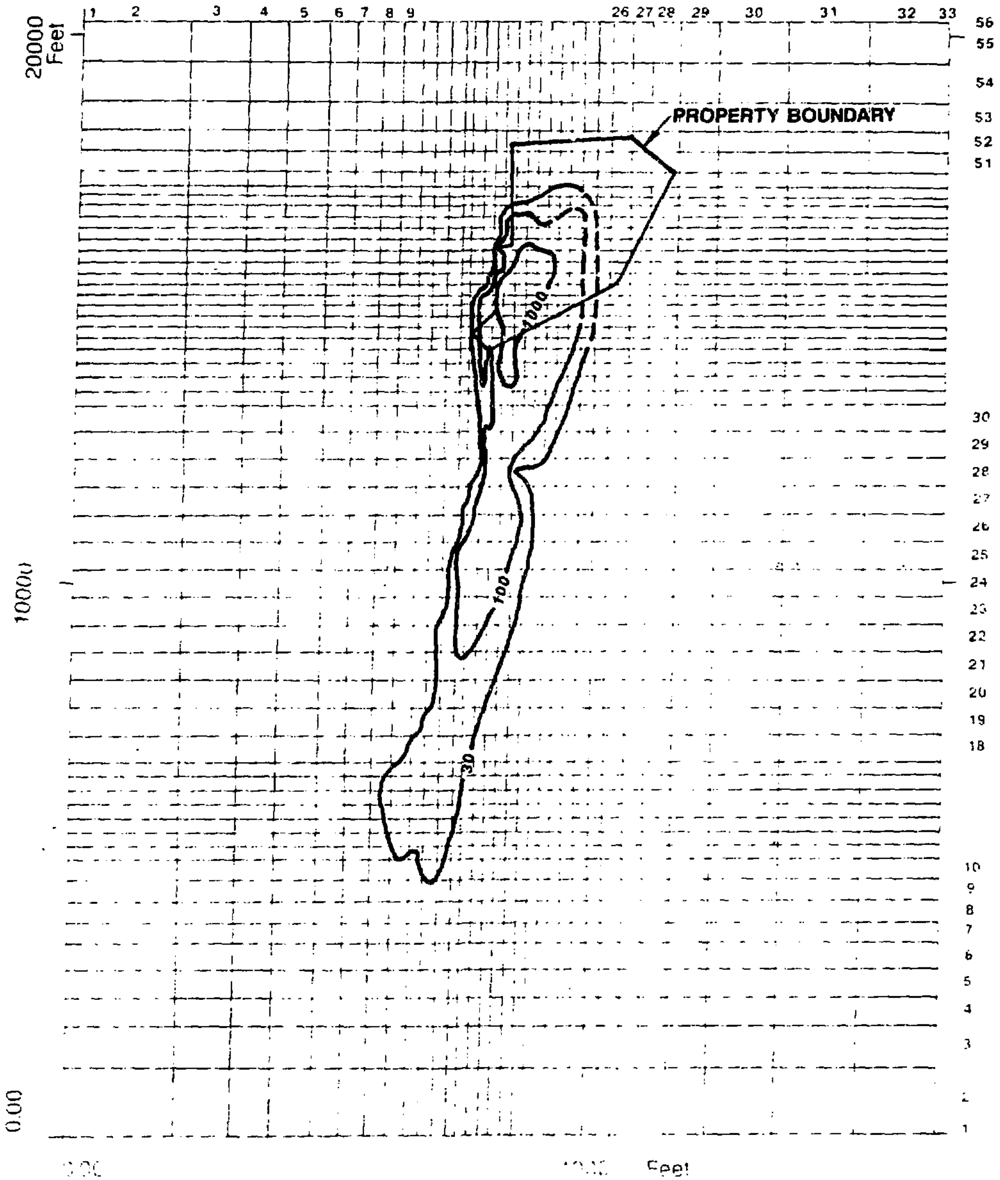


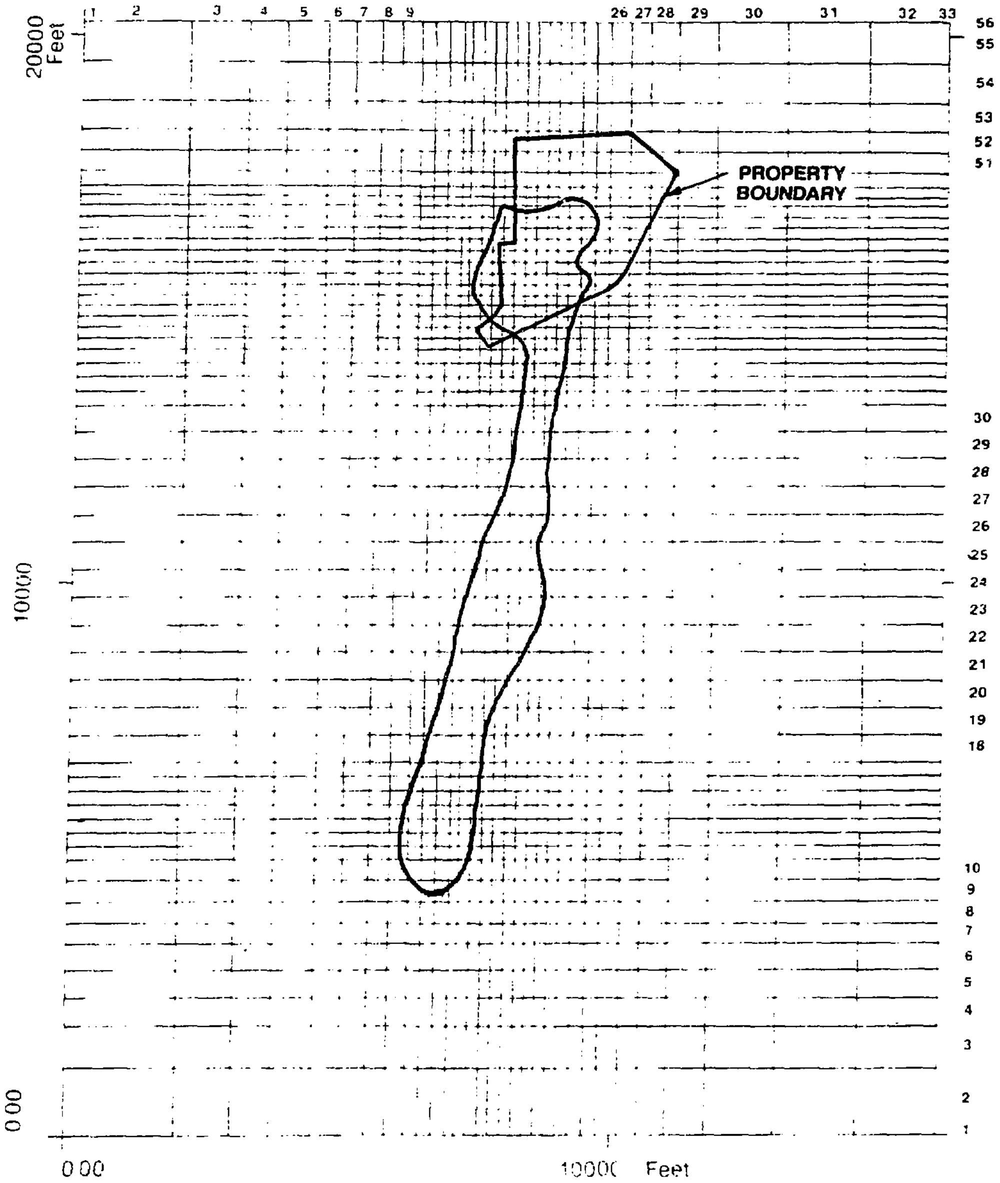
Figure 6. Pentachlorophenol plume distribution in the aquifer B zone (Fall, 1987).



LEGEND

—— SIMULATED PCP CONCENTRATION ISOPLETH (ppb)

Figure 7a. Simulated pentachlorophenol plume in aquifer zone B at calibration.



LEGEND

—— OBSERVED PCP CONCENTRATION ISOPLETH (ppb)

Figure 7b. Observed pentachlorophenol plume in aquifer zone B (1987).